SCHOOL OF ENGINEERING AND THE BUILT ENVIRONMENT

DEVELOPMENT OF A SEMANTIC KNOWLEDGE MODELLING APPROACH FOR EVALUATING OFFSITE MANUFACTURING PRODUCTION PROCESSES

BY

KUDIRAT AYINLA

A doctoral thesis submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy at Birmingham City University

November, 2021

DECLARATION

The work contained in this thesis or any part thereof has not previously been submitted in any form to the University or to any other body whether for the purpose of any other degree, professional qualification, assessment, publication, or for any other purpose (unless otherwise indicated). I confirm that the intellectual content of the work entirely represents my effort except were duly referenced and conforms to relevant academic practices. At this date, copyright is owned by the author © by Kudirat Ayinla (2021).

Student Name and Signature ………………………..

Director of Study Name and Signature ……………………….

DEDICATION

I dedicate this thesis to my dearest husband (Abdulfatai Sanni) and my precious daughter (Reyyah Sanni) born during this PhD journey.

APPRECIATION

It has been a very long journey indeed and I thank the Almighty for his grace and blessings and for granting me the wisdom and strength to complete this PhD. I also thank my parents for their prayers and support all through my PhD journey.

My sincere gratitude goes to my supervisory team Dr Franco Cheung and Dr Abdel-Rahman Tawil for their dedication and support towards guiding me in my research work. Most especially my Director of Studies, Dr Franco Cheung, for his patience in guiding me through the research journey and for being overly considerate in handling my work. I honestly cannot ask for a better supervisor, I count myself as one of the most fortunate in this regard.

Lastly and by no means the least, my sincere appreciation goes to the experts that have helped me in fulfilling this research work. Firstly to Walsall Housing Group (WHG) Team - Paul Nichole and Tim.OShea, and Hadley Group - Ben Towe, and finally QM Systems - Jason Glasse and Guy Sweeney.

I would also like to thank Birmingham City University for the opportunity given to me and for funding my studies.

To my colleague Akinola Siyanbola, BCU could have been a nightmare without you. Thank you so much for being a good friend.

ACKNOWLEDGEMENT

This research was supported by an Innovate UK funded project (Project no. 21800) "Collaborative Knowledge-Based DfMA approach to building cost-efficient, low impact and high-performance houses". The authors would like to thank the participating industrial partners of the research project, particularly Mr Paul Nicol and Mr Tim O'Shea of WHG group, Mr Jason Glasse of QM systems, and Ben Towe of Hadley Group for their contribution to this study.

ABSTRACT

The housing sector in the UK and across the globe is constantly under pressure to deliver enough affordable houses to meet the increasing demand. Offsite Manufacturing (OSM), a modern method of construction, is considered to be a key aspect in meeting these demands given its potential to increase efficiency and boost productivity. Although the use of OSM to increase the supply of affordable and efficient homes is getting popular, the focus has been on 'what' methods of construction are used (i.e. whether implementing OSM or traditional approach) rather than 'how' the alternative construction approach shall be done (i.e. choice of OSM method to meet set objectives). There have been criticisms of the approaches used by professionals implementing OSM methods as some of these approaches are non-structured and these methods have been criticised for being similar to the conventional onsite methods with little process gains. There are previous studies that have compared the performance of OSM and other modern methods of construction with conventional methods of construction. However, there is hardly any attempt nor quantitative evidence comparing the performance of various competing OSM approaches (i.e. methods with standardised and non-standardised processes) in order to support stakeholders in making an informed decision on choices of methods. In pursuit of the research gap identified, this research aims to develop a proof-of-concept knowledge-based process analysis tool that would enable OSM practitioners to efficiently evaluate the performances of their choice of OSM methods to support informed decision-making and continuous improvement.

To achieve this aim, an ontology knowledge modelling approach was adopted for leveraging data and information sources with semantics, and an offsite production workflow (OPW) ontology was developed to enable a detailed analysis of OSM production methods. The research firstly undertook an extensive critical review of the OSM domain to identify the existing OSM knowledge and how this knowledge can be formalised to aid communication in the OSM domain. In addition, a separate review of process analysis methods and knowledge-based modelling methods was done concurrently to identify the suitable approach for analysing and systemising OSM knowledge respectively. The lean manufacturing value system analysis (VSA) approach was used for the analysis in this study using two units of analysis consisting of an example of a typical non-standardised (i.e. static method of production) and standardised (i.e. semi-automated method of production) OSM methods. The knowledge systematisation

was done using an ontology knowledge modelling approach to develop the process analysis tool – OPW ontology. The OPW ontology was further evaluated by mapping a case of lightweight steel frame modular house production to model a real-life context. A two-staged validation approach was then implemented to test the ontology which consists of firstly an internal validation of logic and consistency of the results and then an expert validation process using an industry-approved set of criteria.

The result from the study revealed that the non-standardised ad-hoc OSM production method, involving a significant amount of manual tasks, contributes little process improvement from the conventional onsite method when using the metrics of process time and cost. In comparison with the structured method e.g. semi-automated OSM production method, it is discovered that the process cost and time are 82% and 77% more in the static method respectively based on a like-to-like production schedule. The study also evaluates the root causes of process wastes, accounting for non-value-added time and cost consumed. The results contribute to supporting informed decision-making on the choices of OSM production methods for continuous improvement.

The main contributions to knowledge and practice are as follows:

i. The output of this research contributes to the body of literature on offsite concepts, definition and classification, through the generic classification framework developed for the OSM domain. This provides a means of supporting clear communication and knowledge sharing in the domain and supports knowledge systematisation.
ii. The approach used in this research, integrating the value system analysis (VSA) and activity-based costing (ABC) methods for process analysis is a novel approach that bridges that gaps with the use of the ABC method for generating detailed process-related data to support cost/time-based analysis of OSM processes.
iii. The developed generic process map which represents the OSM production process captures activity sequences, resources and information flow within the process will help in disseminating knowledge on OSM and improve best practices in the industry.
iv. The developed process analysis tool (the OPW ontology) has been tested with a real-life OSM project and validated by domain experts to be a competent tool. The knowledge structure and rules integrated into the OPW ontology have been published

on the web for knowledge sharing and re-use. This tool can be adapted by OSM practitioners to develop a company-specific tool that captures their specific business processes, which can then support the evaluation of their processes to enable continuous improvement.

Keywords: Activity-Based Costing (ABC), Cost Modelling, Value System Analysis (VSA), Knowledge-based Engineering, Offsite Manufacturing (OSM), Ontology, Process Modelling, Root Cause Analysis (RCA).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY OF TERMS

AAQS – African Association of Quantity Surveyors

ABC – Activity-based costing

AEC – Architecture, Engineering and construction

AI – Artificial intelligence

ANN – Artificial neural network

API – Application programming interface

BIM – Building Information Modelling

BoM – Bill of material

BoQ – Bill of quantities

BPMN – Business process mapping notation

CAA – Computer aided analysis

CAD – Computer aided design

CBR – Case-based reasoning

CE – Concurrent engineering

CWA – Closed World Assumption

DfMA – Design for Manufacture and Assembly

DL – Description Logic

EBC – Elemental-based costing

EM – Enterprise Modelling

ES – Expert systems

EJ – Expert judgement

FLogic – Frame Logic

GA – Genetic algorithm

HA – Housing association

IBS – Industrialised building systems

IDEF – Integrated definition

IFC – Industry foundation classes

IHB – Industrialised house building

JIT – Just In Time

KBE – Knowledge-based engineering

KBS – Knowledge-based systems

KIF – Knowledge interface format

KP1 – Key Performance Indicator

LSF – Light steel frames

MCS – Monte Carlo simulation

MMC – Modern methods of construction

NRM – New rules of measurement

OCL – Object Constraint Language

OCML – Operational Conceptual Modelling Language

OI – Offsite industrialisation

OIL – Ontology Interchange Language

OKBC – Open Knowledge Base Connectivity

OPW - OSM Production Workflow

OWA – Open World Assumption

PML – Ontology Markup Language

OSF – Offsite fabrication

OSC – Offsite construction

OSM – Offsite manufacturing

OWL – Web ontology language

RBC – Resource-based costing

RC –	Root Cause
RDF –	Resource description framework
RICS –	Royal Institute of Chartered Surveyors
RuleML –	Rule Markup Language
SB –	System building
SPAQRL –	SPARQL Protocol and RDF Query Language
SQWRL –	Semantic Query-Enhanced Web Rule Language
SWRL –	Semantic web rule language
TQM –	Total Quality Management
UML –	Unified modelling language
VA –	Value Analysis
VSA –	Value System Analysis
W3C –	World Wide Web Consortium
XML –	eXtensible Markup Language
XOL –	Ontology Exchange Language

CHAPTER 1: INTRODUCTION

1.1 Background to Study

The steady decline of manual and skilled trades in the construction industry has increased the recognition of offsite manufacturing (OSM), an aspect of Design for Manufacture and Assembly (DfMA) methods as one way to boost productivity and performance. The idea of improving efficiency in the construction industry by learning from other industries is not new and has gained much significance lately. This is partly because the construction industry has for a long time been associated with inefficiencies, which is argued to be mostly facilitated by the traditional procurement and method of construction (Barbosa *et al.* 2017). A recent government-commissioned report by Farmer (2016) has advised the industry to either 'modernise or die' while citing low productivity and predictability as some of the symptoms of failure and poor performance by the industry. This together with the increasing expectations of clients and end-users creates pressure and opportunities for the industry to improve. Therefore, the adoption of advanced factory production systems such as those used in the car manufacturing sector into the construction sector paves a new way for transferring expertise between sectors (Gann 1996). Several attempts have been made with regards to knowledge transfer with regards to the concept of customisation and mass production into the construction of low-cost housing and this is being achieved through the implementation of off-site manufacturing in construction. However, the decision to introduce new methods of construction is a major challenge for construction professionals due to change resistance and also because the knowledge required to make the decision is fragmented and partially owned by individual experts on a case-by-case basis (Sabol 2008).

Offsite manufacturing (OSM) enables large aspects of the construction process to be carried out in controlled environments, e.g. a factory environment where components are constructed and assembled in a factory, then transported to the final point of use, usually the construction site (Meiling *et al.* 2012a, Pan and Goodier 2012, Quale *et al.* 2012). The benefits of this method have been widely studied to include reductions in construction time, increased quality, low health and safety risks, low environmental impact, reduced whole-life cost, and a consequent increase in predictability, productivity, whole-life performance and profitability

(Blismas *et al.* 2006a, Pan *et al.* 2008, Pan and Goodier 2012). These benefits are argued to be the outcome of process improvements from integrating concepts like lean manufacturing (Pasquire and Connolly 2002) and DfMA which are synonymous with factory house building methods (Gbadamosi *et al.* 2019) with the goal to optimise the production performance and efficiency. The government and public sector in various nations, particularly those from the developed countries have created various incentives to encourage cross-industry learning from other industries such as automotive, aerospace, and manufacturing with focuses on developing more efficient alternative construction methods through accommodating automation and standardisation of processes (Pan and Sidwell 2011, Hairstans and Smith 2018). In the UK, for instance, the government commissioned reports such as Latham (1994) and Egan (1998) have previously identified the needs and barriers for technologically-driven innovations. Offsite manufacturing (OSM) is seen as the approach to improve the products from the industry (Cabinet Office 2011, HM Government 2013), and a requisite to changing the craft-based and labour-intensive nature of the construction industry (Gibb and Isack 2003, Miles and Whitehouse 2013). This pressure by the government also stems from the shortage in supply of low-cost housing all over the UK (Secretary of State for Communities and Local Government 2017). OSM is seen as a means to speed up housing production and is widely accepted as one direction for the industry to meet the housing shortage and efficiency required (Venables *et al.* 2004, Miles and Whitehouse 2013).

However, although the use of offsite construction has been proven to be advantageous with a significant number of publications on its potential improvements, its market uptake and acceptance is still quite low in both developed and developing countries (Goulding *et al.* 2015). Construction practitioners are still caught between the decision to use OSM or the conventional method of construction, and the latter remains competitive and more accepted than the former. The low uptake of OSM in the construction industry could perhaps be a result of limited quantitative-based evidence on the process improvements achieved. This lack of evidence is also a hindrance in determining the various types of OSM methods that could be used to achieve specific objectives. While most of the benefits of using OSM are linked to process improvements through lean manufacturing/production (Pasquire and Connolly 2002), it appears to be generalised that these benefits can be achieved regardless of the approach to OSM implemented, and there has been limited discourse on the implications/impacts of the choice of OSM methods on the realisation of these associated process benefits.

There are various approaches to building a house offsite ranging from the use of standardised and non-standardised methods. Unlike onsite operations that focus predominately on the organization of labour and materials, the planning of OSM is more complex involving the organisation of various production line workflows, design configurations of different workstation arrangements, different automated processes, and various levels of human intervention (Zhang *et al.* 2016). However, the extent to which these factors are implemented varies depending on the choice of OSM method used. OSM methods involving non-standardised approaches have been criticised for merely replicating non-standardised practices similar to conventional onsite methods, under an enclosed environment (Pasquire and Connolly 2002). On the other hand, more standardised OSM methods are encouraged due to perceived higher efficiency achieved from the introduction of robotics systems in production, transportation, and assembly. The implication for OSM practitioners is the varying amount of risk and capital investment involved in these two competing OSM methods (i.e. standardised and non-standardised methods), which is partly due to lack of uncertainty on demand (Lang *et al.* 2016) amongst others.

There have been recognised efforts and contributions on developing decision support tools for comparing methods of construction (Murtaza *et al.* 1993, Aldridge *et al.* 2001, Chen *et al.* 2010a, Pan and Goodier 2012, Pan *et al.* 2012). However, the techniques and tools developed in these studies have only enabled qualitative or quantitative comparison between OSM and the conventional construction method in parts. There is currently no documented evidence relating to developing a decision support model to enable stakeholders in understanding the process benefits between the various methods of OSM. This poses a key question around if the process improvements associated with the OSM method are indeed practical regardless of the approach for OSM selected (i.e. whether structured or non-structured). However, the data needed for this level of assessment is not readily available in literature and is often based on individual company approaches and processes. It is in view of this that this study proposes a bespoke performance assessment model for OSM production methods that implicitly captures information on low-level processes, thus enabling value evaluation in the process while being easily accessible to construction practitioners for informed decision making.

The use of Knowledge-based engineering (KBE) techniques and semantic models (ontologies), in this regard, is particularly useful as it links data of many contexts. Ontologies are a well-established approach for leveraging data and information sources with semantics and have track records of being efficient in knowledge capture and sharing (Lin *et al.* 2006). Their capability in terms of enabling intelligent real-time and context-specific knowledge modelling which would be useful in the OSM domain. Knowledge-based systems (KBS) are considered suitable for solving problems that demand considerable expertise, judgment or rules of thumb (Chau and Anson 2002) and could help with offsite manufacturing process modelling and analysis. The knowledge-sharing process can be further enhanced through web technologies where users can gain access to the captured/stored knowledge (Lin *et al.* 2006) about OSM systems and methods. This approach will help obtain a realistic and holistic analysis of OSM methods and support the decision-making process. This opportunity is what the research intends to explore.

1.2 Problem Statement

The UK housing sector has been under pressure to increase low-cost housing delivery to combat the housing shortage experienced and fix the 'broken housing market' (Shostak and Houghton 2008, Secretary of State for Communities and Local Government 2017). There is a persisting situation of demand for houses being greater than supply. In England for instance, between 225,000 to 275,000 or more homes are needed per year to keep up with population growth. However, only an average of 160,000 new homes is built each year on average since 1970 (Secretary of State for Communities and Local Government 2017). Given these persisting issues, many governments (such as the UK government) have taken the initiative to raise awareness that construction needs to be re-engineered to accommodate automation and standardisation and use of alternative methods are being explored through OSM (Pan and Sidwell 2011). However, despite the well-documented benefits of OSM, its uptake in the construction industry has been very low (Pan *et al.* 2008, Pan and Goodier 2012) with a reported 5% market share in the UK in 2009 (Taylor 2009). A slight increase of 6% was reported in 2012 in the UK (Goulding *et al.* 2012a) and 7% by 2016 (KPMG 2016). A similar market share or even lower was also noticed in other countries. For instance, as of 2014, the market share of OSM in the US was 3% (Future Focus 2017). While the implementation of OSM is increasing in recent years, it is not as rapid as would be expected given the widely studied benefits of the OSM method.

One major barrier to the use of the OSM method reported in past research studies remains the lack of evidence-based benefits of the OSM method over the traditional approach (Blismas *et al.* 2006a, Pan *et al.* 2008, Pan and Goodier 2012). However, a bulk of the research studies has been done on the development of decision support tools in choosing between OSM and the conventional onsite construction methods (e.g. Murtaza *et al.* 1993, Aldridge *et al.* 2001, Chen *et al.* 2010a, Pan *et al.* 2012, Pan and Goodier 2012) to support the use of OSM. These research studies have been successful in guiding the judgment on the implementation of OSM and could perhaps have contributed to the slight increase in acceptance in the last decade. However, despite these efforts, there are still other challenges inhibiting the use of OSM. For instance, researchers have argued that OSM domain knowledge is fragmented and there is still a lack of understanding/evidence of its holistic benefit compared to the significant capital investment required to set up a manufacturing process (Blismas *et al.* 2006b, Blismas and Wakefield 2007, Pan *et al.* 2008, Jabar *et al.* 2013), and the lack of in-depth understanding of the associated business risks with the use of OSM (Luo *et al.* 2015) such as in cases of low demand or market burst.

Generally, OSM is recognised for its superior process benefits compared to the conventional onsite methods since OSM attempts to streamline and automate production in a controlled factory environment while incorporating principles of lean manufacturing and its associated process benefits. However, the methods to producing building elements and components offsite can be generally categorised into two based on the level of standardisation involved – i.e. standardised and non-standardised processes (Lawson *et al.* 2010). The latter is criticised for providing very little improvement from the conventional onsite method (Pasquire and Connolly 2002, Zhang *et al.* 2020). Zhang *et al.* (2020) and Pasquire and Connolly (2002) in their studies have reported non-standardised practices in OSM processes and emphasised the need for the industry to avoid repeating 'onsite practices under a roof' if the benefits of implementing DfMA and lean manufacturing are to be realised to ensure the profitability of OSM method compared to the conventional onsite method.

Considering that the construction sector is dominated by private housing and more than three-quarters of all recently completed houses are built for the private sector (GOV.UK 2020), it is perhaps safe to argue that most current and prospective OSM practitioners are profit-based.

These key stakeholders may thus be discouraged from adopting OSM due to the inability to effectively determine the business risk with switching to OSM due to the unpredictable housing market typified by the ‘boom and burst cycles’ (Lang *et al.* 2016). Their approach to construction is described as operating on a speculative business model to mitigate the risk with unpredictable market conditions thus allowing these stakeholders to respond well to the market fluctuations (Lang *et al.* 2016). Unfortunately, OSM does not offer this flexibility as it most times requires high capital investment to set up a production line, and running of factory space regardless of demand and market conditions. Arguably, the choice of OSM method used may increase or decrease this risk due to varying degrees of flexibility with the integration of automation and standardisation. However, the extent of the risk impact is still unknown. For instance, while non-standardised OSM methods might be able to allow for flexibility and low capital investment similar to onsite practices, the level of efficiency from the process may be compromised and productivity gains may be impacted. The latter is more concerning as the implication to the OSM domain is that practitioners may struggle to remain competitive in the volatile market especially in terms of the final cost of the product, which is a major factor in decision making for choosing a construction method (Pasquire and Connolly 2002).

Although the governments in various countries have been encouraging the use of OSM over the conventional onsite methods, the focus has been on ‘what’ is done (i.e. switching to OSM from the conventional onsite method), with little attention paid to ‘how’ it is done (the method of OSM to be used to achieve identified goals). Emphasis should be rather placed on the latter since a large proportion of the benefits of using OSM is linked to the result of process improvements realised through this method (Pasquire and Connolly 2002). This implies that some practitioners implementing OSM may not be well aware of the inefficiencies in their processes and the perception that OSM helps them attain better and more competitive products may be flawed depending on how it is done. It is thus important for existing and/or potential OSM practitioners to pay attention to their approaches and be able to evaluate their processes in terms of their performance using certain metrics. The availability of a process analysis tool could reduce the scepticism towards the use of OSM with sufficient information to support practitioners in analysing their current or proposed processes and recognising areas of inefficiencies and opportunities for improvements. However, the aspect has received little or no attention from existing research studies.

To develop such a tool, an in-depth understanding of various OSM production workflows and processes is required. However, other challenges are surrounding this requirement due to the nature of the required knowledge. To start with, there is a lack of consensus or coordinated effort in regard to agreeing on what shall be included in its definition (Yunus and Yang 2012, Baghchesaraei *et al.* 2015). The lack of consensus further compounds the issue of how to appraise various OSM methods (Song *et al.* 2005, Blismas *et al.* 2006b, Pan *et al.* 2008, Abdullah and Egbu 2010, Arif and Egbu 2010, Haron *et al.* 2015). Other issues reported involves the unavailability of documented sources of information about modularisation (Murtaza *et al.* 1993, Aldridge *et al.* 2001, Pasquire *et al.* 2005). Although there are a lot of publications on OSM, the knowledge is not well-structured and is described as being fragmented (Blismas and Wakefield 2007, Jabar *et al.* 2013). Lastly, this fragmentation perhaps indicates that the knowledge on OSM processes may reside with individual companies and practitioners and there is no consensus on what can be regarded as best practices for benchmarking. These issues must be addressed in order to support systematisation of OSM domain knowledge to support the development of the process evaluation tool.

The nature of the research problem and the knowledge gap can thus be divided into two major aspects; (i) lack of a production process performance evaluation tool that allows comparison of the various OSM production methods in terms of their process performance thus supporting informed decision making on choices, (ii) the fragmented nature of OSM knowledge thus posing challenges with systematisation of the domain knowledge to allow for the development of a generic tool that can be adapted.

1.3 Research Questions

The preliminary review of existing literature on the subject and identification of gaps in existing knowledge on OSM led to the following research questions that this research intends to answer:

1. Is the current understanding and representation of the knowledge of OSM domain accurate and how best can existing knowledge be modelled for accurate representation and to support knowledge sharing and clear communication?

2. What methods and approaches can be used to analysis OSM processes to provide information and allow for value-based analysis of the processes to support accurate decision-making on choices?
3. In what means can the knowledge of OSM processes be formalised and modelled for the purpose of systemising and automating process analysis of OSM methods considering the current data and information-driven advances in the construction industry?
4. Are there major differences in the process performance when using non-standardised and standardised OSM methods, and what are the major causes of any differences observed?
5. What method can be used to validate the developed decision-support tool to test the logic and to determine its fitness for purpose?

1.4 Research Aim, Objectives

1.4.1 Research Aim

In pursuit of the research gaps identified, this study aims to develop a proof-of-concept knowledge-based process analysis tool that would enable OSM practitioners to efficiently evaluate the performances of their processes to support informed decision-making and continuous improvement.

1.3.2 Research Objectives

The following objectives will be used to pursue the research aim:

1. To examine the contemporary issues with existing knowledge of OSM and where necessary to develop theoretical definitions and classifications to support better understanding and communication in the OSM domain;
2. To apply industry-based approaches for analysing manufacturing processes and determine a suitable approach for evaluating the performance of competing OSM processes;
3. To investigate the use of knowledge acquisition and modelling methods and languages and determine the best-suited approach to support formalisation and systematisation of OSM knowledge in a tool to support objective (2);

4. To assess the performance of competing OSM production methods using the tool developed based on the outcome of objective (2) using an example of methods involving non-standardised (i.e. static method) and standardised (semi-automated method) processes;
5. To investigate the constraints in the performance of the OSM methods from objective (4) and determine causes of these constraints to support informed decision and continuous improvements;
6. To validate the developed tool and provide guidance/recommendations on the use and application.

1.5 Research Justification

The research challenges with the implementation of OSM as identified in existing literature include the lack of systemised knowledge for OSM compounded with the unavailability of sufficient data to allow for such detailed evaluation of choices (Rahman *et al.* 2008). To encourage the use and implementation of OSM in the construction industry, many aspects need to be addressed. One aspect is the demand for offsite manufactured houses which must be increased so that product prices are competitive with the conventional method and manufacturers can find the business profitable given the level of capital investment involved. Also, there is a need to create opportunities for knowledge retrieval and sharing in the domain where existing and potential OSM practitioners are able to access the relevant information and tools to evaluate their processes and understand how they are performing, and where improvements are necessary. This will contribute to reducing the level of uncertainty and risk in the business.

Therefore, a system that captures the knowledge of OSM processes and systems, and enables analysis of choices will help in bridging the information accessibility gap and enable informed decisions on the advantages and long-term value provided by this method of construction. OSM process information is however as sensitive data that involves approaches used by individual companies in gaining competitive advantage in the market, and this sort of data is not readily available in published sources. Hence, the importance of developing an industry-based approach and tool which will capture key aspects of OSM such as its systems, product, manufacturing methods and processes, and associated process information such as cost drivers, resource requirement, cost and time consumption, etc. to be able to facilitate automation using advanced intelligent process analysis.

This research study intends to develop a platform-independent semantically rich and formal representation of OSM knowledge (including its systems, methods, processes, and products) that is generic and reusable for OSM practitioners and capable of being adopted for specific company needs, which will enable process analysis of OSM production methods and support decision making on the use of competing methods.

1.6 Outline Research Methodology

The methodology adopted for this research has been carefully selected based on the research problem and questions. A combination of qualitative and computational/analytic research methods (i.e. case study, interviews, focus group workshops, and computer programming method) are adopted. The research process was carried out in five major phases as outlined.

Phase 1: Literature Review Analysis

The first phase comprises a robust and systematic critical review of literature on key aspects related to the research such as (i) offsite manufacturing OSM; (ii) lean manufacturing tools and process modelling methods and techniques (iii) an overview of semi-formal knowledge modelling method to represent the manufacturing processes of (iv) a general overview of knowledge-based engineering (KBE) and the use of ontology for structuring domain knowledge. This phase is critical to addressing the question of 'what' data is needed for process analysis for OSM as well as 'how' the data is to be stored, retrieved and presented to end-users.

Phase 2: Conceptual model development

The second phase of the study involved the development of three major models from secondary data obtained from the literature review: (i) a classification system for OSM to support knowledge structuring in the ontology; (ii) development of a framework to support process modelling and analysis for OSM production stage which would form the basis of an activity-based costing approach (iii) development of a framework to represent the architecture and interactions of the systems in the knowledge retrieval process of the developed ontology. This phase is crucial to help ensure that there is a structure to guide the data collection phase.

Phase 3: Industrial visit and case study method for initial data collection to support the developed conceptual models

In this phase, the conceptual models developed were further populated using observations and expert input from a real-life selected offsite case. Additionally, this stage involved the collection of primary data from targeted experts using series of semi-structured interviews and focus group discussions. This was followed by a focus group discussion with other OSM manufacturing companies in order to generalise the process model developed. The purpose of the later stage is to ensure that the company-specific process can be refined into a more generic process that captures common practices in the industry and provide for a reasonable level of adaptability. The various qualitative data obtained during the discussion sessions were analysed using content analysis in order to extract knowledge delivered from the sessions.

Phase 4: Ontology development stage

This stage featured a desktop study approach to model the data gathered in the knowledge-based system. Protégé ontology builder was selected for this purpose because it implements a rich set of modelling structure of knowledge and allows for effective manipulation of the ontology (Sivakumar and Arivoli 2011). Web-ontology language (OWL) was used in this study as this is the supported language in the tool - Protégé. For the purpose of the analysis intended, some estimating rules were modelled in the ontology using semantic rule-based language (SWRL) to support reasoning in the ontology. Also, the ontology was checked for consistency using the Pellet reasoner.

Phase 5: Testing, Validation, Modifications and final model development

A two-stage validation approach was adopted in this study. First, the ontology was tested with a use-case of a real-life OSM project as an internal validation approach, and this was followed by a second stage validation of the results by industry experts. This followed a modification process to implement feedbacks from experts, and then the final model development that was published on the web.

1.7 Research Scope

Given the nature of the research which is multidisciplinary and cuts across many facets, it is necessary to define the scope and identify any limitation associated with the research strategy and data collection methods that may influence the findings from the study. Also, as the research study is intended towards a proof-of-concept, its boundaries need to be defined.

The scope of this research is as follows:

- Manufacturing/production stage: the study is limited to the production stage of OSM methods of construction. The starting point of the data collected is from the point of material delivery to work stations and the endpoint is the point of loading the finished products onto the transport trolley or vehicle. The performance of the design stage and onsite assembly processes are not included in the analysis and results of this research study.
- Product type: Although the developed OPW ontology (the tool) includes classifications of various systems of OSM such as volumetric, panelised, hybrid methods. The ontology has only been populated and tested with process data relating to the panelised system of OSM and has this only been used in analysing this system of OSM.
- Production process type: The ontology only contains information on two methods of OSM production, the static and semi-automated methods representing typical examples of non-standardised and standardised OSM methods respectively. Thus, for more methods to be accommodated, actual data relating to the low-level shop floor activities will have to be modelled into the ontology.

The implication of this is that the data obtained from the semantic model needs to be used with caution bearing in mind that other factors may impact overall decision making. In a situation where results obtained are in a close range, there may be a need to consider data outside of the boundaries of this research to make a more informed decision. Also, there are only two units of analysis currently that can be compared using the tool. However, as the ontology is extendible, these can be covered in future works.

1.8 Structure and Content of Thesis

The thesis is subdivided into nine chapters which consist of an introductory chapter, three literature review chapters cutting across the various discipline of knowledge applied in the study, a chapter explaining the conceptual model development, a methodology chapter, a chapter on the knowledge modelling and development, a chapter for the use case implementation and validation, and finally a conclusion chapter. The contents in each of these chapters are outlined below and illustrated in Figure 1.1.

Chapter 1*, **Introduction***: provides a background and context to the study by highlighting the relevant knowledge and contributions in the OSM domain and the issues surrounding OSM knowledge documentation. This leads to the identification of the research problems and the research questions. An outline of the aim and objectives of the study are also in this chapter. A justification for the research is provided and the main contributions are also highlighted.

Chapter 2, Review of Offsite Manufacturing (OSM): introduces the literature and historical context of OSM and its practices in the construction industry of many countries. Also, the issues of defining and classifying OSM to support knowledge modelling are reviewed.

Chapter 3, Review of process analysis methods and techniques: this chapter reviews the methods of process analysis and the data required for analysis. The various types of cost modelling methods that are used in the construction and manufacturing sectors were reviewed and the suitability of each method for analysing OSM processes was critically evaluated.

Chapter 4, Review of knowledge-based modelling methods: the concept of knowledge modelling was introduced and its application in different domains. This chapter reviews the body of knowledge on informal, semi-formal and formal representation of domain knowledge for better communication.

Chapter 5, Conceptual model development: three research frameworks were developed based on the reviewed literature in previous chapters in order to guide the data collection processes of the study. One of the frameworks represents the architecture of the proposed knowledge-based system, another presents the generic classification system to represent common vocabularies and understanding in the OSM domain to guide the knowledge modelling process, while the last framework illustrates the ABC approach to be used for analysing the process data in the ontology.

Chapter 6, Research methodology: this chapter covers the philosophical underpinning that guides the selection of the research method for this study while also examining the research problems in detail in order to develop a suitable research strategy and design.

Chapter 7, Computational modelling of OSM production process data: this chapter analyses the data collected for the purpose of the modelling exercise. A semi-formal representation of the OSM process data is developed, and this is further modelled formally using OWL to support reasoning and analysis of the data. The rules developed in the ontology are presented and explained in this chapter.

Chapter 8, Evaluation, Testing and Validation of ontology: this chapter presents the analysis of the data modelled in the ontology using a use-case to test the model. A synthesis of the findings from the USE CASE is presented while also linking back to existing literature. The results of the two-stage validation are also presented in this chapter.

Chapter 9, Conclusion, Recommendations and Implication of research: Finally, a conclusion was drawn from the overall research in the chapter and some recommendations for further research were outlined. The practical implications of the research are also discussed.

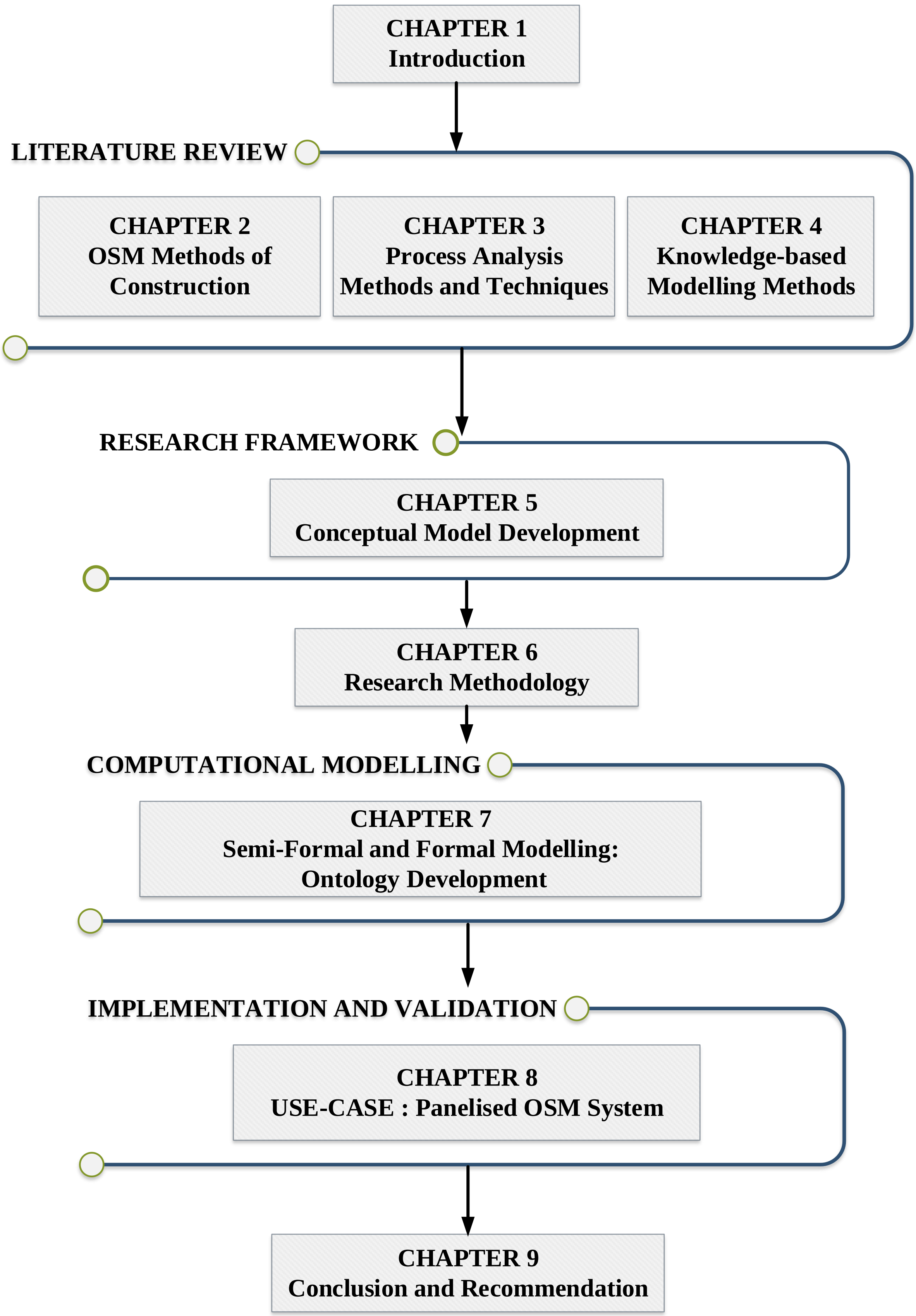


Figure 1.1: Thesis Structure

1.9 Summary of Publications and Output

Some part of the research output has been published in peer-reviewed journals and conferences, a copy of the papers are attached in Appendix E: outlined as follows:

1. Ayinla, K, Cheung, F, and Skitmore, M, (2022) Process waste analysis for offsite methods of house construction – A case study of factory wall panel production. Journal of Construction Engineering and Management, Vol. 148 No. 1: 05021011. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002219

2. Ayinla, K, Edlira, V, Cheung, F and Tawil, R-A (2021) A Semantic Offsite Construction Digital Twin- Offsite Manufacturing Production Workflow (OPW) Ontology In: Proceedings of the Second International Workshop on Semantic Digital Twins (SeDiT 2021), 6 June 2021, Greece.

3. Ayinla, K., Cheung, F. and Tawil, A. (2019), "Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system", Construction Innovation, Vol. 20 No. 2, pp. 223-246. https://doi.org/10.1108/CI-07-2019-0064

4. Ayinla, K, Cheung, F and Tawil, R-A (2019) Towards an Ontology-Based Approach to Measuring Productivity for Offsite Manufacturing Method In: Gorse, C and Neilson, C J (Eds) Proceedings of the 35th Annual ARCOM Conference, 2-4 September 2019, Leeds, UK, Association of Researchers in Construction Management, 587-596.

CHAPTER 2: TOWARDS MANUFACTURING IN CONSTRUCTION – UNDERSTANDING OSM METHOD OF CONSTRUCTION

2.1 Introduction

This chapter presents the relevant literature relating to the background of OSM implementation in the AEC industry with the main focus on the UK construction industry. This is presented in two parts, the first part reviews some of the contemporary issues relating to the construction sector and provides some context on the need for cross-industry learning from manufacturing to construction. The second part presents a thorough critical review and analysis of existing knowledge in the OSM domain aimed at developing a generic formal knowledge representation of accepted vocabularies used by domain experts. This chapter is aimed at addressing research objective 1 by identifying common themes from literature and critically examining the body of knowledge around the subject matter with the aim of using the information gathered to establish the knowledge acquisition stage of the proposed process analysis tool for evaluating OSM methods.

2.2 An overview of the construction industry and its peculiarities

The construction industries in many countries have for a long time been associated with inefficiencies such as cost and time overruns. The UK construction industry for instance has been characterised as low in productivity and lacking efficiency according to several reports commissioned by the government such as Latham (1994) and Egan (1998). The improvement over the years has been little as compared with that of other industries such as manufacturing (Yitmen 2007) which perhaps recently initiated another government-commissioned report by Farmer (2016) who emphasised that the industry should either 'modernise or die'. The major issues identified by Farmer (2016) are low productivity and predictability of the industry together with failure and poor performance being experienced by clients and end-users. This scenario poses a major challenge to the UK construction sector. For instance, the need for improved performance by the industry has been documented in past studies as well as identification of the major barriers to technologically-driven innovations which are lacking. The industry generally is characterised as being slow at embracing new emerging innovative technologies (Yitmen 2007, Goulding *et al.* 2012a), thus sticking to its old inefficient ways of production and building its products.

2.2.1 Global issues with the construction industry

The issues faced by the construction industry can be grouped into three major aspects: people; processes and products (Baloi 2003, Gu and London 2010, Nadim and Goulding 2011) which categorises the areas that need improvements and also contextualising construction-related challenges.

2.2.1.1 People issues

'People' issue in construction is commonly attributed to culture, skills and knowledge deficiencies. Culture and fragmentation is the most commonly mentioned issue associated with the people aspect of construction challenges (Ofori 2000, Pheng and Leong 2000, Chan and Tse 2003, Yitmen 2007, Ochieng and Price 2009). Construction by nature requires multicultural team integration due to the diverse number of skills and specialties required to successfully deliver a construction project. However, the traditional method of construction supports stakeholders to work in silos thus leading to fragmentation and preventing adequate communication and collaboration. This in turn inhibits the effectiveness of project delivery although it has been reported that multicultural team integration results in a better performance (Ochieng and Price 2009). The construction industry is also described as being resistant to change and thus sticking to its old inefficient methods (Goulding *et al.* 2012b), construction practitioners often fail to adapt and respond to their changing environment (e.g. the digital era) and lose opportunities to integrate innovative practices in project delivery. This is despite the increasing demands for a reform championed by major construction clients and stakeholders, actuals changes have been limited. The various emerging modern methods of construction (MMC) have thus placed great emphasis on breaking the silos and enabling integrated project delivery although, the cultural mindset of the industry is still making change resistance unavoidable (Yitmen 2007). Additionally, skill shortage as a result of less qualified workforce, leadership, management inefficiencies and inadequate experience are some of the people challenges faced in the industry (Assaf and Al-Hejji 2006, Nadim and Goulding 2011, Jarkas and Bitar 2012). The skill issues faced by the industry are said to be as a result of less qualification and upskilling of construction practitioners rather than with technology (Nadim and Goulding 2011) as technology has been evolving rapidly while the industry is lagging in terms of catching up.

2.2.1.2 Process and technological issues

The traditional method of construction, which is still the most widely adopted method in the industry by its nature, is labour intensive and involves a great percentage of on-site production thus results in significant waste generation together with other associated risks (Baldwin *et al.* 2006). Such wastes and inefficiencies can be traced to the ‘craft’ based approach to production that dominates the construction industry, whereas other sectors such as the manufacturing industry, for instance, have embraced automation, modularisation, and mass customisation (Vibaek 2014). This situation is deemed unacceptable as resource efficiency in the construction industry has become a point of focus due to the challenges of resource scarcity facing the globe. The aforementioned scenario has led to debates on attaining more sustainable practices towards finite resources in the industry (Volk *et al.* 2014).

One major issue with the traditional craft-based method used in construction is its consequent low productivity which is unable to meet the industry’s demand in most regions as a result of congestions and increasing population. In spite of the continued pressure resulting from increased housing demand, supply has unfortunately been relatively low (CIC 2013). Past studies on productivity improvement (Lim and Alum 1995, Arditi and Mochtar 2000, Durdyev and Mbachu 2011, Jarkas and Bitar 2012) have revealed the need for improvement in construction process and techniques as a key solution. Also, compounding the issue with inefficiency in traditional processes, the hazardous nature of construction processes both on the environment and on its workers amplifies the need for better and safer processes (Baloi 2003). The negative environmental impacts are evident, construction consumes on average 40% raw stones and 25% virgin wood (Baloi 2003). Results from a survey conducted by Tam *et al.* (2007) revealed that construction waste generation can be reduced up to 100% with the adoption of prefabrication, Jaillon *et al.* (2009) result however reported a 52% potential waste reduction thus indicating conflicts in results. Although it is well acknowledged that the use of prefabricated elements indeed reduces construction waste generation significantly (such as Jaillon and Poon 2008, Jaillon *et al.* 2009), realising a 100% waste reduction as claimed by Tam *et al.* (2007) is somewhat optimistic. It is unclear what basis of measurement was adopted by the survey and interview respondents to account for the disparities in their judgement, thus implying elements of subjectivity. Nonetheless, this gives a notion of the significant waste reduction that can be achieved using modern methods of construction as opposed to the traditional method with the common theme being a reduction potential. Also, it is recorded that the material production and construction phase of a building accounts for 60% of the life cycle (LC) energy consumption (Quale *et al.* 2012). This is of great concern and there is a need to reduce the impacts associated with these phases of a building life cycle. In summary, the awareness of alternative approaches and choices of techniques used in construction contributes to the challenges faced in the industry.

2.2.1.3 Products issues

Time, cost, quality, and sustainability are commonly reported issues related to construction products. The quality and sustainability of construction end products seem to be of greater interest lately. While the people and process issues basically affect construction deliverables, quality forms a larger part of this issue in the product category. The choices of techniques and methods of construction affect the quality of the product and construction products are criticised and describes as having low functionality (Yitmen 2007). The finished quality of the products from onsite construction methods have been criticised as relatively low and requires more time for snagging and defects checks as compared to manufactured products (Goodier and Gibb 2005, Nadim and Goulding 2011). Another associated inefficiency with the onsite method is the minimal control on product quality (Nadim and Goulding 2011).

2.2.2 The need for change

Having reviewed that problem facing the construction industry, it is apparent that the current most widely adopted onsite production method presents a lot of challenges and there is a need for improvements. A general initiative by governments in countries like the UK is the raising of awareness that construction needs to be re-engineered to accommodate automation and standardisation and use of alternative methods are being explored (Pan and Sidwell 2011). The use of prefabricated products has thus been seen as a prerequisite to changing the craft-based culture of the industry (Gibb and Isack 2003, Miles and Whitehouse 2013). There are arguments that the implementation of mass customisation for housing units has great potential to allow for greater flexibility and customer satisfaction in the construction sector (Leishman and Warren 2006) and empowering this sector is one key solution to realising efficiency in the industry. Also, the collective sustainability agenda of the government in most countries serves as a strong drive for promoting innovative technologies in the industry and prefabrication is regarded as one potential solution that should be revisited (Blismas *et al.* 2006b, Nahmens and Ikuma 2012, Pan and Goodier 2012). Thus, applying manufacturing techniques in traditional construction processes has been the talk of the industry in the present time.

2.3 Towards Manufacturing in Construction

The idea of introducing manufacturing into construction gained more attention after the post-Egan (1998) report on ‘Rethinking Construction’. The term ‘industrialisation’ in the construction context is used to describe an interception between the manufacturing culture of standardisation and construction craft-based culture in which prefabrication forms part of the construction process (Vernikos *et al.* 2013). Standardisation is defined as the extensive use of components, techniques, and methods in which regularities and repetitions are accommodated (Gibb 2001). The idea of mutual learning across manufacturing and construction is to develop a manufactured construction sector that is geared towards achieving the aim of improved impact on physical conditions encountered on site (Gann 1996). In the manufacturing industry, productions are undertaken in a controlled environment and the product in question is standardised such that only slight variations occurs based on specific design requirements (Vernikos *et al.* 2013), e.g. the production line for car manufacturing concept from Henry Ford (Gann 1996). In the manufacturing sector, standardisation is a prerequisite to mass production. For instance, in automotive manufacturing, whole life cycle analysis of a model is carried out in order to enable the prediction of the cost and possible sales of a product before planning for production on a large scale (Vernikos *et al.* 2013). The idea of standardisation has also been implemented in the construction sector in parts as far back as 1914. This is associated with the production of bricks and blocks. Brick/block is one of the oldest construction materials/components that are traditionally produced on a large scale in a factory using batches (Gann 1996). However, transferring such knowledge on a large scale to other building elements and components has been very slow (Vernikos *et al.* 2013).

Learning from manufacturing into construction is to follow the manufacturing industry’s culture of increasing productivity, quality, and obtaining economy of scale through mass customisation. Thus resulting in an overall decrease in the unit cost of products (Fernández-solís 2009). However, there are debates on the possibilities of effectively transferring the concept of standardisation used in manufacturing into the construction of houses because construction in its own right is a unique and complex sector thus makes buildings differ from other manufactured products in several aspects. Gibb (2001) argued that buildings have a longer lifecycle than cars, and standardisation and mass customisation are not easily achievable as implemented for automobiles. It is further argued that houses are not cars and the myth of obtaining maximum standardisation should be dispelled. The products of both sectors are different in that there are physical differences in houses and cars, and also, the organisational aspect of delivery for both products makes a huge difference (Gann 1996). Houses as a product are immobile with a high degree of complexity, require many distinct but interrelated disciplines collaboration, involve a wide range of different component parts, vary in uniqueness due to project context, and also usually more expensive than many other manufactured products. Hence there are arguments that the extent to which new production processes can be transferred is somewhat restricted (Gann 1996, Vernikos *et al.* 2013). Therefore, the transferred techniques and solutions can be made to work effectively if they are being re-engineered to suit construction practices. Simply moving construction off-site to a factory does not guarantee expected results if the processes of construction itself are not properly re-engineered and designed.

There are benefits and drawbacks to the concept of standardisation in construction processes and products. However, the trade-offs should also be understood. One major trade-off in adopting standardisation is associated with reduced flexibility experienced in product layouts. Its reduced bespoke and customised designs may not satisfy the customers. According to Gann (1996), the manufactured end products are often socially unacceptable because customers have little choice in the designs. Construction by nature requires more flexibility in design which can be achieved through customisation. Industrialised housing producers are investing significantly in flexible designs to enable the provision of customisation to their customers although, there is still reduced varieties for customers when compared to the bespoke on-site construction method (Jonsson and Rudberg 2014). Therefore, there are still research requirements into how to improve the delivery of pre-manufactured products in meeting customer choices and at the same time realising production efficiency.

2.4 Offsite manufacturing (OSM) – an overview of the potential solution

Offsite manufacturing (OSM) is not a new concept to the construction industry, there are many publications in existence that covers this method of construction, and its inception as reported can be traced back to the era of the second world war (WWII) in 1945 (Finnimore 1989, Bottom *et al.* 1996, Aldridge *et al.* 2001, Miles and Whitehouse 2013, Li *et al.* 2016). According to literature on the historical context of OSM, the result of the war left a situation of severe housing crisis and an urgent need for temporary housing solution (Miles and Whitehouse 2013) as majority were left homeless. This consequently resulted in an increase in housing demand which unfortunately coincided with a shortage of skilled labour in the construction sector. Following this, prefabricated building components such as slabs, beams, wall panels, roofing systems, stairs, sanitary units, and many more were produced offsite to cope with the increased demand experienced (Jaillon and Poon 2009). Also, the use of precast unit systems experienced wide adoption in the early 50s with countries like the UK, US, Singapore, Denmark, Netherlands, Germany, Sweden, Japan implementing the system for their large scale public housing development schemes (Jaillon and Poon 2008, Li *et al.* 2016).

OSM is popularly referred to as a sustainable construction technology (Jaillon *et al.* 2009, Pan and Sidwell 2011, Li *et al.* 2016). Offsite manufacturing is a process where the construction process is carried out in a controlled environment (usually a factory) and then transported to a construction site for installation (Nasereddin *et al.* 2007). The difference between the conventional construction method and OSM is that in the former, resources and materials are brought to the construction site where the building components are manufactured and assembled whereas, in the latter, the construction is carried out in a factory and the units are transported to the construction site for installation and finishing. The offsite method is thus a promising technique that possesses great potential in reducing construction impact on the environment (Quale *et al.* 2012). However, OSM is still experiencing low adoption in the construction industry. So far, apparent observation gathered from various publications on OSM shows a significant amount of issues inhibiting its wider acceptance in the construction industry of various countries. These are based around the lack of consensus or coordinated effort with regards to agreeing on what shall be included in its definition (Yunus and Yang 2012, Baghchesaraei *et al.* 2015). The lack of consensus further compounds the issue of how to appraise various OSM methods and compare them with traditional construction methods (Song *et al.* 2005, Blismas *et al.* 2006b, Yitmen 2007, Pan *et al.* 2008, Abdullah and Egbu 2010, Arif and Egbu 2010, Yunus and Yang 2012, Haron *et al.* 2015). Other issues reported involved the unavailability of documented sources of information about modularisation (Murtaza *et al.* 1993, Aldridge *et al.* 2001, Pasquire *et al.* 2005).

One way of addressing these issues is to formally model the domain knowledge of OSM for better communication and accessibility amongst practitioners. To facilitate systematisation of knowledge, it is essential to attain consensus on widely adopted and accepted terminologies used in the domain and the taxonomies of this information to organise the knowledge for better communication. The next few sections would review the domain knowledge relating to the OSM method of construction in terms of its definition and classification.

2.4.1 Defining offsite manufacturing (OSM)

Offsite technologies embrace a number of innovative modern-day construction technologies. Without prior awareness of the ideas and concepts of those technologies, it is difficult to appreciate the terminology used in association. The terminology for the use of offsite technologies in construction has been developed over years with regional preferences. For instance, the terms 'prefabrication', 'offsite construction', 'offsite manufacturing', 'offsite production' and 'modern method of construction' are predominantly used by UK researchers (Gibb 1999, Gibb and Isack 2003, Jaillon and Poon 2008, Pan *et al.* 2012), whereas 'industrialised building systems', 'industrialised housing system', 'offsite industrialisation' and 'system building' are found in Malaysia (e.g. Roy et al., 2007; Abdullah and Egbu, 2009; Mohd Kamar *et al.*, 2011), Hong Kong and China (e.g. Zhang and Skitmore, 2012; Zhai, Reed and Mills, 2014; Luo *et al.*, 2015), and 'Pre-assembly, Prefabrication, Modularisation, and 'offsite fabrication' are commonly used in the US (e.g. Song *et al.*, 2005). Many of these terms are generally considered interchangeable (e.g. Gibb and Isack, 2003; Jaillon and Poon, 2009; Arif and Egbu, 2010; Pan and Sidwell, 2011).

Wong, et al. (2003), however, argue that the choice of the terms depends on the user experience and understanding. Pan *et al.* (2012) grouped the terms by four affixes: (i) *Pre* (as in *pre*fab, *pre*fabrication and *pre*assembly), (ii) *Building* (as in industrialised *building* system and system building), (iii) *Offsite* (as in *offsite* construction and *offsite* manufacturing), and (iv) *Modern methods* (as in *modern method* of construction and *modern method* of house building). Although there has been considerable effort in documenting the various definitions and facets of OSM (such as Elnaas 2014), there is a lack of analysis and synthesis of the definitions to recognise their commonalities and differences. It is also important to analyse the essential elements in the definitions so as to reach a conclusion on what fits as OSM and what does not. Table 2.1 shows the various definitions from different literature grouped in accordance with Pan *et al.* (2012) affixes.

Table 2.1: Definitions of terms

Category	Term	Some key definitions	Source
'Pre'	Preassembly	"a ***process*** of ***manufacturing and assembly*** of building ***components*** in a ***factory environment*** prior to ***transportation*** … for installation."	(Gibb and Isack 2003)
	Prefabrication	"describe the ***manufacturing process*** of ***components*** in a ***controlled environment*** … are ***assembled*** together to form components parts for ***installation***"	(Jaillon and Poon 2009)
		"a ***manufacturing process*** and ***transporting*** to a site … to be ***erected or assembled***."	(Baghchesaraei *et al.* 2015)
		"… ***process of building components or full modules*** in … a ***factory environment***…."	(Richard 2005)
		"… **a *manufacturing process***, generally taking place at a ***specialized facility*** and involves joining different materials to form a ***component*** part of the final ***installation***"	(Jaillon and Poon 2008)
		"The ***manufacture*** of housing ***components*** offsite in a ***factory setting***"	(Steinhardt *et al.* 2014)
		"… a ***manufacturing and preassembly process*** in which joining of materials to form a ***component*** part takes place at a ***specified facility***"	(Chiang *et al.* 2006)
'Building'	Industrialised building system (IBS)	"… a construction process that involves the use of ***standardised mass produced building components*** in a ***factory or onsite, transported and assembled*** into a structure using appropriate machinery"	(Musa *et al.* 2015)
		"… it requires the integration of smaller ***components and subsystems*** into an overall process/product with a full utilisation of ***industrialised production, transportation, and assembly techniques***"	(Roy *et al.* 2007)
	System building (SB)	"…adopts the concept of ***mass production*** of ***building components* in a *controlled environment*** either onsite or offsite"	(Kamar *et al.* 2011)
	Industrialised house building (IHB)	"… is used for describing a strategically different ***process- and product-oriented*** alternative to traditional project-oriented house-building methods and principles"	(Lessing *et al.* 2015)
'Offsite'	Offsite industrialisation (OI)	"… a process of moving construction operations traditionally undertaken onsite to a ***manufacturing environment*** prior to ***final installation*** in required position"	(Zhai *et al.* 2014)
	Offsite construction (OSC)	"… the creation of the built environment in a ***factory environment*** such that part of the construction ***process*** …	(Mtech Group 2007)
	Offsite manufacturing (OSM)	"…a ***process*** that requires a higher percentage of the ***value-adding*** activities being carried out offsite (in a ***controlled environment***) with just ***installation and finishing*** done onsite."	(Jonsson and Rudberg 2014)
		"… a unique mix of general construction procedures integrated into a ***production flow line*** ..."	(Nasereddin *et al.* 2007)

	Offsite manufacturing (OSM), offsite construction (OSC) and offsite fabrication (OSF)	"collectively used to describe a method of production and delivery through ***factory manufacture and assembly***"	(Miles and Whitehouse 2013)
'Modern methods'	Modern method of house building	"manufacture of homes in factories with potential benefits"	(Post 2003)
	Modern method of construction (MMC)	"as a description of new products, techniques and technologies in construction"	(Miles and Whitehouse 2013)
		"… industrialisation as the use of advanced technology (mechanical tools, computerised systems) in a continuous process to improve efficiency in terms of ***standardisation, modularisation and mass production***"	(Girmscheid and Scheublin 2010)

Observing from Table 2.1, the definitions seem to focus on either the nature of the finished product or outcome that is obtained (Roy *et al.* 2007, Musa *et al.* 2015, Li *et al.* 2016), the process of carrying out the construction (Kamar *et al.* 2011, Zhai *et al.* 2014, Lessing *et al.* 2015), or both (Miles and Whitehouse 2013, Baghchesaraei *et al.* 2015, Lessing *et al.* 2015). The common concept found in a number of definitions from the *Pre* and *Offsite* groups is the adoption of a manufacturing process, in which part of the production as components are assembled in a controlled working environment. The *Building* group contains the same fundamental concept together with standardisation or mass production as an additional element in the definitions, which arguably is a major contribution of the "higher percentage of the value-adding activities" in Jonsson and Rudberg (2014). The *Modern methods* group appears not limited to methods that integrate a manufacturing process and thus are more inclusive as alternative methods to traditional construction. (McKay 2010, Tennant *et al.* 2012, Kolo *et al.* 2014). For instance, some *Modern methods* techniques are used in conjunction with onsite work hence forming a hybrid systems construction without any manufacturing process involved (e.g. Arbizzani and Civiero 2013), which cannot be classified to be under the *Offsite* or *Pre* group. Thus, the other three groups can be considered as a sub-set of *Modern methods*, and hence this study does not consider *Modern methods* to be interchangeable with the other three groups.

Based on the comparison in Table 2.1, it is established that OSM terminologies in the Pre, Building, and Offsite categories can be used interchangeably. However, the term 'modern methods' is a broader term, which using the definition for OSM will not be considered satisfactory. OSM used in this research is thus described as:

> *'a value creation process of the built environment involving a combination of conventional construction procedures and manufacturing processes in which components for construction are produced in a controlled environment, and are transported and installed in the final position onsite.'*

It is important to note that the controlled environment referred to in the above definition is not limited to activities outside of a construction site. In the situation where a site is big enough to accommodate a factory or yard for production purposes, the production process can actually be onsite as seen in (Young *et al.* 2015). Nevertheless, the finished components are required to be transported and installed to the final positions disregarding whether the production process is onsite or offsite. Also, the definition follows that of Jonsson and Rudberg (2014) in capturing "value-adding" as the main rationale for offsite manufacturing processes in contrast to the counterpart of conventional onsite processes. It is thus implied that value can be added through the adoption of standardisation, mass customisation, and lean methodology which are concepts applied in manufacturing processes.

2.4.2 Taxonomy of offsite manufacturing (OSM)

Similar to the variations found in the definitions for OSM, there is also a lack of consensus on ways to classify OSM methods and systems. This section attempts to review these classifications with the aim of developing a common understanding that potentially serves as the basis for structuring OSM knowledge to address the issue of fragmentation and lack of consensus in communication.

There are various sources of information on OSM types, systems, and methods in the construction sector. The majority of these can be obtained in published literature from researchers in the domain. There are also industry sources such as standards used by professional bodies in construction. However, the approach to identifying and classifying OSM observed is not consistent and this makes it challenging to develop formal and systemised knowledge for various purposes such as process analysis. A critical review of the documented knowledge in the domain will be conducted with the objective of addressing the knowledge fragmentation issue.

2.4.2.1 Review and analysis of OSM classification systems – based on past literature

Table 2.2 summarises the OSM taxonomy established from previous literature. One general acknowledged classification for OSM adopted by most researchers (Gibb 2001, Gibb and Isack 2003, Jaillon and Poon 2009, Arif and Egbu 2010, Quale *et al.* 2012) is the subdivision of offsite manufacturing based on product orientation – generic types according to the geometric shape, assembly approach, extent of offsite operation, and state of completion of the product.

Table 2.2: OSM taxonomy according to existing literature

Group	Classification	Definition	Examples	Source
Product orientation	a. Whole building/modular	…make up the actual structure and fabric of the building. They enclose usable spaces and may be fully finished or partly finished	Retail outlets, office blocks, and motels, concrete multi-storey modular units.	(Gibb 1999, Arif and Egbu 2010, Quale *et al.* 2012)
	b. Volumetric pre-assembly	Three-dimensional building parts that enclose a usable space. Installed onsite within independent structural frames and do not independently form the building itself.	Toilet pods, plant room units, kitchen spaces, stair shaft and building service risers and lifts, shower rooms etc.	
	c. Non-volumetric pre-assembly	Two-dimensional building components that do not enclose a usable space. May include several other sub-assemblies that constitute part of a building.	Pipework assembly, wall panels, structural sections such as slabs, beams, columns etc.	
	d. Component manufacture & sub-assemblies	Factory manufactured items that are manufactured offsite and will no way be considered for onsite production.	Bricks, tiles, windows, lighting, door furniture etc.	
	a. Volumetric systems	Three-dimensional volumetric building units		(Abosoad *et al.* 2009)
	b. Panelised systems,	Two-dimensional building components	e.g. Slabs	
	c. Hybrid systems	A mix of two or more sub-categories and usually a combination of the volumetric and panelised sub-categories		
	d. Sub-assemblies and component systems	Small factory-manufactured items	Bricks, tiles, windows, lighting, door furniture etc.	
	e. Modular	Whole house building	Retail shops, whole residential houses	

	a. Panel systems (open & closed)	Two-dimensional building components		(Hashemi and Hadjri 2014), (Hashemi 2015)
	b. Volumetric systems	Three-dimensional volumetric building units	Kitchen, bath	
	c. Pods			
	d. Hybrid systems (semi-volumetric)	A mix of volumetric and panel systems sub-categories	Brick/block	
	e. Sub-assemblies and components	Small factory-manufactured items		
	a. Construction materials	Standard building materials for construction	Timber or bricks	(Steinhardt *et al.* 2014)
	b. Components	Low-level pre-cut or assembled components	Trusses, doors	
	c. Panels	Structural elements defining space	Walls	
	d. Pods	Volumetric units added to existing structure	Bathroom pods	
	e. Modular	Volumetric units, joined onsite to form house	Part-house	
	f. Complete	Whole houses including multiple rooms and fittings.	Whole house	
	a. Sub-assembly components	Factory-produced items not counted as full systems	Floor cassette, roof cassette	(Abanda *et al.* 2017)
	b. Volumetric	Factory-produced 3D units that enclose usable space	Bathroom pods, plant rooms, lift shafts	
	c. Panelised	Factory-produced flat panel units assembled onsite to produce the 3D structure.		
	d. Modular	Preassembled volumetric units that jointly form the whole building	Hotel modules	
	e. Site-based			
	f. Hybrid	A combination of volumetric and the panelised units	Tunnel form, aircrete	
	a. Frame system (pre-cast or steel)	Load bearing components	precast concrete framing, prefabricated timber framing system and steel framing system	(Kamar *et al.* 2011)(Kamar *et al.* 2011)
	b. Panelised system	2D components		
	c. Onsite fabrication		Roof truss, balconies, staircases, toilets, lift chambers	

	d. Sub-assembly and components			
	e. Blockwork system			
	f. Hybrid System	A mix of two or more sub-categories		
	g. Volumetric and modular system	3D modules systems		
Modular type	a. Pure modular	Do not accommodate changes, design is predetermined thus renders the client fully obliged to accepting the available design options		(Doran and Giannakis 2011)
	b. Hybrid modular	Combination of onsite and offsite methods which allows customisation and is associated with a higher requirement for coordination		
	c. Onsite modular	Pre-manufacture of modules onsite thus accommodating greater flexibility in terms of transportation		
Location of productio n	a. Offsite production	Involves transferring building operations from site to factory		(Bari *et al.* 2012, Mostafa *et al.* 2016)
	b. Onsite production	Involve casting structural building elements at the site before erecting to its actual location		
Market sub-sector	a. Complete structures (permanent or reloadable)		Relocatable volumetric units, Permanent volumetric units	(Mtech Group 2007)
	b. Structural elements and systems		Foundation Substructure Superstructure Building envelope Building services Preassembled civil engineering structures Special structures	
	c. Civil engineering			
	d. Special			
Productio n process	a. Static production	Module is manufactured in one position, and materials, services, and personnel		(Lawson *et al.* 2010)

			are brought to the module		
	b.	Linear production	Manufacturing process is sequential, and is carried out in a discrete number of individual stages that are analogous to automotive production lines		
	c.	Semi-automated linear production	Based on the same principles of conventional linear production as non-automated lines, but tend to have more dedicated stages.		
	a.	Factory production	Features moving assembly lines with different stations		(Duncheva and Bradley 2016)
	b.	Workshop production	Small open-plan buildings where products are moved between material and workers and modules are assembled without being moved		
Geometry and configuration	a.	Linear or skeleton	Load-bearing structures that transfer vertical and/or lateral load.	Beams and columns system,	(Warszawski 1999)
	b.	Planar systems	Structures where load are distributed through large floor and wall panels	Panelised systems-slab, floors	
	c.	Box systems	Structures that do not support vertical loads itself	Three-dimensional modules	
	a.	Frame systems	Load-bearing structures that transfer vertical and/or lateral load to the foundation.	Include beams and columns	(Badir *et al.* 2002)
	b.	Panel systems	Refer to structures that carry load through slabs (i.e. floor) and wall panels	Slabs (i.e. floor) and wall panels	
	c.	Box systems	Structures that do not support vertical load itself but rather depend upon the panel systems to carry their load and also provide lateral stability.	Kitchen and bathroom pods	
	a.	Frame or post and beam system	Structures that carry the loads through their beams and girders to columns and the ground		(Roy *et al.* 2007) (Thanoon *et al.* 2003)
	b.	Panel system (2D structural elements)	Structures where load are distributed through large floor and wall panels.		
	c.	Box system (3D elements)	Systems that employ three-dimensional modules for the		

		fabrication of habitable units, which are capable of withstanding load from various directions due to their internal stability.	
	a. Frame	Load bearing components,	(Baghchesaraei *et al.* 2015)
	b. Panel	2D components ideal for façade application whether straight, curved or angled.	
	c. Cell	3D modules systems	
Others	a. Frame system b. Panel system c. Onsite fabrication d. Sub-assembly and components e. Blockwork system f. Hybrid system g. Volumetric / Modular system		Musa *et al.*, (2015)

This type of classification was first suggested by Gibb (1999) with four groups identified, namely: *whole building/modular, volumetric pre-assembly, non-volumetric pre-assembly, and component manufacture & sub-assemblies* (see Table 2.2). Although widely recognised and accepted, Gibb's classification seems incomplete as other researchers (e.g., Abosoad et al., 2009; Hashemi and Hadjri, 2014) have identified similar product-oriented classification that incorporates panelised and hybrid systems products, which deviates from Gibb's (1999) classification. Inconsistencies are noticed in the various classifications. For instance, pods are considered as an independent type from volumetric systems according to Hashemi and Hadjri (2014) and Steinhardt et al. (2014) but the type is well within Gibb's definition for the volumetric sub-category as pods are three-dimensional volumetric building parts (Gibb 2001).

Perhaps, the type 'modular' is most confusing. For instance, Steinhardt et al. (2014) used the term 'modular' to refer to a level of prefabrication in a 6-level progressing continuum of a prefabricated house, from materials for a house (Level 1) to a complete house (Level 6) while other studies such as Arif and Egbu (2010), Gibb (1999), Mtech Group (2007) and Quale et al. (2012) consider 'modular' as a type of whole building offsite method. Also, Doran and Giannakis (2011) used the term 'modular' instead of offsite construction and sub-divided it according to (i) pure modular, (ii) hybrid modular, and (iii) onsite modular depending on the level and type of onsite activities. Their classification distinguishes onsite or offsite works involved in using a modular method, with more attention to the design and construction approaches but little attention to the type of products or state of completion of a building. Furthermore, the location of production is used by Bari et al, (2012) and Mostafa et al. (2016) in their classification.

In a survey study to evaluate the UK offsite construction market commissioned by BuildOffsite _ a UK industry-wide campaigning organisation that promotes the uptake of offsite techniques, Mtech Group (2007) classified offsite according to the market sub-sectors including (i) complete structures (i.e., for permanent or reloadable volumetric units), (ii) structural elements and systems (i.e., for foundation, substructure, superstructure, building envelope or building services), (iii) civil engineering (i.e. for pre-assembled civil engineering structures) and (iv) special (i.e. for special structures or project specific offsite construction). Recognising the lack of common definitions and the arbitrary nature in classifying offsite construction, the suggested sub-sectors clearly follow the lineage of product-oriented classification such as Gibb's (1999) with slightly different groupings.

Another product aspect that has been used for classification is according to its geometry and configuration. For instance, researchers have come up with a classification for industrialised building systems (IBS) based on the geometry and configuration of framing components regardless of their enclosing materials. Warszawski (1999) gives IBS classification as (i) linear or skeleton (as in beams and columns) systems, (ii) planar systems (panelised systems), and (iii) three-dimensional or box systems. Similar classifications are used by Badir et al. (2002) for precast concrete IBS and Roy et al. (2007) for housing. There is, however, a major doubt about this type of classification in terms of its completeness and practicality. According to Thanoon *et al.*, (2003), some new innovative systems could not be classified under this categorisation, such an example is the interlocking load-bearing blocks, which do not fall into any of the three categories. Additionally, Lawson *et al.* (2010) classified OSM according to various production processes as static production, linear production, and semi-automated linear production depending on the design of the production line while Duncheva and Bradley (2016) termed the processes as: factory and workshop production. Both classifications are similar in definitions but Lawson *et al.* (2010) classification give room for a combination of both with their semi-automated linear production category.

The critical review reveals that there is no single previous classification of OSM that covers all the properties and characteristics of the components, materials, complete products, and processes relating to OSM. The lack of a generic and standard classification may perhaps explain the fragmentation in the domain knowledge of OSM. For instance, according to Kamar *et al.* (2011), the blockwork system sub-category is being separated from components and sub-assemblies even though most definitions of sub-assembles insinuates that blockwork is an example of this category. Also, Baghchesaraei *et al.* (2015) in their recent study argued that prefabrication should be divided according to criteria such as materials, methods, and structural configuration. However, their classification can only be grouped under structural/geometrical configuration. Similarly, Musa *et al.*, (2015) also argued that the classification of IBS should be based on three criteria – materials, process, and systems however their classification does not reflect enough the categories they proposed.

2.4.2.2 Review and analysis of OSM classification systems – based on the UK construction industry standards

Apart from the attempts by researchers in previous studies to classify OSM, some standard classification systems have also been developed in the UK construction sector for classifying OSM for different purposes, e.g. for design and building information modelling such as (i) Uniclass 2015 classification system and (ii) Industry Foundation Classes respectively. These classification systems are reviewed and compared to the existing taxonomies in literature materials.

(1) **Uniclass 2015** is a classification system used to represent the construction sector in the UK. The classification system is aimed at providing a structured library of materials and product models, and project information (Afsari and Eastman 2016). It provides an information structure that is useful for categorising information for costing, briefing, preparation of specification documents, and layering of CAD drawings (Delany 2015).

For off-site products, the top level of classification under Uniclass 2015 is ‘Entity’, which is a discrete unit such as a building, bridge, or tunnel (Delany 2015). The information for this suite according to the Uniclass can be broken down further into ‘Elements’, ‘Systems’ and ‘Products’ according to the level of granularity. An element can be made up of a system or a collection of systems and a system is composed of individual products. For instance, the element ‘wall’ for a building can be composed of two systems, masonry wall systems, and prefabricated metal wall systems. Masonry wall systems will typically include a collection of insulation, blockwork, brickwork, and wall finishes whereas prefabricated metal wall systems may include a collection of metal studs, metal joists, plasterboard, insulation, and wall finishes. The products for the prefabricated metal wall systems may include aluminium, hardwood, light steel frames (LSF) etc. In Uniclass 2015, prefabricated systems and product are not independently classified, rather they are listed together across each element group thus making it difficult to extract a holistic product list if a fully prefabricated building is involved. As a result, efforts were made to identify instances of prefabricated systems in the element groups *Frames* (group 20) and *Walls* (group 25) as an example for the review (Table 2.3).

Table 2.3: Example of Uniclass 2015 classification for prefabricated frames and walls (Source: NBS 2015**)**

Group	Element/Code	Systems/Codes
20	Frames (EF20_10)	Prefabricated framed and panelled structures (Ss_20_10_60)
		Prefabricated room systems (Ss_20_10_65)
		Composite pods (Ss_20_10_65_15)
		Concrete pods (Ss_20_10_65_17)
25	Walls (EF_25_10)	Prefabricated metal wall systems (Ss_25_12_85_60)
		Prefabricated glass block wall systems (Ss_25_13_33_64)

Based on the classification, panelled offsite structure and room systems are classified under the group element frames, which do not follow the trend and definitions previously examined in the literature (section 2.4.2.1). The review of literature materials describes frame offsite systems as load-bearing structures that transfer vertical loads (Badir *et al.* 2002, Kamar *et al.* 2011), which in their case can be prefabricated columns or beams. Thus, a prefabricated room or pod system (i.e. volumetric) does not qualify under the frames group element. Also, a wall being a two-dimensional system is normally classified as a panelised system of OSM whereas it is classified differently from panels in Uniclass 2015. If classifications are a means of grouping things with similar characteristics, then a prefabricated metal-framed wall system is more likely a branch of panelised elements. Also, there is no classification for whole-house offsite systems, which is a typical product category different from a room unit volumetric system (Gibb 1999) as reviewed earlier. To conclude, it is challenging to consistently evaluate OSM options with the use Uniclass 2015's classification.

(2) **Industry Foundation Classes (IFC)** was first developed to serve as a standard format for data exchange in the AEC industry. It is a high-level object-oriented data model for all types of AEC projects that gives a hierarchical structure of different aspects ranging from building, geometry properties, materials properties, organisations, and many more (Froese 2003). IFC classification is used to arrange the objects of common characteristics or purposes (buildingSMART 2016). IFC classifies object models and allows different classification systems to be referenced (Grani 2016) in a situation where there is a need to adopt a specific classification system or where IFC does not include enough information of properties and attributes of an object (Grani 2016). The latest standard is IFC4 Addendum 2, which was published in 2016 (buildingSMART 2016). IFC classifies building element as *IfcElementType* when populating values for export (*IfcExportAs)* between different applications and systems. The group *ifcSharedBuildingElements* (Table 2.4) represents the high-level categories of building elements used to represent the architectural design of a building according to IFC4.

IFC4 group element, however, does not include provisions for prefabricated systems such as volumetric units (e.g. pods, room units) and whole-building systems. Also, prefabricated panel systems are not specifically categorised. This is perhaps because the data exchange format (i.e. IFC) has been mainly driven by the need of designers who are traditionally not trained to design with the use of OSM. Thus, the data structure in IFC emulates the traditional approach to element classification and attribute assertions. This is a major concern to use IFC as a basis for sharing information of prefabricated elements as it may result in a lot of inconsistency and incompleteness regarding the information created and shared.

Table 2.4: Example of IFC4 Add2 building element classification (Source: buildingSMART 2016)

Group	Type
IFC Shared Building Elements	IfcBeamTypeEnum
	IfcBuildingElementProxyTypeEnum
	IfcBuildingSystemTypeEnum
	IfcChimneyTypeEnum
	IfcColumnTypeEnum
	IfcConnectionTypeEnum
	IfcCoveringTypeEnum
	IfcCurtainWallTypeEnum
	IfcDoorTypeEnum
	IfcDoorTypeOperationEnum
	IfcMemberTypeEnum
	IfcPlateTypeEnum
	IfcRailingTypeEnum
	IfcRampFlightTypeEnum
	IfcRampTypeEnum
	IfcRoofTypeEnum
	IfcShadingDeviceTypeEnum
	IfcSlabTypeEnum
	IfcStairFlightTypeEnum
	IfcStairTypeEnum
	IfcWallTypeEnum
	IfcWindowTypeEnum
	IfcWindowTypePartitioningEnum

2.4.2.3 Review and analysis of classification system: Professional body standards - New rules of measurement (NRM)

The New Rules of Measurement (NRM) are documents issued by the Royal Institute of Chartered Surveyors (RICS) to serve as a standard set of measurement rules to be applied for the quantification of building works in the UK.

The RICS new rules of measurement for cost estimating 1 (NRM 1) based on UK convention classifies prefabricated building units into three major groups for early-stage cost estimation (RICS 2012a):

- Complete buildings – Complete or substantially complete self-finished building superstructures of proprietary modular construction, largely prefabricated.

- Building units – Complete or substantially complete modular room units of proprietary construction largely prefabricated and manufactured offsite, for incorporation into buildings.
- Pods – Bathroom, toilet, and shower pods supplied as completed units manufactured offsite.

Similarly, RICS new rules of measurement 2 (NRM 2) further breaks down this classification (see Table 2.5) for the purpose of obtaining detailed measurements for tendering (RICS 2012b).

Table 2.5: NRM 2 prefabricated building classification

Group	Classification	Definition	Examples
Product	Component	Used to describe prefabricated proprietary components that are not adequately covered by the other work sections	
	Prefabricated structures	Used to refer to complete or substantially complete building elements of proprietary construction, largely prefabricated	Roofs. External walls. Internal walls/partitions. Floors. Stairs. Bridges. Masts.
	Prefabricated building units	Used to refer to complete or substantially complete room units, usually of proprietary construction, for incorporation into buildings, structures	Toilet/bathroom units. Soundproof rooms. Cold rooms. Spray booths. Kiosks.
	Prefabricated building	These are complete or substantially complete building superstructures of proprietary construction, largely prefabricated.	

These classifications are similar to those in previous literature materials classified according to products such as Gibb (1999). For example, although the phraseology is different, *'prefabricated building'* in the NRM's classification is similar to the *'whole building'* by Gibb. Similarly, *'prefabricated building units'* is almost the same as the *'volumetric unit'* (see section 2.4.2.1). However, according to NRM 2, the unit of measurement for the purpose of cost estimating is to enumerate the products (counting in numbers). The cost is thus estimated according to a unit rate based on the number of units. This is less detailed than the approach laid down if the same product was to be constructed in the conventional construction method. This method arguably is not detailed enough to account for how OSM systems are produced and assembled, and the different considerations according to the interaction of various systems. In terms of cost estimation, using the conventional method of establishing cost variables for offsite has evidently resulted in many issues of cost underestimation thus leading to project cost overrun (Blismas *et al.* 2006b). A better approach needs to consider systems, materials, processes and structural configuration (Baghchesaraei *et al.* 2015, Musa *et al.* 2015). Other cost considerations include the influence of the production methods, assembly approach, work sequence, the location of production, and the type of workforce used, etc.

2.5 Chapter Summary

This chapter makes a case for the use of OSM in the construction sector by examining some of the issues associated with traditional methods of construction around three facets: people, process, and product. It covers discussions on how OSM as a method of construction presents a solution to some of these issues and the OSM method was critically reviewed. Also, the chapter examines some of the issues associated with OSM as a method of construction. It was determined that OSM domain knowledge in the AEC industry is still a work-in-progress with many inconsistencies, duplications and lack of formalisation. This makes it challenging to systemise the knowledge for facilitating other tasks, such as retrieving knowledge for process analysis, cost modelling, time modelling, and analysis, risk management, etc. This perhaps contributes to the scepticism in the use of OSM and why the knowledge lies with individual organisations with limited standardisation across practitioners. There is a need for more concise taxonomies and classifications for the purpose of encouraging knowledge sharing, access, and re-use. This will serve as a major step to obtaining an adequate analysis of the various types of OSM and consequently, allowing a fair comparison with alternative methods of construction.

The next chapter will review the approaches, techniques, and methods used in monitoring process improvement in the manufacturing sector and how process analysis has been used in supporting informed decision-making and continuous improvements.

CHAPTER 3: CROSS-INDUSTRY LEARNING BETWEEN CONSTRUCTION AND MANUFACTURING – PROCESS ANALYSIS APPROACHES

3.1 Introduction

Having looked into the existing issues with the use of OSM in the construction sector, the unavailability of structured information to support systemitisation of OSM domain knowledge for facilitating various tasks to support decision making on using OSM is a major aspect. Given that OSM is a borrowed concept inspired by practices in other sectors that have been successful in integrating more efficient processes in their product development stage, there is, therefore, a need to understand and examine how these sectors have successfully advanced their processes in a bid to support cross-industry learning into the construction sector especially the OSM domain.

In this chapter, the use of lean philosophy/principle in the construction industry and how this has been applied in process improvements is reviewed, this is linked to the various approaches for process analysis and modelling that are suitable to support informed decision-making on OSM methods. Also, an evaluation of the sort of data to be used for modelling similar to that used in the manufacturing industry to ensure accurate information on the comparison of the various OSM methods is examined. This part is aimed at fulfilling research objective 2 relating to the investigation of process analysis and evaluation methods and techniques best suited for assessing the various OSM methods.

3.2 Overview of Lean Principle and Philosophy

Toyota car manufacturing company has moved the industrialisation in the manufacturing industry forward since the 1940s by introducing the lean concept to address issues of material shortage, human resources and financial issues after World War II (Melton 2005, Abdulmalek and Rajgopal 2007, Wahab *et al.* 2013). Lean Manufacturing also used interchangeably with Lean Production or Lean Thinking is a system that originated from the Toyota production system (TPS) (Wilson 2010). The term ‘lean’ is used to denote ‘less’ of resources. Lean manufacturing aims to minimise process waste and maximise value by meeting service demands with minimal inventory. The concept of lean production systems (also known as lean manufacturing) has been used widely in the manufacturing sector and has been adopted in the construction sector as “lean construction” − a concept to reduce and eliminate hidden wastes (including both physical and non-physical wastes) in the construction processes (Nikakhtar *et al.* 2015).

OSM methods provide opportunities to exploit lean production systems. According to Pasquire and Connolly (2002), a significant proportion of the benefits achieved from implementing OSM is the outcome of process improvements from implementing lean manufacturing in a factory environment. Several offsite manufacturing companies embed the lean concept in their processes as an element for continuous improvement (CI) (Meiling *et al.* 2012b), of which optimisation of the design and construction processes by taking into account the manufacturing approaches is one core approach (Gbadamosi *et al.* 2019). This often involves different levels of automation to be implemented through the use of OSM to improve efficiency and productivity (Zhang *et al.* 2016), including the introduction of robotics systems in production, transportation, and assembly. However, while the offsite approach is continuously developing and advancing, there is little documented knowledge of the performance of the various competing OSM methods previously reviewed (see section 2.4). The OSM domain will benefit from learning from the other sectors in terms of their processes and approaches to gaining competitive advantage to support its successful implementation in the construction sector. There is a need to take a process view in order to establish and quantify improvements in the product development practices of OSM (Barber *et al.* 2003) to support informed decisions on the various available choices.

3.2.1 Process Analysis using lean philosophy

The lean philosophy/concept is an initiative that has been used in major manufacturing and automotive companies in improving their competitiveness in the global market through running a more streamlined process focused on reducing cost and eliminating waste (Rahani and Muhammad 2012). The concept is supported by a set of tools and techniques used in enhancing process improvement and increasing value. The process analysis aspect of lean manufacturing is aimed at minimising process waste and maximising value by meeting service demands with minimal inventory. Process waste in this regard is anything in addition to the minimum requirement for a business operation to function, i.e. minimum amount of equipment, materials, manpower that are vital to production.

Previous literature suggested that there are five major aspects of minimisation: material, investment, inventory, space, and people (Wilson 2010), and process waste can be classified into seven categories as summarised in Table 3.1 (Melton 2005, Naufal *et al.* 2012, Wahab *et al.* 2013, Nikakhtar *et al.* 2015). Wahab *et al.* (2013) argued that there should be an additional waste reduction aspect about people's ability not being used fully, thus an additional category of "unused or underused talent" is added to Table 3.1. Traditional mass production line, known as the 'push system', contains standardised parts that are processed following a station-by-station plan. This can lead to an unsynchronised flow of processes and often, overproduction as a result (Wilson 2010). Lean manufacturing method, on the contrary, implements a 'pull system' with only one piece flowing at a time. By implementing a balanced and synchronised operation, helps to reduce the 8 types of process waste and prevents inventory build-up as the process can flow smoothly.

Table 3.1: Different types of process waste in manufacturing processes

Type	Description	Example of cause
Overproduction (OP)	Production of excess product thus leading to other types of waste such as the need to store, transport, inventory and rework on the waste.	• Result of making products too early • Products that cannot be sold due to defect • Imbalanced production process
Waiting (W)	Workers being ideal for whatever reasons either on a short or long term not adding value to customer.	• Short term waiting as a result of unbalanced line • Long term waiting results from this like waiting due to machine failure • Intermediate product waiting for processing • Large amount of work in progress (WIP) inventory
Transportation (T)	Moving parts around between processing steps, production lines and shipping products to end consumers.	• Moving pallets of intermediate products within the factory or between/to site • Movement of materials continuously before final destination
Over-processing (P)	Processes/steps in product development beyond the need of customers.	• Over specification • Overdesign • Iterative design • Poor and inefficient processing equipment
Movement (M)	Unnecessary and non-value adding movement of people. Active workers looking busy does not equate to adding value to product or process.	• Looking for tools or materials • Inefficient workstation design
Inventory (I)	Intermediate storage of products, raw materials, equipment, tools, etc.	• Queued batches of materials waiting to be used • Warehouse/site inventory not translating to sales.
Defect	Producing defective work requiring additional work or generating scrap	• Error in design • Error in processing

(D)	leading to a waste of material, manpower and machine processing time and overall a loss of production unit.	• Miscommunication • Omission
Un/Under used Talent **(UT)**	More people involved in the job than necessary and not leveraging potentials of workers to the optimum	• Uneven work distribution • Unchallenged employees • Wrong staff to task • Wasteful admin task

Process waste can also be classified according to (i) waste generated from non-value adding activities (NVA), and (ii) unavoidable waste generated due to the nature of work, e.g. indirect work (Nikakhtar *et al.* 2015, Lee *et al.* 2012). The latter is unavoidable due to product quality, health and safety, or customer's specific requirements. Thus, they are necessary non-value adding activities (NNVA). For an activity carried out in a process to be considered value-adding (VA), three criteria must be fulfilled: (i) it must physically transform the product a step further, (ii) customer must be willing to pay for the change, and (iii) it must be correctly done with no need for rework (Wilson 2010).

The quantification of these process waste often relates to determining the resources consumed (in relation to cost, time, carbon footprint, etc.) in the product development stage and analysing what proportions falls into the three categories – VA, NVA, NNVA. This concept has also been applied to construction processes. Previous researchers in the construction domain have studied the process waste involved in various traditional onsite construction activities. For instance, Lee *et al.* (2012) analysed the process waste in relation to time spent in an onsite steel erection process for a university building and recorded 56.93% NVA activities. Mossman (2009) also reported 56-65% NVA, 30-35% NNVA and only 5-10% value-adding (VA) activities in the traditional construction process. Similarly, it was reported that the time spent by workers on productive activities in the traditional construction method is only 30% of the overall construction time on average (Forsberg and Saukkoriipi 2007). However, published studies that analyse process wastes in the OSM production workflow as compared with those of traditional methods are lacking.

3.2.2 Lean based tools and techniques used in process analysis

In practice, the application and implementation of lean philosophy rely on the use of a set of tools that assist in the identification and steady elimination of process waste (Abdulmalek and

Rajgopal 2007, Rahman *et al.* 2013, Sundar *et al.* 2014). There are various tools and techniques used in supporting lean production and are often interrelated and sometimes have similar objectives in identifying or eliminating process wastes or non-value adding activities. These tools have become widely used in management practices. Table 3.2 highlights examples of the major tools used and the lean aspects they address including waste, inventory, quantity, quality, people and process controls.

For instance, value system analysis (VSA) and 5whys method are used for analysing the processes and identifying sources of waste whereas total quality management (TQM), just in time (JIT), Kanban and 5S are often used as a corrective tool to eliminate the waste.

Table 3.2: Tools for implementing lean manufacturing

Tool	Description	Aspects					
		Waste Control	Inventory	Quantity Control	Quality/	People	Process Control
Just In Time (JIT)	A concept of supplying the exact amount of resources needed at the exact quantity, in the exact time and at the exact location of need. It is a tool to control the level of inventory and regulate production		✓	✓			
Kanban	A signalling system for implementing JIT production which is used for visual signal to support flow by pulling products as required by customers		✓	✓			✓
5S Housekeepin g	A set of techniques beginning with the letter 'S': sort, set to order, shine, standardise, and sustain. Focuses on workplace housekeeping improvement through practices that facilitates organisation and standardisation of work procedures.					✓	✓
5Whys of Lean	Used for root cause analysis for identifying where "muda" (waste) is located throughout the process asking why the problem exist	✓					✓
Kaizen	The term means continuous process improvement (CI) which is a management driven effort to cultural change by continuously improving the process in a series of small steps.				✓	✓	✓
Jidoka	Deals with the cultural aspect of manufacturing regarding the use of manpower and machines. This lies with efficient use of people for unique tasks that can efficiently perform (such as problem solving) and the use of machines for repetitive tasks (such as quality control).	✓		✓		✓	✓

Poke Yoke	This term translates to resistant to error and a means of Zero Quality Control (ZQC) system used as an error proofing technique			✓	✓
SMED/OTED	Means ‘Single Minute Exchange of Die’ or ‘One Touch Exchange of Die’, a technique used to reduce set-up time during tool change over in a production line thus resulting into better management of lead time	✓	✓		✓
Total Quality Management (TQM)	A CI system involving participative management based on customer’s needs.			✓	
Value Stream Mapping (VSM) or Value Stream Analysis (VSA)	Used to define values stream for each activity comprising of Value-added (VA) and Non Value-added (NVA) activities in the process	✓			✓
Cellular Manufacturing	A tool for smoothing the process by defining facility grouping required to produce product with minimum time (processing, waiting and transportation).				✓

3.2.3 Process analysis techniques – cost and time modelling

The volatile and competitive business climate is continuously forcing organisations to deliver better value by producing low-cost and high-quality products to meet the needs of their customers (Roy *et al.* 2011). Product cost is one of the major factors in decision-making and can serve as an evaluation criterion. According to Xu *et al.* (2011), the process of cost estimation in construction is one of the most important aspects of any construction project as it contributes to the success of production and delivery of functional needs. Cost criteria stand as one major criterion and economic factor that influences competitiveness in any industry and influences decision making at the inception/early stage of a project.

The highly competitive nature of the construction industry has increased the drive for seeking meaningful and detailed cost estimation both at the early development and detailed stage of a project as this sometimes often determines the success in winning or losing a project (Gunduz *et al.* 2011). Therefore, companies are constantly in need of evaluating their processes to accommodate an increased level of flexibility and innovativeness at a reduced cost (Roy *et al.* 2011, Xu *et al.* 2011). There are various methods and models for generating the cost of a product. The suitability of each model is often dependent on the type of project, the information required for completing the cost estimate, and the field of application. Particularly in the construction field, the use of these cost models could be a question of what phase the project is and what data is available at that point in time (Gunaydın and Dogan 2004). In order to analyse the performance of a process in terms of cost and time, various sectors have adopted different models and the level of details involved varies with the modelling method. As the intention is to analyse and categorise process waste, it is necessary to carry out a thorough review on the available methods used in construction and other sectors to determine the most suitabele approach for modelling the cost of OSM processes to suit the objectives of this study.

3.3 Categories of cost modelling and forecasting techniques

There have been various documented attempts to classify cost modelling methods (Table 3.3). The classification by Datta and Roy (2009) identified three major classifications of cost modelling methods. According to these experts, cost models can be obtained using the (i) analogous, (ii) bottom-up, and (iii) parametric methods. Another classification is given by Xu *et al.* (2011) which includes four methods as (i) intuitive methods, (ii) parametric techniques, (iii) variant-based models and (iv) generative cost estimating. Also, some researchers like Duverlie and Castelain (1999) and Ben-Arieh and Qian (2003) have also given the classification as (i) intuitive; (ii) analytical; (iii) parametric and (iv) analogical.

The analogous method according to Datta and Roy (2009) is known to be a top-down approach in which cost estimate is derived by comparing the present to the past and has been applied in both manufacturing and construction sectors at the early product development stages. This method has many names such as the variant-based costing method as in Xu *et al.* (2011) classification and analogical method according to Duverlie and Castelain (1999) and Ben-Arieh and Qian (2003). Examples of these methods can be found in standard forms of measurement used in the construction industry using the functional unit method or superficial area method of cost estimating as explained in the New Rules of Measurement 1 (RICS 2012a). The challenge with the method is the availability of historical cases and its accuracy would be in question in the case of new products as it does not reflect accurate advancement in technology or change in materials. The need for consideration of extra parameters is termed as complexity in making allowances for differences in the products (Hueber *et al.* 2016).

Table 3.3: Cost Modelling Categories

Source	Classification	Definition	Example
(Datta and Roy 2009)	• Analogous method	Also known as the traditional method of cost estimating adopts comparison by evaluating similarities and differences with other past projects in terms of various aspects such as their functions, geometry/configurations or spatial arrangements in estimating cost.	Functional unit Superficial floor area.
	• Bottom-up method	A detailed model that generates cost through the aggregation of material quantities, labour time and rates as well as machine rates which leads to an estimation of direct cost. Indirect cost are estimated through percentage allocations.	Elemental-based method Activity-based-costing (ABC) technique
	• Parametric method	Involves the use of mathematical representations and algorithms to derive cost estimates.	Regression analysis, fuzzy logic and neutral networks
(Xu *et al.* 2011)	• Intuitive method		Case-based reasoning, expert systems etc.
	• Parametric techniques,	Based on simple mathematical relations with certain parameters (cost drivers). Mathematical correlations and statistical analysis are used to derive equations for cost estimates.	Neural networks
	• Variant-based model	It is done by comparing similarities and differences with other projects or previously manufactured products in order to derive cost estimates	Functional unit Superficial floor area.
	• Generative cost estimating	The models are created by modelling the consumption of resources used in the product manufacturing stages in detail.	Elemental-based method Activity-based-costing (ABC) technique
(Duverlie and Castelain 1999) and (Ben-Arieh and Qian 2003))	• Intuitive	Based on past experience of the cost estimator and results are wholly based on the estimator's knowledge and abilities.	Case-based reasoning, expert systems etc.
	• Analytical		Elemental-based method Activity-based-costing (ABC) technique
	• Parametric		Multiple regression analysis Artificial neural network (ANN)
	• Analogical	Based on comparing similarities to other products to generate cost estimates.	Functional unit Superficial floor area.
(Niazi and Dai 2006)	• Quantitative	This method requires detailed analysis to generate cost estimate. Cost is calculated analytically by summing up elementary units for the whole life cycle of a product.	Parametric Analytical
	• Qualitative	This method is subjective and majorly based on comparison with previously manufactured products to understand and identify similarities.	Analogical Intuitive

Another category is the bottom-up approach according to Datta and Roy (2009). As the name implies, a lower level of granularity starting from estimating the components is used to derive the cost of the whole product. Another name for this is found in Ben-Arieh and Qian (2003), named the analytical method, or the generative method based on Xu et al. (2011). The problem with this method is that it is highly data-intensive and time-consuming due to the estimates being based on individual component cost value (Caputo and Pelagagge 2005). Additionally, it requires the use of detailed design and grounded knowledge of the production process (Hueber *et al.* 2016) hence considered not very suitable for early-stage estimation. However, it presents the advantage of communicating major cost drivers as a breakdown of how the cost is distributed is well presented and gives room for adjustments where necessary. This method arguably is the best suited in situations such as changes in process, technology, and new design of products.

The parametric approach, also known as the feature-based method is another category of cost modelling methods (Duverlie and Castelain 1999, Ben-Arieh and Qian 2003, Datta and Roy 2009). This method is built based on a series of Cost Estimate Relationship (CER) of various variables, (cost drivers) and a mathematical constant to model a specific situation that defines the product. This method is particularly useful in the early development stage of projects due to its simplicity and quickness in generating estimates without a great deal of data (Gunduz *et al.* 2011). The last category is the intuitive method which is highly subjective and relies solely on experience of the estimator. Another name for this method is expert judgement (EJ) (Roy *et al.* 2011). There are limitations to this method and the accuracy of the method is dependent on the knowledge and abilities of the estimator, this makes it non-repeatable for a third party (Hueber *et al.* 2016).

However, these previous classifications lack a more detailed level of distinction and may not be suitable to fit all available modelling techniques where some models are a combination of one or two of these categories. Perhaps this is better addressed in Niazi and Dai (2006) method using a 2 category classification namely the quantitative and qualitative cost modelling methods. Their classification is comprehensive yet broad and provides the opportunity to follow some taxonomies in classifying cost models (Figure 3.1) previously reviewed methods such as the parametric and analytical methods which require some form of computational analysis falls into the quantitative category while the more subjective method such as intuitive and analogical methods are grouped under the qualitative methods. The quantitative method has been proven to give more accurate result compared to the quantitative method due to the disadvantage with the latter in case of unavailability of data/cases or lack of experience (Niazi and Dai 2006).

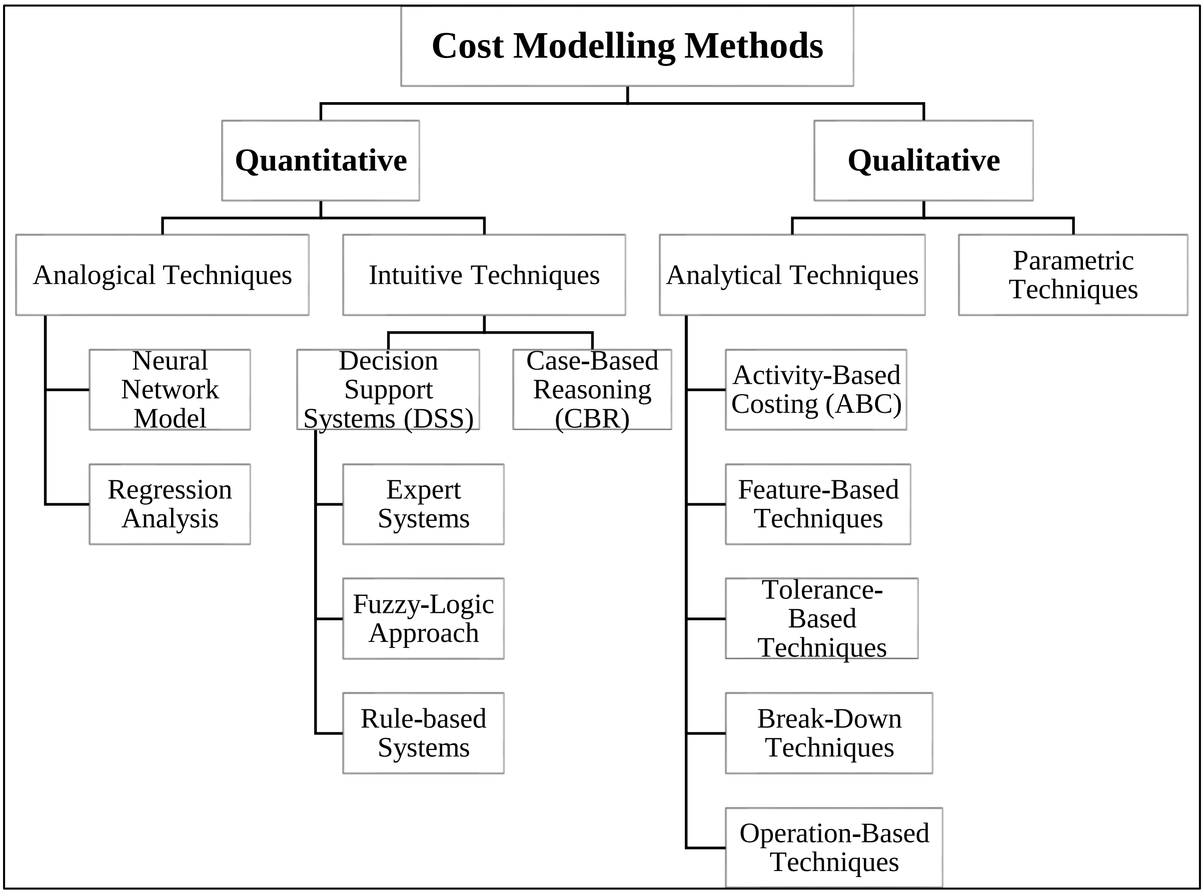


Figure 3.1: Classification of cost modelling techniques (source: Niazi and Dai 2006)

However, it is imperative to state that no method is superior to the order as methods are usually selected depending on context. For instance, some methods work best at the early conceptual/development stage of a project where the interest and priority are to determine a rough estimate of the possible project cost. While other methods will be better off at the detailed design stage or product development stage where breakdown analysis of cost is of interest. Next is to review further into the various techniques in these categories and their evolvement over time as used in the various sectors.

3.4 Analysis of cost modelling techniques – Historical progression

The prediction of project cost received great interest during the early 1970s to the late 1980s in the construction industry because of the need for more accurate estimation due to the capital value of construction projects and the level of uncertainties involved. Although few models were already in existence before this time, the early cost models were criticised for being less value-driven because of their failure to account for future uncertainties in construction and inability to generate reliable cost estimates. Consequently, it has been a common practice to classify cost models used in the construction sector into different generations based on their time of acceptance and implementation (Khosrowshahi and Kaka 1996, Yaman and Tas 2007). Accordingly, the historical development of cost estimating techniques/tools have progressed from three stages in the construction industry: first, second and third generations (Figure 3.3).

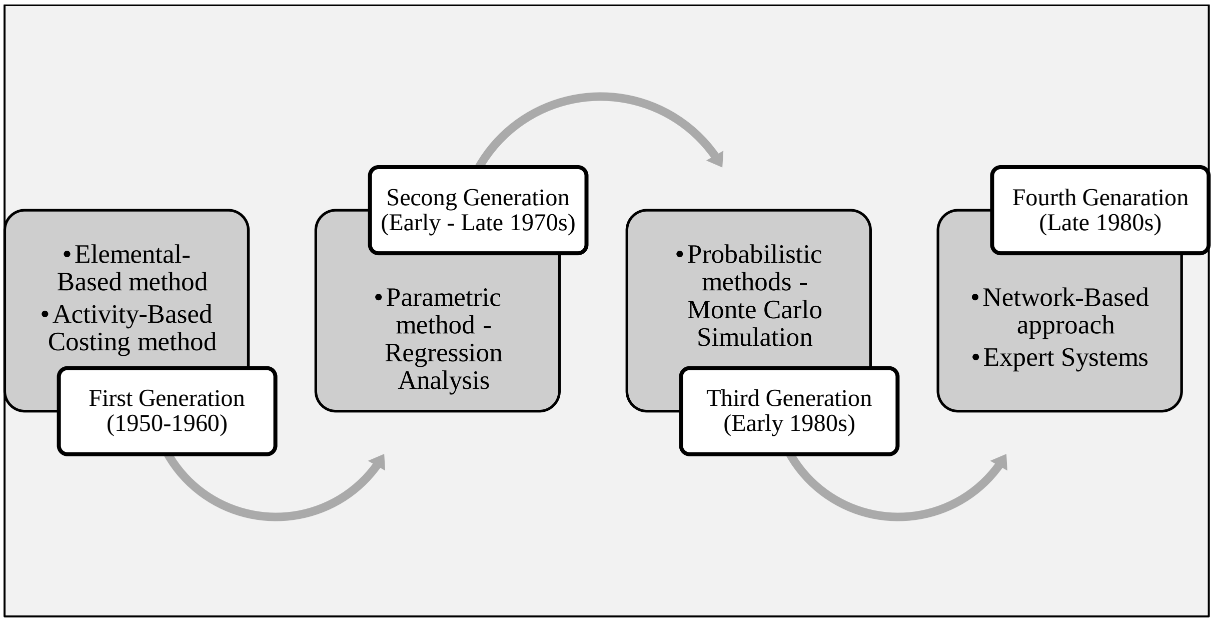


Figure 3.3: Progression of Cost Modelling Methods in Construction Industry

3.4.1 First Generation Cost Modelling Techniques

The first generation tools experienced wide usage from the 1950s until the end of the 1960s and are based majorly on building functional elemental cost analysis approaches. Examples include the elemental-based and activity-based costing models.

3.4.1.1 Elemental-Based Costing (EBC) Method

The elemental-based costing (EBC) method also known as the resource-based costing approach of estimation involves a detailed breakdown cost estimation following a quantity take-off. Cost estimates are generated based on quantities of materials usually measured in units, squares, cubes, or rather building envelope (Gunaydın and Dogan 2004). The total cost is usually calculated by summing up each units, squares or cubes by the unit or cubic rates and considering other allowances. Also in the RBC method, there are different levels of analysis and cost is calculated by breaking down the building into elements or sub-elements and obtaining the unit cost of each (Ogunlana 1989). This method is still the most widely used method of generating cost estimates in the construction industry and has been identified as the most established technique (Khosrowshahi and Kaka 1996). As a result of its wide acceptance, this method is what is found in most construction estimation books/guides such as the African Association of Quantity Surveyors (AAQS 2016) guide on building works cost analysis, RICS (2012b) guide on cost analysis and benchmarking such as the NRM 2 and many more.

However, despite its wide usage in the industry, the RBC method faces certain criticisms, a major of which is its lack of detailed consideration of risk and uncertainties which arguably makes it inaccurate in generating real-life cost estimates (Akintoye and Fitzgerald 2000). Also, the EBC method is not suitable for the early developmental stage and practically impossible to develop an accurate estimate at the conceptual stage of a project. Despite the criticism, this method is still experiencing wide usage and is observed to be what is mostly adopted by the popular cost estimating software. As an advancement, the computerised method of using the traditional model of estimation has subtly incorporated sensitivity analysis that allows a more realistic range of cost value to be picked from (Akintoye and Fitzgerald 2000).

3.4.1.2 Activity-Based Costing (ABC)

This method is has been around for a long time and has experienced wide acceptance mostly in the manufacturing industry. Compared to the elemental-based method, the ABC method has experienced fewer applications in the construction sector. The idea behind the ABC is that product development consumes activities and each activity consumes resources. Hence, allocating overhead costs accurately to value-added activities results in cost-efficiency. The total cost of a project is therefore calculated by adding the cost of materials to the cost of all value-adding activities used to produce it (Gunasekaran and Sarhadi 1998). To elaborate on this, the idea that product consumes activities and activities also, in turn, consumes resources, allows resource consumption to be traced to each activity so as to calculate the cost of each activity (Ayachit *et al.* 2014, Gurcanli *et al.* 2015). The number of unit activities in the product development stage is summed up to generate cost estimates.

The ABC method presents an advancement to the RBC method in terms of its advantage of identifying major cost centres. In other sectors such as manufacturing, petroleum and automobile, there has been a change from RBC to the ABC method because of the distortion experienced with using the RBC method and the lack of process view (Gurcanli *et al.* 2015). ABC is a method that associates cost to business activities in a manufacturing process by tracing cost to activities performed in the product development stage (Gurcanli *et al.* 2015). Also, this method is argued to be more accurate or perhaps to improve the accuracy of the cost data due to its ability to accurately trace cost/unit of products (Kim and Ballard 2001, Tsai *et al.* 2014). Its adoption presents an opportunity for identifying value-adding and non-value adding activities, and eliminating activities that consume resources but do not add value. However, the reported applications of ABC method in the construction industry are limited with little documented evidence. Few instances of practical application documneted incudes the work of Staub-french *et al.* (2002) involving the development of a generic process for feature-driven activity-based costing for product model that relates resources, activities, activity productivity and estimator's rationale to regular cost. Ayachit *et al.* (2014) also developed a means of applying ABC technique to optimise construction cost and schedule by recognising value and non-value adding activities while Tang *et al.* (2015) in their paper proposed a method of construction cost management based on activity-based costing.

However, both these first-generation models (RBC and ABC) have limitations in the aspect of cost prediction (Khosrowshahi and Kaka 1996). This led to the development of other tools to fill this gap in the early 70s.

3.4.2 Second Generation Cost Modelling Techniques

The second-generation tools widely used in the 1970s are based on statistical and probabilistic approaches such as the regression analysis method.

3.4.2.1 Regression Analysis

Statistical based approaches to cost estimation are dated back to the 1970s (Kim *et al.* 2003), the use of linear regression and multiple regression analysis are powerful approaches to estimating and achieving reliability. These techniques use historical data to obtain a linear relationship between the cost of past cases and current cases, hence relationships between certain selected variables are used in the forecasting of a new project (Niazi and Dai 2006). The regression model is built based on statistical relationships using equations from mathematical formula comprising of three data types (i) technical specifications; (ii) relationships connecting data to some intermediate or final variables (iii) constants (Duverlie and Castelain 1999). Regression models have experienced wide acceptance in estimating early-stage cost in the construction field. Some applications are found in early-stage estimation for light rail transit (Gunduz *et al.* 2011). This method is useful in terms of speed of execution and they are considerably accurate. However, one of its major criticism is that it is like a "black box" method (Duverlie and Castelain 1999) that generates cost without users understanding the processes and origin of the estimates. Also, it has been criticised for its inability in providing an accurate estimate in the case of non-linear relationships consisting of a varying number of inputs and outputs (Kim *et al.* 2003, Gunduz *et al.* 2011).

Overall, the second-generation approaches although good at prediction and have a good reputation in terms of accuracy, are regarded as being over-simplistic of the problem and undermine the role of many variable cost drivers that influences project cost (Khosrowshahi and Kaka 1996).

3.4.3 Third Generation Cost Modelling Techniques

Third-generation cost modelling tools used for construction projects experienced usage at the beginning of the 1980s. These techniques are based on simulations and risk models and are initiated as the field of project management continues to expand in the sector. The need for analysing risk and uncertainties as part of project management led to a shift from traditional costing methods (RBC/EBC) to more value-based analysis to suit the nature of construction projects. Examples of this generation costing technique is the network-based and knowledge-based approaches.

3.4.3.1 Probabilistic/Simulation methods

Risk analysis has gained more interest in the field of project management. One reason is because of cost and time overrun usually experienced with construction projects having used the single value estimation models. Single-value estimation approaches are also argued to be deficient in helping estimators understand the potential risk associated with construction cost (Chau 1995). Monte Carlo simulation eradicates or at the least significantly reduces the risk associated with cost estimates. In essence, the range estimating approach can be described as a decision support technique, which is an adjunct to traditional estimating. Estimators determine the minimum, most likely, and maximum possible cost (Chou *et al.* 2009) and also the probability of exceeding the 'most likely' estimate thus avoiding the case of a single value estimate characterised with other methods. The use of range estimating provides information on the probability of a cost overrun, on how large the overrun can be, and on what to do to eliminate or reduce cost overrun risk, including how much contingency to add to the estimate in order to reduce any residual risk to an acceptable level (Akintoye and Fitzgerald 2000). Some examples of previous studies on Monte Carlo simulation include Chau (1995) that investigated the validity of these models for construction cost estimation. Chou *et al.* (2009) used Monte Carlo simulation (MCS) methods to develop a probabilistic cost estimation for highway bridge replacement projects. Also, Chou (2011) proposed a stochastic process of generating accurate cost range estimates using MCS. Generally, simulation methods using MCS are mostly based on the assumption of triangular distribution. However, the assumption of triangular distribution is argued to likely result in overestimation thus rendering the estimate invalid (Chau 1995).

3.4.4 Fourth Generation Cost Modelling Techniques

More novel approaches have since arrived after the simulation method as a result of the implementation of artificial intelligence and its implementation into cost modelling. Artificial intelligence (AI) approaches such as artificial neural networks (ANN), expert systems (ES) and case-based reasoning (CBR) models have been investigated since the late 1980s.

3.4.4.1 Network-based approach

During the 90s, another approach to cost estimation through the application of neural networks (NNs) experienced acceptance in predicting construction cost (Kim and Shim 2014). The development of computer software and artificial intelligence (AI) has changed the concepts of cost estimation by incorporating a novel approach that produces very accurate results as well as reducing the time for estimation. These are intelligent systems that simulate the learning process of a human brain (Kim and Shim 2014) and the accuracy of these systems are argued to be superior to regression analysis (Smith and Mason 1996, Niazi and Dai 2006, Kim and Shim 2014). NNs are used for cost forecasting and are able to predict future cost by learning from past projects and provide generalised solutions for future practices (Elhag and Boussabaine 1998). NN is similar to the regression model because it can deal with non-linearity cases. NNs are also designed for a specific number of input and corresponding outputs, these values are however not restricted which serves as an advantage for the NN models (Kim and Shim 2014). According to Niazi and Dai (2006), NNs are trained to store knowledge and suggest answers to questions, this system is also capable of inferring answers to questions they have not seen before and drawing a conclusion therefore very useful under uncertainties.

The use of artificial neural networks (ANN) for cost estimation is often commonly used in the manufacturing industry and has experienced limited application in construction. However, attempts have been made to apply it to construction cost estimation. Gunaydın and Dogan (2004) developed a NN model to estimate square meter cost of structural systems of buildings during the early project phase and their results proved that this model can provide up to 93% accurate estimate. Adeli and Wu (1998) also applied the concept of regularisation NN to estimate the cost of construction projects using reinforced concrete pavement as an example. The use of NN has also experienced application in the highway construction sector (Sodikov 2005). Other applications at the early stage of construction projects are also reported such as Arafa and Alqedra (2011) and Elhag and Boussabaine (1998) in the studies developed an ANN system for costing construction projects. These researchers from their work have reported a common benefit of ANN which is efficiency and reliability when compared to other models.

Nonetheless, this method also faced criticism close to the probabilistic regression approach in terms of transparency. According to Kim *et al.* (2003), one shortfall of this method is the difficulty and time it consumes in learning the process hence why it is regarded as a black-box approach.

3.4.4.2 Case-based Reasoning (CBR)

CBR is a technique that makes use of information contained in past cases (i.e. previous projects) to generate cost estimates. The best matching example similar to the project at hand is determined to cost the new project (Niazi and Dai 2006). Information on previous projects is usually stored in a database and the characteristics that match the specification of the new project (based on percentage similarity score) while taking note of changes in systems. Simple calculations through interpolations of data from previous similar cases are used and expert judgement is used to determine possible variations. A case-based reasoner hence works based on experience by adopting solutions from other similar older projects with some adjustments to suit the current problem called case adaptation (Kim *et al.* 2003, Ji *et al.* 2011). The newly generated solution is then retained as part of the database and the trend continues. As a result of being based on historical data, this method reduces the need to design from scratch however, mostly only accurate in the conceptual stage of a project.

CBR has experienced wide acceptance and application in construction and is still currently being used by researchers to find solutions to costing construction projects. Ji *et al.* (2011) developed a case adaptation method for estimating construction cost with the CBR method. CBR systems have been applied to various real-life cases cost estimation, it has been applied with the concept of genetic algorithm to accurate weight value assignment. Kim and Shim (2014) proposed a hybrid CBR system featuring genetic algorithm (GA) for predicting the construction cost of high-rise buildings at the preliminary design stage. Ji *et al.* (2011) also developed a CBR cost estimate model for building projects using a Euclidean distance concept and genetic algorithms. CBR is argued to be efficient and reliable because of their possibility of reasoning and ability to call on the intuition, the judgement, and the habits of the expert, to obtain a result or decision (Duverlie and Castelain 1999) while also functioning on a transparent manner. However, the need for sufficient historical data makes it limited when considering new systems with insufficient data.

3.4.4.3 Knowledge-based models

Similar to the ANN and CBR approach is the use of knowledge-based models. These systems are supported with AI thus reducing the estimating time while increasing the accuracy of cost estimates. A Knowledge-based system (KBS) is an intelligent system that applies artificial intelligence (AI) to facilitate reasoning in utilising expert knowledge in solving problems. The knowledge-based models are known to be very useful in evaluating alternatives (Niazi and Dai 2006), and assist cost estimators in making a better judgement. Examples of these models are expert systems, rule-based systems, and fuzzy logic approach. Information is stored to contain different fractions of the product and processes, and relationships are applied through rules to insinuate actions to be taken for decision support. Expert systems are built up from rules or instructions which usually are executed one at a time to arrive at an answer.

Similar to other cost models, there are limitations to using ES. ES is criticised as only being applicable when theories and knowledge about a system are established such that formalisation of the knowledge in form of rules is possible (Duverlie and Castelain 1999). The rules development is also considered complex and impossible when the area of application is weakly theorised. However, compared to the other two methods – ANN and regression model – which both require historical data, expert systems are considered advantageous because they can be used for newer innovative technologies or resources with less historical data availability (Caputo and Pelagagge 2005). In order to select a suitable modelling method to be used in generating cost values to support process analysis for OSM, it is necessary to determine the granularity desired and the type of information intended to be retrieved from the modelling method. The next section will review the data sets and variables that makes up the cost of an OSM product to support decision making on a suitable method to suit the objective of this study.

3.5 Data Set for modelling: Identifying cost drivers

In using any cost estimating model, being able to identify respective cost drivers is crucial. Cost drivers are factors that drive cost up. Therefore, the cost of a product can be reduced by changing its cost drivers. These variables vary from product to product depending on the nature of the project, field/sector, etc., and are what feeds into cost models to generate overall cost values. There is a considerable difference in the factors considered when generating cost estimates for construction projects which also may depend on the construction method and techniques used. The next few sections will look into the differences based on the traditional method and OSM.

3.5.1 Traditional construction processes and associated cost drivers

The understanding of how building features affect its cost is a very crucial aspect of construction cost estimation (Staub-french *et al.* 2002). In the conventional method of construction, the most common method is to generate total cost is based on elemental breakdown using unit quantities in form of the bottom-up approach and summing up to arrive at a total estimate. This is often referred to as the standard estimating procedure in construction and establishment of cost drivers are majorly materials, labour, equipment, subcontractors cost while factoring in allowance for overhead and profit (Akintoye and Fitzgerald 2000).

Another way of grouping cost drivers is into direct and indirect cost or fixed and variable cost (Carr 1989). Direct costs of construction projects are costs that are physically traceable to activities performed while the indirect cost (also known as overheads) are those that cannot be traced to any construction activity however are considered in estimates. The UK standard method of measurement as detailed in NRM 1 and 2 (RICS 2012a, 2012b) adopts the format of considering plant, material, labour, subcontractors, and overhead in developing estimates. This is an industry-wide standard in which materials, labour and plants/equipment are classified under direct labour, while subcontractors and other overhead costs (e.g. cost of running the business) are grouped under indirect cost.

According to NRM 1 standard on detailed estimation (RICS 2012a), for a typical building project using the conventional onsite method of construction, the following aspects would be considered in the cost estimate: (i) facilitating work, (ii) substructure (iii) superstructure (iv) internal finishes (v) fittings, furniture and equipment (vi) services (vii) external works (viii) main contractor's preliminaries (ix) main contractor's overheads and profits. The challenge is that there is no transparency in terms of other cost drivers such as cost of transportation and storage, which would be considered to be part of the overhead cost. Therefore, arguably using this method is unsuitable with some new methods of construction especially where manufacturing of the building element offsite is involved.

3.5.2 OSM and associated cost drivers

In comparison to the conventional construction method, the cost drivers when using OSM as a construction method are arguably considerably different because of the nature of construction and its similarity to manufacturing. Logically, the category/level of offsite implementation in terms of automation and standardisation determines the cost driver that will be associated. However, the explicit identification of these cost drivers has fallen short in majority of offsite research. Little has been documented to differentiate cost factors in the OSM method from the conventional method consequently resulting in misconception or miscalculation when deriving cost estimates for OSM.

Few publications have tried to consider the cost drivers of using OSM. In comparing the cost of using precast concrete technique to the cast insitu method, Baldwin *et al.* (2006) grouped the cost drivers of precast (a form of OSM) as:

i. Material cost – includes raw materials, formwork/moulds and finishes;
ii. Manufacturing cost – comprises of labour, concrete pouring, quality control/supervision;
iii. Storage cost – for offsite storage facilities in a factory or yard;
iv. Transportation cost – including delivery and protection for transported components;
v. Installation cost – such as the cost for providing special lifting equipment like cranes and hoist;
vi. Inspection cost – which includes the cost of offsite and onsite inspection and testing.

Pasquire *et al.* (2005) also developed a toolkit in form of a CD-ROM named IMMPREST in which they described in detail what should be considered in measuring cost, risk and benefit of using prefabrication by studying offsite construction works in form of case studies. Figure 3.4 summarises the various drivers considered in their toolkit.

Material Cost	• Basic Materials plus fittings and finishes • Extra over structural materials • Special packaging • Waste
Labour Cost	• Manufacture (offsite) labour • Construction/installation onsite labour • Comission and testing
Plant Cost	• Small plant and equipment • Large plant
Access Cost	• Acess to enabling works • Tansport cost
Complex Construction Cost	• Rectification and rework • Work stoppage/intefernce/productivity loss • Testing cost • Production changeover cost (usually for bespoke designs)

Figure 3.4: Factors to consider when measuring manufacturing cost (Adapted from Pasquire *et al.* (2005))

Notably, both lists of cost drivers have independently outlined transportation, storage, installation, and inspection cost which is different from what is considered for the onsite method of construction (see section 3.5.1). These factors would normally go into the overhead/preliminary section with the conventional onsite method, however, are of great significance in the offsite method thus arguably rendering the use of the traditional estimation method inadequate for OSM. However, the breakdown according to Pasquire *et al.* (2005) and Baldwin *et al.* (2006) are not exhaustive and mostly focused on the direct cost associated with OSM process. It is unclear where other head office overheads would be embedded using their categories. Given that OSM is a method adopted from manufacturing and the processes involved varies to a different extent based on standardisation and automation (see section 2.4.2), it will be plausible to learn from manufacturing cost estimation approaches while taking note of construction peculiarities as this will be a positive step towards obtaining a more accurate representation of OSM cost.

3.5.3 Learning from manufacturing – A comparison of cost drivers/variables

Techniques used in cost estimation are sometimes specific to some sectors e.g. aerospace, automotive, construction, telecommunications, oil and gas, shipbuilding, and many more (Niazi and Dai 2006). Most industries have developed cost models to suit their processes. Thus given the similarity of OSM to manufacturing processes, learning from these sectors may present a good chance of addressing the issues with OSM cost modelling thus enabling accurate process analysis and comparison of various competing OSM methods. Both OSM and manufacturing concepts are built on production processes using a line factory production of components (e.g. for automobiles) which perhaps could pave way for cross-sectorial learning. In manufacturing, production/machining cost is usually a priority at the early design stage in order to inform decision-making on the viability of the design and allow for alternative solutions to be explored where cost is over budget. To achieve this, most manufacturers make use of concurrent engineering (CE) philosophies where design and manufacturing are parallel such that communication occurs between designers and manufacturers to understand how a design can be achieved (Jong 2002).

Xu *et al.* (2011) group cost drivers in the manufacturing industry into (1) design cost (2) manufacturing cost (3) operating cost (4) disposal cost. Design costs are referred to as non-recurring costs at the design stage of a project which leads to the production of design drawings ready to be transferred to the manufacturing stage. The design costs usually include a planned and unplanned cost, the planned cost being the initial estimate for the design process (human effort required to completer the design) and the unplanned being as a result of rework (Xu *et al.* 2011). The manufacturing cost incorporates the cost of (i) product (ii) process (iii) personnel used in the product development stage (Staub-french *et al.* 2002). The operating cost constitutes cost incurred during usage of a product such as electricity consumption, fuel usage, maintenance, etc. This is a very important aspect of manufacturing as it increases product competitive advantage, unlike the construction industry where a significant focus is placed on project initial capital cost. According to Xu *et al.* (2011), limited data availability often restricts the prediction of operating cost. Disposal cost is the final aspect in cost engineering for manufacturing processes, industrial applications are argued to have given more attention to the disposal aspect of a product right from the design process in terms of recycling, remanufacturing and reuse. Hence based on Xu *et al.* (2011), manufacturing cost can be represented as:

Manufacturing cost = material cost + machining cost + assembly cost

While the material costs are calculated based on product geometry, machining and assembly cost are usually based on process planning (Xu *et al.* 2011) i.e. activity-based as per the work rate with respect to construction. Manufacturing cost is argued to be majorly determined by the shape, complexity, precision and tooling process of a supposed product (Ou-Yang and Lin 1997). Another cost driver is identified by Jung (2002) who classified manufacturing cost as comprising of cost drivers such as materials, labour, machining and overheads. Jung (2002) separated labour cost from machining cost compared to Xu *et al.* (2011). Also, both of these classifications have not accounted for transportation, storage, and access cost. Perhaps because manufactured products are considerably smaller in size than buildings and all the production and assembly processes are finished off in the factory. This is not the case for OSM since onsite assembly is a major aspect and getting the elements to the final destination is crucial.

Studies in cost modelling for manufacturing have documented a great use of the ABC and feature-based methods because of its benefit in allowing transparency in overhead cost allocation (Ozbayrak *et al.* 2004). Examples of these as studies like Ong (1995) developed an ABC approach to estimating the manufacturing cost for printed circuit board (PCB) assembly. Ozbayrak *et al.* (2004) developed an ABC method to estimate manufacturing and product cost in an advanced manufacturing system. Ou-Yang and Lin (1997) also proposed a feature-based approach to estimating manufacturing cost based on the product shape and precision. Ben-Arieh and Qian (2003) also developed an ABC method for the design and development stage of a product. It is argued that the ABC method gives an indication of what activity incurs higher cost than the other. This presents an approach for analysing processes and provides an opportunity for alternative designs to be made with the informed decision.

Jung (2002) argued that the machining cost is proportional to the machining time. Thus the shape characteristic of a product determines the machining process/technique required (e.g. turning operation, milling, drilling etc.). Considering the level of automation involved in OSM method, keeping the machining cost low would be of great interest and may present a way to maintain competitive advantage for offsite manufactures as a result of benefiting from the process view and cutting down non-value adding activities. Also, the overhead cost in a manufacturing industry is reported to be between 20 to 40 percent by Raz and Elnathan (1999), this cost has gone up to 30 to 50 percent in a recent report by Lou *et al.* (2017), thus making overhead cost allocation another critical aspect of manufacturing cost per unit of products. Since construction activities are being moved to a factory environment, it is apparent that overhead costs could pose great concern for OSM method as well and the ability to trace this accurately would be a major chance for improvement.

3.6 Synthesis of cost and time modelling methods: Which method for OSM?

Having reviewed the various cost modelling methods to determine which one is best suited for generating process analysis data for OSM methods, it is apparent that newer generation cost modelling approaches are mostly based on predictions and/or rely heavily on historical data. Also, these methods are mainly suitable for early-stage estimates and predictions, thus lacking detailed information necessary for a bottom-up analysis. Both the RBC and ABC methods are suitable for generating estimates in the product development stage. The RBC method is most widely used in the construction sector for estimating the cost of projects. This also forms the basis of the rules of measurement outlined in the standard methods of measurement by professional organisations (for instance the UK RICS). This is partly because of the goal of the estimating process, which is largely focused on deriving the cost of a project either through determining the cost of each building element as detailed in NRM 1 (RICS 2012a) or work sections/trades as detailed in NRM 2 (RICS 2012b). However, the sort of data generated from the cost modelling process in the RBC method is not suitable for evaluating the process involved in the product development stage.

Although the ABC method is rarely used elsewhere in the construction sector, there seems to be a strong case for using the ABC method for OSM methods since one of the major motivations for using OSM is related to the process benefit associated with the manufacturing process. The ABC method seems more suited in terms of the level of data that can be generated relating to a process and because it provides more accurate cost information by tracing cost to activities performed in developing a product (Ben-Arieh and Qian 2003, Lou *et al.* 2017). Compared to the RBC method that allows distortion of cost as a result of the arbitrary allocation of overhead cost (Kim and Ballard 2002, Carli and Canavari 2013), the ABC method measures the cost and performance of cost objects (manufactured products) and gives accurate and more traceable cost information. Therefore, more suitable as a method for evaluating processes and supporting decision-making on optimisation of a production process.

ABC also performs better in supporting analysis of a process given the opportunity for classifying activities as either value-adding or non-value adding (Gunasekaran and Sarhadi 1998, Ben-Arieh and Qian 2003) so that there is the possibility of eliminating or reducing the non-value adding activities that consume resources. This is well suited in facilitating process waste calculation using the lean principle of waste categorisation (see section 3.2.1). Thus, decision-makers are presented with more in-depth information that encourages corrective actions and enhanced profitability (Carli and Canavari 2013).

3.6.1 Implementation of Activity-Based Costing (ABC) method for tracing product cost

To implement ABC, generally, two stages are followed: the first stage involves assigning resource cost to various activities in the production process using the resource cost drivers. The second stage is where the activities are then linked to the cost object using the activities cost drivers (Tsai *et al.* 2014). ABC accounts for the manufacturing cost of a product by attributing direct or indirect cost to cost drivers thus avoiding a situation of cost compensation (Lou *et al.* 2017) where some products consuming more overhead are under-priced and other products consequently been overpriced to get a balance. ABC method also recognises that not all activities and resource consumption rates are proportional to the number of units produced (Raz and Elnathan 1999). Therefore, activity cost drivers occur at different levels due to various activities needing them. These cost drivers are classified according to Table 3.4.

Table 3.4: Categories of cost drives for ABC method

Levels of activities	Characteristics	Example	Source
Unit	Resources consumed on activities performed on each unit of product changes	e.g. product inspection and testing for each unit	(Lere 2000)
Batch	Resources consumed on activities that relate to a group of product units. The cost of batch activities varies with the number of batches not the number of units.	e.g. cost of purchasing raw materials or transportation to site for a construction project	(Lere 2000)
Product	Product supporting costs that benefits all units of a product	e.g. design, planning and control cost of a product	(Raz and Elnathan 1999)
Facility	Resources consumed on activities that cannot be tracked to individual products.	e.g. cost of depreciation, property taxes, insurance of facility	(Raz and Elnathan 1999)

Various challenges of the ABC method have been reported in previous studies. The major shortfall of the ABC method is the additional time and expenses required in implementing the method and obtaining information needed for analysis (Ben-Arieh and Qian 2003, Akyol *et al.* 2007, Rundora *et al.* 2013). This results in manufacturers avoiding this method of costing despite its established benefits. A conclusion by Akyol *et al.* (2007) is that the ABC method should be avoided when the traditional method gives a close estimate due to the time, effort and data required in implementing the ABC method. Also, Almeida and Cunha (2017) in their study concluded that the implementation of the ABC method requires gathering a wide set of information with a high level of detail in order to be useful for the purpose intended. Similarly, Ayachit *et al.* (2014) acknowledged that the rate of implementation of ABC is low in construction which could be perhaps due to the time and data requirement of the method.

However, without evaluating the activities in production and assembly as required in the ABC methods, organisations will miss the chance for continuous improvement of their processes. The most critical aspect of using ABC is arguably not only how close or far the estimate obtained is with the traditional methods as suggested by Akyol *et al.* (2007), but rather the potential opportunities provided by the data collected through the ABC method. Advancement in technology and the digital era has however helped improve efficiency in many aspects through the use of expert systems (ES) such as those implemented using the knowledge-based cost modelling methods. To encourage the application of this method in OSM process analysis, it would be plausible to investigate how the rich data set required for ABC implementation can be modelled in an ES and automated to support analysis and decision making. Also, given the increasing digitisation of the construction industry and the improvement in data interoperability with approaches like Building Information Modelling (BIM), there is an opportunity to explore the linked-data concept with web technologies for facilitating sharing and reuse of knowledge to encourage OSM implementation (Ayinla *et al.* 2019). This potential development is rather new and has not been well covered in past literature and would be explored in the next chapter.

3.7 Chapter Summary

This chapter presents a critical review and analysis of approaches to process analysis used in other sectors and how this relates to OSM methods of construction. The application of lean manufacturing concepts in process analysis is examined alongside the tools and techniques used in supporting its application. Also, the data set required to facilitate analysis of OSM processes is examined by comparing construction approaches to manufacturing methods. It was determined that the ABC modelling method is best suited for modelling cost-related process information for OSM given the detailed level of information that could be obtained about involved processes. Other methods such as the RBC and prediction models are deemed unsuitable as a modelling method for evaluating and optimising the product development stage when using OSM methods.

The next chapter will look into the use of knowledge-based modelling methods for the formalisation and systematisation of OSM knowledge. This is required to facilitate the integration of the ABC and the lean-based process analysis methods for monitoring process improvement and supporting informed decision-making for continuous improvements.

CHAPTER 4: A KNOWLEDGE-BASED APPROACH TO SYSTEMATISATION OF OSM KNOWLEDGE

4.1 Introduction

The previous chapter provided an overview of process analysis techniques based on lean philosophy and also historical context on cost modelling methods for generating process data from a sector-based perspective. It is clear from the review that the traditional RBC method does not provide sufficient accountability for the level of detail required for process analysis. The ABC method was proven to bridge this gap and has been proposed for OSM. In this chapter, the use of AI through knowledge-based modelling to facilitate systematisation of OSM domain knowledge so as to enable automated process analysis and reasoning on knowledge will be investigated. Representing OSM knowledge in a structured way presents potential in facilitating sharing and reuse of such knowledge for various purposes such as process analysis, cost and time modelling, etc. The application of knowledge-based engineering to support lean-based process analysis based on the principle of ABC would be explored. A review and analysis on knowledge modelling standards both in a semi-formal and formal representation to capture OSM domain knowledge will thus be explored. This chapter is intended for addressing research objectives 3 relating to investigating the available knowledge modelling and acquisition methods and selecting a suitable one for the development of the proposed tool for OSM process analysis.

4.2 Understanding knowledge-based systems (KBS)

A knowledge-based system (KBS) is a platform/database used for knowledge management that represents the expertise of a domain in order to support problem-solving and decision making (Milton 2008, Motawa and Almarshad 2013). A domain represents the content of a specialised field whose knowledge is represented. Knowledge bases serve as background support systems for KBS where the latter are computer applications that are used to store knowledge for problem-solving logic as the underlying mechanisms with reasoners, similar to a human expert, in order to generate answers from a dedicated knowledge base (La Rocca 2012).

The process of transferring knowledge from humans to a computer system involved a number of principles and tools. Since the mid-60s a number of methods have been used for knowledge transfer and have evolved over time starting with search engines to the more recent CommonKADS methodology (Figure 4.1).

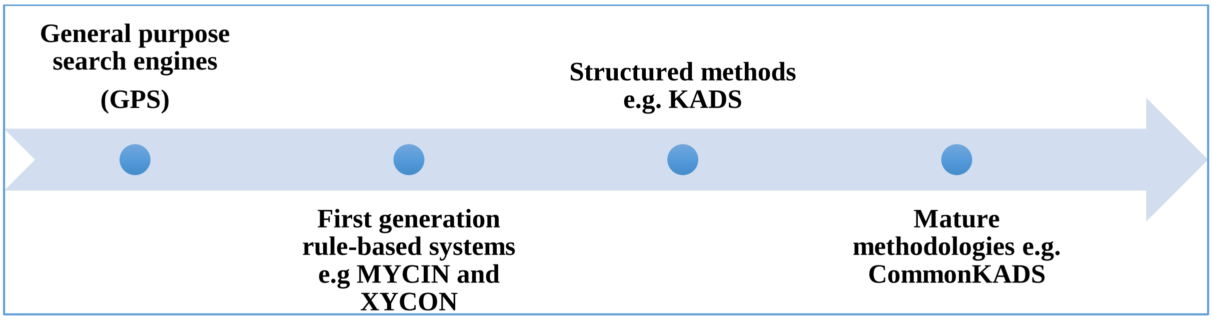


Figure 4.1: Development of knowledge systems over time (Source: Schreiber et al. 2001)

KBSs are also referred to as expert systems (ES) which mimic the reasoning process of a human expert to develop solutions for a given problem (Shadbolt and Milton 1999, Milton 2008). Although, both KBS and ES are mostly used interchangeably by many researchers in the field (Formoso 1991, Shadbolt and Milton 1999, Milton 2008), some few others have distinguished KBS from ES (Liao 2004) on the basis that KBS contains a deep knowledge of a field while ES contains more generic knowledge. The important aspect of any knowledge modelling is to be able to facilitate sharing and reuse of knowledge in a domain (Cutting-Decelle *et al.* 2007). This is made possible by storing the domain knowledge in a formalised/structured format that can be easily understood and processed by the reasoning mechanisms to provide solutions to a problem. Schreiber *et al.* (2001) describe knowledge systems as an offspring of Artificial Intelligence (AI) which are developed to aid human problem-solving. Their benefits include a quicker decision-making process; increased productivity of workers; increased quality of decision-making for designers and organisations which would be of great interest to the OSM domain. Such knowledge is represented firstly in an informal way such as the use of frames-based systems (hierarchical/flow chart grouping) which are then transformed into a formal machine-readable representation using a rule-based approach (IF-THEN) to support reasoning (La Rocca 2012).

KBSs have experienced wide acceptance in many fields. However, has also encountered some challenges when applied in the engineering field. This is because engineering in general, especially the aerospace and automotive fields requires the development of complex hardware for their design and the common rule-based systems are incapable of translating engineering design knowledge - characterised by involving computations and arbitrarily complex data processing activities - into formal rules as a core requirement (La Rocca 2012). Usually, these tasks are performed using computer-aided design (CAD) systems and computer-aided analysis (CAA) tools. Hence, the need to incorporate the abilities of CAD tools with the reasoning techniques of KBS. This resulted in the emergence of the knowledge-based engineering (KBE) field. KBE, therefore, is rather seen as a knowledge modelling system than a transfer system. KBE is more a sophisticated technique in that it is capable of dealing with repetitive engineering design tasks while producing similar results for a given problem for every attempt.

4.3 Knowledge-based engineering (KBE) - Definition and concepts

In the engineering domain, the need to capture and reuse knowledge of complex engineering processes in order to achieve greater efficiency attracted researchers into the field of artificial intelligence (Verhagen *et al.* 2010) thus resulting in the development of knowledge-based engineering (KBE) systems. KBE is categorised as a subset of KBS. While KBS are expert systems used to store knowledge (such as a database) to replicate human problem-solving skills, KBEs are specially designed for the engineering field, provided with geometry capability (as that of CAD systems) and engineering knowledge to help with engineering design (Lovett *et al.* 2000). Engineering fields such as aerospace, automotive, manufacturing, and shipbuilding have adopted KBE to automate repetition in design to save time and cost especially in the automation of certain tasks like analysis, design, manufacturing, production and costing (Milton 2008, La Rocca 2012). Similarly, KBE has been applied in the construction sector to some extent to facilitate knowledge digitisation in the areas of prefabricated façade (Montali *et al.* 2018), the development of network knowledge maps for construction projects to manage tacit and explicit construction related knowledge between project stakeholders (Lin *et al.* 2006) and many more.

In the early eighties, knowledge engineering was viewed as a transfer process of human knowledge into a knowledge base because of the common belief that the required knowledge for a KBS is already in existence and thus just needs to be collected and stored (Studer *et al.* 1998). According to Studer *et al.* (1998), the knowledge capture process takes the form of interviews with experts on some specific problem-solving tasks for each project. The extracted knowledge is then used to generate some rules to help understand how to carry out these tasks.

The application of this in supporting process analysis based on lean and ABC methods would be useful in addressing some of the challenges reported by researchers (Ben-Arieh and Qian 2003, Akyol *et al.* 2007, Rundora *et al.* 2013) concerning time consumptions and volume of data required.

The stages of KBE include knowledge identification; acquisition; and codification. This involves the formalisation by using special languages to model the knowledge in the KBE systems (La Rocca 2012). KBE applications undergo a coding process using programming languages that allows modelling of domain knowledge, the common modelling methods that predominate the field of knowledge acquisition being: (a) the problem-solving methods and (b) the domain ontology method. The problem-solving methods (e.g. rule-based) involve identifying the sequence of actions required to complete a given task within a domain, while the ontology method involves creating a vocabulary of representational terms whose definition has been agreed upon are used to model knowledge in a machine-readable format (Chan and Johnstonb 1996). Although KBE is mostly used in developing design capabilities, its application has been extended to product specification and costing (Lovett *et al.* 2000). The costing capability of KBE systems in terms of developing comprehensive estimates and quotations for products has also experienced usage in the building construction industry with a significant number of software built to automate design/analysis and costing processes. The use of ontology as a KBE tool is a potential technology that supports rapid design and production based on modular design in the industry (Verhagen *et al.* 2010) and has proven useful in developing a solution to offsite construction cost modelling. The next sections would explore formal, informal knowledge modelling methods for the implementation of KBE systems in order to facilitate automation of the process analysis aspects of OSM methods based on ABC and lean principles.

4.4 Informal and semi-formal knowledge modelling for KBS – Methods and techniques

Based on the literature analysis presented in chapter 3, it is clear that in order to carry out a detailed process analysis of OSM methods based on the lean waste categorisation approach and the ABC method, there is a need for a comprehensive knowledge of products (parts, and subassemblies), the various direct activities involved in the product development stage, the resources consumed by those activities and any supporting activities used to realise the objectives. This requires capturing information and raw knowledge of the process. However, this knowledge has to be modelled and formalised in order to support automation and reasoning by a KBE system, the first stage to this is using informal modelling languages to represent the process in order to facilitate analysis of such process. Informal or semi-formal models can be used as high-level knowledge representation languages that can be used in developing knowledge systems (Schwitter 2010). Such models usually are built with natural languages that are easy to read by humans and can sometimes be translated automatically into formal representations to support automated reasoning. One way of using these models is in business process modelling (BPM) or enterprise modelling (EM).

Process mapping/modelling is a systematic approach to documenting the activities of a process. It is recognised for its ability to facilitate a shared understanding of the process (Aguilar-Savén 2004, Akasah *et al.* 2010). Process modelling has experienced rising acceptance in modern-day businesses and is mostly used for improvement, re-engineering, IT implementation initiatives, and software development (Nurcan *et al.* 2005, Adamides and Karacapilidis 2006, Doomun and Jungum 2008, Shi *et al.* 2008). The use of business process modelling techniques in the past focused on enabling a common understanding and analysis of a product/service development process of an organisation. Organisations are described as a set of business processes, that can be improved using business process modelling (BPM) and re-engineering approaches (Melão and Pidd 2000). The objective of modelling business processes is to link production procedures with an organisation's business goals and objectives (Gunasekaran and Kobu 2002) in order to enable analysis and improvement. There are various process modelling techniques for informal or semiformal capturing of the knowledge in a process and these techniques will be analysed in the next section.

4.4.1 Review of Process Modelling languages

A process is defined as a group of interrelated activities that produces an output that is greater than the input through one or more transformations - these could be physical, transactional, locational or informational (Karhu 2000). Process modelling on the other hand is a means of systematically describing the activities in a process, their relationships and information flow. It helps to understand the best way to perform a task by describing the operational performance of the tasks that produce an output (Nurcan *et al.* 2005). The requirement for a suitable modelling technique and method to represent an organisational process or product development process in a manner that accurately represents important aspects necessitates the need to critically review available tools for process modelling. There are various tools developed for modelling business processes which usually are designed to focus on a defined viewpoint from one or a combination of aspects such as functional, information, organisation or behavioural aspects in a process. Some of the popular methods used in process modelling in past studies include Flow charts, Unified Modelling Language (UML), Data Flow Diagrams (DFD), Business Process Mapping Notation (BPMN), and Integrated Definition (IDEF).

Both UML and IDEF are a family of methods that allows modelling of different aspects of an enterprise system. IDEF originated in the 70s by the US Air Force program for Integrated Computer-Aided Manufacturing (ICAM) to increase manufacturing productivity (Cheng-Leong *et al.* 1999). The IDEF family comprises of methods ranging from IDEF0 to IDEF14 used for various system representation as: IDEF0 (for business activity and functional modelling), IDEF1 (for information modelling), IDEF1X (for data modelling), IDEF2 (system dynamic modelling), IDEF3 (for process flow modelling), IDEF4 (Object-oriented design), IDEF5 (Ontology description capture) etc.

UML is another modelling language which is an object-oriented language that covers both conceptual aspects (such as business processes and system functions) and concrete aspects (such as programming and software components) (Aguilar-Savén 2004). The UML family of languages consist of nine different representation/methods: Class Diagram (to describe the structure of a system); Object Diagram (to represent object combination of a class diagram); Activity Diagram (describe the activities of a system); State Chart Diagram (expresses the state of a system); Use Case Diagram (illustrate the relationship between various use cases); Component Diagram (describes the components of a software); Collaboration Diagram (describes the collaboration between various sets of objects); Sequence Diagram (represents the sequence of messages sent amongst objects), and Deployment Diagram (represents and describes the hardware within a software system).

Table 4.1 presents the definition and features of each of the informal/semi-formal modelling methods. According to Akasah *et al.* (2010), each method has a specific scope for which it has been designed for and the choice of methodology depends on the objective of the modelling activity. It is therefore important to understand the criteria for selecting the most suitable method. Researchers (e.g. Ijomah and Childe 2007, Waissi *et al.* 2015) previously have come up with various frameworks for evaluating and selecting process mapping tools. The choice depends on the criteria as summarised in Table 4.2.

Table 4.1: Definition and description of process modelling methods

Technique	Description	Features/representations
Flow chart	Represents a formalised graphical sequence of activities in a process while capturing movements, delays, and decision points.	Consist of connecting boxes and arrows denoting tasks, sequence, and decision points
Unified Modelling Language (UML) - Activity Diagram	An object-oriented language used for specifying, visualising and constricting the structure of a system and its relationship.	Consist of connecting boxes to represent activities, arrows for sequence, and nodes for start, end and decision points.
Data flow diagram (DFD)	A graphic network of symbols showing data flows, data stores, data processes, and data sources and destinations for an information system	A rounded rectangle to represent process, a straight lines with incoming arrows for input data flow and a straight lines with outgoing arrows for output data flows
Integrated Definition (IDEF0)	A structural modelling technique, which is used for developing a graphical representation of the processes in an organisation	A box notation represents functions (activities) while the arrows represent the interfaces including the input, output, control and mechanism
Business Process Mapping Notation (BPMN)	A graphical representation technique that adopts a visual model to show the sequential flow of activities. It uses a flow chart technique with graphical objects representing activities and flow controls.	There are four types of element namely the actor, processes, connections, and artefacts

Table 4.2: Criteria for process modelling method selection

Key Requirements	
Accuracy	Correctness of representation of the process to match the purpose intended
Ease of understanding	Ability to be easily learnt and used by non-experts (i.e. by the intended audience)
Flexibility	Easy to modify for creating specific organisational based models from generic models
Adaptability	
Standardised	Precise rules and notations, standardised syntax and semantics
Scalable	Ability to support different level of details and decomposition;
Desired Features	
Programmable	Ability to be integrated into other applications to support implementation.
Complete	Various functionalities
Comprehensibility	Meaningful and easily understood function to support communication

For this study, some key requirements are crucial to fulfilling the objectives of the study. Firstly, the ability to accurately represent the production process of OSM is important for preventing erroneous analysis. Also, given that finite level details of the OSM processes is required for ABC modelling, different level of composition that can be linked together is needed to avoid a cumbersome model. Ease of understanding of the modelling language is important in order to engage industry practitioners/experts during the knowledge acquisition stage and to enable communication. Flexibility and adaptability are also crucial for any mapping notations selected so as to allow for a generic model to be adapted to suit specific needs of organisations. Finally, standardisation of the syntax and semantics of modelling method helps to achieve other purposes of structured easy to understand, use and modify process model. As noted by Voss *et al.* (2013), the process mapping notations used influence the comprehensibility of the process. Table 4.3 highlights how each of the methods meets the criteria identified in Table 4.2.

Table 4.3: Process modelling methods features, benefits and drawbacks

Features/ Characteristics	**Flow chart**	**Data flow diagram (DFD)**	**Unified Modelling Language (UML)**	**Integrated Definition 0 (IDEF0)**	**Business Process Mapping Notation (BPMN)**
Accuracy	Only represent simple processes Cannot be used to model the actors performing the activities i.e. resources Models high-level processes and can only represent sequential activities	Focuses on information/data flow and weak in representing activities Cannot model decisions points in the process Does not support modelling of timing information of the processes.	Cannot model the actors performing the activities i.e. resources Supports iterations, concurrency of activities and timing	Able to represent activities and resources needed Tend to be misinterpreted as a sequential process Does not contain information on timing	Able to represent activities and resources required Supports iterations, concurrency of activities and timing
Ease of use and understanding	Easy to use and understand and simple representations	Easy for simple processes but cumbersome and difficult to translate for large systems	Easy to understand with simple notations	Fairly simple modelling using graphics and text. Can be complicated for large processes.	Similar to flow chart notation and easily understood
Standardisation	Non-standardised symbols	Varying symbols that can be easily confused.	Standardised notation	Strict modelling rules with standardised	Standardised notation and semantics

				notation and semantics	
Flexibility and adaptability	High-level processes and difficult to describe complex processes	Better for high-level processes and difficult to describe complex processes	High-level processes and difficult to describe complex processes	Easy to modify and adaptable to varying situations and conditions.	Easy to modify and adaptable to varying situations and conditions.
Scalability	Do not support decomposition and breakdown of activities	Supports decompositions and levels	Do not support decomposition and breakdown of activities	Supports hierarchy and structure and useful for decomposition and linking of activities	Supports hierarchy and structure and useful for decomposition and linking of activities
Programmability and Integration	No intelligence and does not integrate with other applications	No intelligence and does not integrate with other applications	Can be integrated to automate the production of software	Standardised notations that are interoperable with IT tools such as software support for business process simulations.	Standardised notations with software support for business process simulations.

4.4.2 Comparative analysis of informal modelling methods for knowledge capturing

According to Table 4.3, all the identified techniques/languages can be used to capture process-based information in a human-readable form using various text and visuals. However, UML, IDEF0 and BPMN languages can also be used to generate formal representations that are machine-readable and processable. Both IDEF0 and BPMN fit well into the criteria required for the study. The choice then is to select one of these methods. The representation of IDEF0 and BPMN are illustrated in Figure 4.2 and Figure 4.3. The activity boxes in IDEF0 are referred to as ICOM (Input, Control, Output and Mechanism) and the arrows are used to represent the flow of activities (Kim *et al.* 2003). This provides a detailed representation of various processes. However, there are some criticisms identified by researchers such as its lack of the ability to model iterative activities, and information generated and used by activities (Voss *et al.* 2013). Also, IDEF0 can be complex to understand and easily misinterpreted to be a finish-to-start process despite not being part of the IDEF0 concept (Karhu 2000). As illustrated in Figure 4.2, the ability to express iterative processes and sequential processes is not well represented in IDEF0 which is of importance in determining the time of activity for some process analysis aspects such as cost estimation.

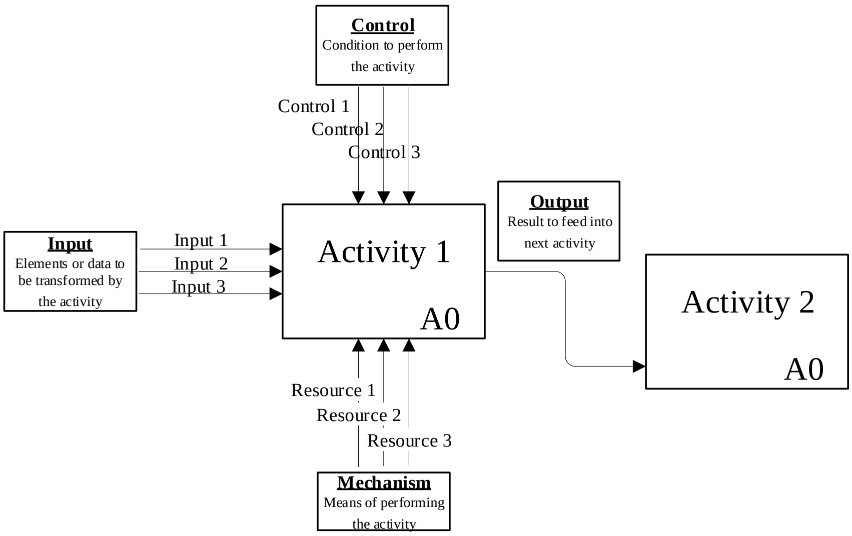


Figure 4.2: Concept of IDEF0 process modelling representation

BPMN modelling language has the benefit of communicating processes and can be used to fill some of these gaps. BPMN as shown in Figure 4.3 can be used to describe activities and their information flow, such as the actors involved, their role, the activities they perform, decision points, the events within the process. BPMN has a notation for representing iterative activities, allowing the use of swim lanes to categorise activities such as showing an actor's role in a system and representing different sectors of an organisation that forms part of the whole process.

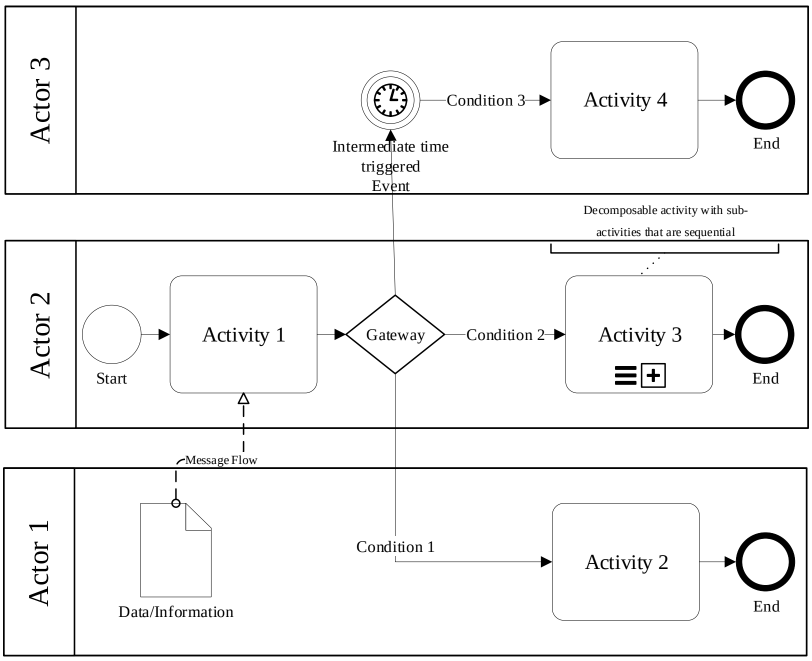


Figure 4.3: Concept of BPMN process modelling representation

It can be concluded that BPMN gives better clarity and is more advanced in its explanatory power in modelling a process. The latest trend of construction process modelling studies mostly adopts BPMN method (e.g. Persson *et al.* 2009, Kenley *et al.* 2012, Nawari 2012, Xu *et al.* 2020). Also, BPMN method was used to develop the Industry Foundation Classes (IFC) data exchange format, which is a standard form of exchange used in the AEC industry (buidingSMART 2007, Voss *et al.* 2013). This could be a reason why it is gaining popularity for its application. However, these languages are semi-formal models and do not provide sufficient semantics for supporting computational reasoning which is needed in KBE systems for generating new knowledge through reasoning on existing knowledge. This necessitates further development of the informal/semi-formal model into a formal representation and would be explored in the next section.

4.5 Overview of formal knowledge modelling and representation methods

Formal languages contain well-defined syntax used for knowledge representation that is unambiguous and is capable of supporting automated computational reasoning (Schwitter 2010). The issue with the previously identified process modelling methods is that the different representations may have problems when shared across different platforms due to non-formalised syntax, axioms and semantics (Trehan *et al.* 2015). The use of platform-neutral formal modelling languages enables semantic interoperability across the different languages and is achieved using ontology-based applications. Ontologies are essential parts of applications in which knowledge plays a key role. Ontologies are developed in AI to facilitate knowledge sharing and reuse and have been popular in the field of knowledge management, knowledge engineering, information systems and many more (Corcho and Gómez-Pérez 2000a, Fensel 2000).

4.5.1 Ontology - Definitions and concepts

The former KBSs are built on the basis of several different hardware platforms and programming languages that operate and communicate using formal knowledge representations. The locally-based nature of these applications inhibits knowledge exchange and easy accessibility (Gruber 1995) thus presenting many technical challenges. The act of knowledge representation through the use of ontologies has thus emerged as an advanced solution in the field of knowledge representation and sharing due to ontologies being platform-independent.

The word ontology is a term in philosophy meaning ‘theory of existence’ and a branch of metaphysics used to describe a science of a being (Guizzardi 2007). However, the term ontology in computer and information science is used to describe a domain of knowledge with respect to artificial intelligence (Mizoguchi and Ikeda 1998, Cutting-Decelle *et al.* 2007). It represents a unique form of knowledge representation in a particular domain which is facilitated by a computer process (Abanda *et al.* 2017). The most widely accepted definition of ontology as observed in literature is one given by Gruber (1995) in which ontology is defined as the act of *‘formally’ representing ‘explicit’ knowledge based on a shared ‘conceptualization’*. The keywords in Gruber’s definition being ‘formal’, ‘explicit’ and conceptualisation’. Gruber (1995) defined conceptualization as an abstract simplified view of a representation that is applied to every KBS either implicitly or explicitly. Rezgui *et al.* (2010) gave an extension of the definition of conceptualisation as a socially constructed model based on shared experience of a group of people due to engagements with each other. An ontology is said to be ‘explicit’ in that the terms and concepts used in the ontology are explicitly (clearly) defined and spelt out. The ‘formal’ clause usually attached to ontology definition is explained by the characteristics of an ontology being machine-readable or processable.

The purpose of ontologies is for knowledge sharing and their role to help formalise the shared world view (idea or knowledge) of a domain necessitates a certain degree of independence. As a result, their uniqueness lies in their relative independence of any particular application (Spyns *et al.* 2002) and helps to establish agreement about the knowledge output for a variety of knowledge sharing activities/platforms (Gruber 1995). This knowledge can be easily accessible to different computer systems and repositories thus allowing shared use of knowledge content between systems which is an advancement in the use of locally-based knowledge repositories (Milton 2008). One major characteristic about ontologies is that they are designed to focus on a particular domain (discipline or subject area), as such, different ontologies are developed for different communities. However, designed such that each community can communicate with each other to allow collaboration. Enabling domain knowledge reuse has however been one challenge sought to be sorted out in recent ontology researches i.e. the integration of several existing ontologies to build another or a larger one.

According to Corcho and Gómez-Pérez (2000b), domain knowledge can be described and formalised using five components: concepts, relations, functions, axioms and instances.

1. Concepts can be used to represent abstract or concrete elements of a system and they are represented in taxonomies to show hierarchy/decompositions and inheritance relationships.
2. Relations in an ontology ate used to represent the type of interaction between different concepts of a domain.
3. Axioms serve as a means to model constraints, verification of information and generating new information.
4. Instances are used to represent the elements of a concept.

There are various languages developed for logically representing and expressing these components for modelling the knowledge of a domain. An ontology language must have the ability to specify vocabulary and formally define such data for inferencing and to support automated reasoning (Pulido *et al.* 2006). However, the degree of formality implemented in capturing knowledge varies depending on the language used ranging from natural language to logical formalisms (Horrocks 2002). These languages will be discussed and reviewed in the next section.

4.5.2 Review of formal languages and representations for ontology development

Over the years, there have been various formal languages developed for representing domain ontologies. These are subdivided into two groups: traditional ontology languages such as Ontolingua, CycL, KIF, OKBC, OCML, FLogic, LOOM; and web-based ontology languages such as OIL, OWL, XML, RDF, OML, SHOE, XOL etc. According to Corcho and Gómez-Pérez (2000b), the role of ontology languages falls into two categories: (i) to provide semantics (meaning) of information contained in a document (ii) used as a formal exchange language for ontologies. The choice of modelling language majorly lies in its expressivity and ability to provide the users with a modelling syntax (language symbols/characters) to express concepts relevant to their domain (Guizzardi 2007).

The traditional ontology languages are based on 3 principles in representing knowledge: (i) First-order predicate logic languages (ii) Frame-based languages (iii) Description logics languages (Fensel 2000).

4.5.2.1 Traditional - First-order predicate logic languages

Ontology languages such as CycL and KIF falls into this category. The language syntax for CycL is based on first-order predicate calculus containing vocabularies such as numbers, constants, strings, variables and non-atomic terms. The Knowledge Interchange Framework (KIF) is another first-order predicate logic language that is a format developed for enabling knowledge exchange between different systems and for exchanging ontologies (Pulido *et al.* 2006). KIF contains four categories of vocabulary for expressing a domain – object, functions, relations and axioms. However, CycL provides richer modelling primitives than KIF since KIF is originally designed as an exchange format whereas CycL is a modelling language (Fensel 2000).

4.5.2.2 Traditional - Frame-based languages

The frame-based and object-oriented languages take a different approach from the first-order logic methods. They are based around the modelling primitives of classes (also known as the frames) which have certain properties also known as attributed (Fensel 2000). Ontolingua, Frame logic (FLogic) and OCML are examples of languages in this category. Ontolingua is a KIF based language that is built on frame-based approach. Ontolingua provides an extension of KIF by using additional syntax. KIF, an interchange format offers more expressivity than frame ontology, however, more tedious to use for specifying ontologies (Corcho and Gómez-Pérez 2000b). Ontolingua is another ontology representation and sharing language that takes the form of frame-like representations made up of representations such as classes, objects, functions, relations, and axioms. Flogic is an integration of first-order predicate calculus and frame-based approach comprising of a dedicative system that works on the theory of predicate calculus and structural inheritance (Pulido et al. 2006).

4.5.2.3 Traditional - Description logics based languages

Description logic (DL) also known as terminological logic is a powerful knowledge representation (KR) language that evolved from semantic networks and frames (Corcho and Gómez-Pérez 2000b). DL describes knowledge in form of concepts and roles and the major modelling primitives are concepts and individuals expressions allowing mathematical expressions of which enables reasoning and automatic derivation of new taxonomies (Pulido *et al.* 2006). Some implemented languages in this category include LOOM, KL-ONE etc. LOOM is a high-level programming language used for developing intelligent applications such as expert systems. It offers an integration of frame-based and rule-based logic for modelling objects and relationships and specifying constraints (Corcho and Gómez-Pérez 2000b).

4.5.2.4 Web-based ontology language

The second category of ontology languages are the web-based languages that are used to facilitate knowledge and information exchange on the web. Languages that are web standard compatible also fall into this category. Given the growing importance and contribution of the World Wide Web (WWW) in knowledge sharing, languages need to be developed with consideration of the web. The first generation web was based largely on handwritten HTML pages while the second generation web (current web) has moved to machine-generated HTML pages (Horrocks 2002) that are mainly only human processable. The previous languages used on the web (WWW) faced problems of interoperability with solutions limited to a single application (Djurić *et al.* 2005). The introduction of XML allowed for sharing data of common ground with interoperable syntax however lacks semantics (meaning) of the data it describes. XML is a tag-based language describing a tree structure for describing document structures (Fensel 2000). Information coded in XML format is easily readable to humans hence ontology languages specified in XML can be read and understood easily by humans (Corcho and Gómez-Pérez 2000a). The evolution of the third generation web known as the Semantic Web has been developing in recent times to allow for machine-understandable data described by ontologies to allow for meaningful representation of knowledge (Gómez-Pérez and Corcho 2002, Djurić *et al.* 2005).

Resource Description Framework (RDF) is a standard built on top of XML to solve the issue of semantics. The purpose of RDF is to provide a mechanism for specifying semantics for XML based data (Corcho and Gómez-Pérez 2000b). In the RDF Schema (RDFS) model, interrelationships among resources are identified by declaring properties and attributes and can be used to generate entity-relationship diagrams (Djurić *et al.* 2005). Although RDF and RDFS allow for the semantics of data to be represented, it still falls short of the expressivity required for enabling reasoning compared to full predicate languages such as KIF and CycL. A RDF(S) based ontology can be easily used to define concepts, relations and instances however, due to RDF being a primitive language, it lacks representation of functions and axioms (Corcho and Gómez-Pérez 2000b, Horrocks 2002). For a domain to be described in greater detail, a richer set of modelling primitives of ontology languages that can be mapped to descriptive logic (DL) are needed to enable reasoning is needed. Languages such as OIL, DAML and OWL have been developed to fill the gaps to externs RDF(S) and provide a richer set of modelling primitives.

OIL is an acronym of Ontology Interchange Language, a standard for both describing and exchanging ontologies. It provides a combination of frame-based and description logic ontologies which supports automated reasoning by describing concepts, relations, functions, and axioms (Pulido *et al.* 2006). However, with some drawbacks such as its inability to define default value cannot be used to define instances (Corcho and Gómez-Pérez 2000a). DAML is a US Government initiative at providing a foundation for the semantic generation web. It consists of an ontology language and a language for including constraints and rules to support inferencing (Pulido *et al.* 2006). DAML is an extension of XML and RDF with the latest release being DAML+OIL. DAML+OIL provides a rich set of machine-readable and understandable ontologies due to its well-defined semantics and axiomatic specification. Both languages (DAML and OIL) are designed such that they can be mapped onto a rich and expressive DL to provide formal semantics and understanding of reasoning problems (Horrocks and Sattler 2001). However, these languages have some restrictions in dealing with concrete datatypes (numbers and strings) (Horrocks and Sattler 2001).

Web Ontology Language (OWL) is the latest semantic markup language for publishing and sharing ontologies on the WWW whose formal semantics are based on DL (frame-based and semantic networks) (Golbreich 2004). Its major goal is to provide a common language for ontology representation for the semantic web hence, priority is given to extensibility, modification and interoperability (Djurić *et al.* 2005). OWL is a vocabulary extension of RDF which is derived from a combination of DAML+OIL merging the efforts in these two languages and provides greater power for expressing semantics which includes specifying conjunctions, disjunction, quantifiable variables etc. (Pulido *et al.* 2006). Given that OWL is a semantic web initiated language, the Open World Assumption (OWA) is used, translating that "if a proposition cannot be proven to be true with the current knowledge, the system cannot declare this proposition as false" (Fortineau *et al.* 2012) since the web deals with unlimited knowledge resources. OWL supports calculations and reasoning to carry out logical inferencing. However, its drawbacks include the trade-off between efficiency and ease of use (Pulido *et al.* 2006). This issue has been addressed by introducing three sets of sublanguages options with different levels of expressivity: OWL Full (with maximum expressiveness and syntactic freedom however with less ease of computational expressions), OWL DL (which is based on description logic and enables the maximal amount of expressiveness and allows for computational expressions infinite time) and OWL Lite (to support classification and hierarchy as a simple starting point in providing taxonomies). This gives users the choice of selecting a version based on their need and modelling objectives. OWL DL is the most widely used OWL subset language for industrial application (Fortineau *et al.* 2012) as it allows for automatic deductions and reasoning such as tasks like checking satisfiability, subsumption and instantiation (Golbreich 2004).

4.5.3 Review of reasoning and rule languages for ontology development

Most industries are data-driven and generate a large amount of information. This has necessitated the need for automated intelligent information systems able to make inferences with the information. Reasoning in an ontology allows inferencing on a stored knowledge to provide a new construct. Depending on the expressivity of language selected for building an ontology, the ontology should allow for inferencing by making deductions about classes, instances and properties with the help of inference engines (Fortineau *et al.* 2012). Ontology can be used for reasoning and computational modelling with the help of rules. Rule extensions for languages such as RuleML, SWRL, Metalog and RIF has been developed with the goal of sharing and processing rule with different rule engines.

RuleML is a format for describing and sharing rules on the WWW. RuleML stands for Rule Markup Language is developed based on an international initiative for standardising inference rules – Rule Markup Initiative (Golbreich 2004). It is based on XML schema and the main aim is to define a standard rule that covers different categories of rules (Golbreich 2004). Another language by the W3C and also one of the most prominent ones is the Semantic Web Rule Language (SWRL) to extend OWL DL (Brockmans *et al.* 2006). SWRL is used to define rules as part of an ontology as an additional expression and it is built based on a combination of OWL-DL and OWL-Lite sublanguages, the Unary/Binary Datalog subset of RuleML (O'Connor *et al.* 2005). Users can write rules with SWRL expressed in terms of OWL concept, properties and individuals thus allowing reasoning on OWL instances/individuals and the rules are saved as part of the ontology. However, SWRL has some drawbacks such as difficulty in dealing with complex rules such as one with numbered predicates and containing a more complex combination of atoms (O'Connor *et al.* 2005) and unable to replace existing knowledge in an ontology (Fortineau *et al.* 2012).

Other rule languages include RIF and OCL. RIF (Rule Interchange Format) is another standard rule language for the semantic web which is based on RDF and OWL similar to RuleML. With the several rule languages being developed and their heterogeneity, it is necessary to ensure interaction between them thus RIF was developed as an interchange format to address this need (Ma and Wang 2012). RIF is recognised by the W3C as an interchange format for facilitating sharing of rules between different languages in the semantic web (Ma and Wang 2012). RIF offer two dialects namely: logic-based dialects RIF-BLD (based on first-order logic) and dialects for rules with actions RIF-PRD (designed for production system rules) (Kifer 2008). Object Constraint Language (OCL) can be used to describe additional constraints about objects and also has the ability to check coherency between models (Fortineau *et al.* 2012). OCL is based on Closed World Assumption (CWA) thus suitable for industry-specific purposes with finite information. The language provides a high level of expressivity with limited restrictions thus its drawback lies in the lack of decidability of the reasoning task.

4.6 Applications of ontologies for knowledge formalisation in construction

While the availability of data has been a challenge in analysing OSM processes (Aldridge *et al.* 2001, Pasquire *et al.* 2005, Chen *et al.* 2010b), the inability of computer systems and applications to communicate is arguably a compounding factor to the issue. According to Xu *et al.* (2011), access to product and manufacturing information is very crucial in order to enable timely and accurate performance of various process-related tasks such as cost estimation. This can be easily achieved using a shared conceptual model through an ontology that enables the sharing and managing of common knowledge. There have been various works done in developing formal ontologies to support communication in the construction sector. El-Diraby *et al.* (2005) worked on developing a domain ontology for the construction sector by developing a consistent semantic representation of construction knowledge. Zhang *et al.* (2015) also developed a construction safety ontology for enabling enquiry of safety knowledge for better accessibility.

Xu *et al.* (2011) emphasised the importance of ontology application in manufacturing cost estimation due to its accuracy for future research work. Also, Abanda *et al.* (2017) in their research emphasised the urgent need for an open-access catalogue that is free for users and easily accessible by most Building Information Modelling (BIM) software applications.

Previous studies (Wu *et al.* 2014, Abanda *et al.* 2017) have shown that BIM software applications for cost estimation and quantity take-off (e.g. Navisworks, Autodesk QTO, Synchro, Vico Office, CostX, Solibri etc) faces challenges of inadequate communication because these tools have their independent library of standard measurements which usually is not transferable nor exchangeable with other software (Abanda *et al.* 2017). This lack of interoperability between software is identified as one key reason why the use of BIM in cost estimation is low.

In assessing the benefits of different construction processes, cost is a major factor considered. However, the lack of sufficient and easily accessible data in supporting analysis has been a challenge. The use of ontologies provides a great opportunity in addressing these needs and may perhaps account for the recent increase in the use of ontologies for supporting various needs such as cost estimation. While the development of ontologies for cost estimation has gained interest in the construction industry, there is still a need for more work to be done on incorporating some reasoning in the estimation process to support decision-making (Staub-french *et al.* 2002, Abanda *et al.* 2011, 2017).

4.6.1 Existing ontology in construction domain – Related work in developing a construction cost estimation ontology

Some researchers (Staub-french *et al.* 2002, Abanda *et al.* 2011, 2017, Nepal *et al.* 2013, Lee *et al.* 2014) have done some work in developing ontologies to perform various aspects of construction cost estimation. Staub-french *et al.* (2002) looked into developing an ontology to capture cost estimators' rationale for relating product and cost information. The developed ontology in question is said to represent the features of building product models that are important to estimators and the reasoning of the estimator on how these features affect construction activities, resources, and productivity rates when calculating the cost of a construction project. Their research motivation was to improve the richness of cost estimation process which common cost estimating software are lacking. The developed ontology was thus to create a common vocabulary of representing design conditions that impacts on project cost.

Lee *et al.* (2014) also proposed and developed an ontology to automate the process of searching for information regarding work items during cost estimation. Their rationale as reported is a result of the incompetency of cost estimating tools in automatically inferring and assigning work items. Although their study is with a limited scope and focuses only on tiling work, it demonstrates how ontologies can be used in reasoning to support cost estimation. Nepal *et al.* (2013) developed an ontology-based feature modelling approach to counter the challenge experienced in extracting construction-specific information from BIM models by automating the process through queries of the BIM model in an ontology. In another research, Abanda *et al.* (2011) worked on the development of an ontology application for modelling construction labour cost information to facilitate decision making through modelling a domain ontology of concepts and relationships which was, in turn, facilitated using query rules to estimate labour cost. Liu, Li, *et al.* (2016) also proposed a semantic ontology-based approach to obtaining construction quantity take-off from a BIM model to support cost estimation. However, the ontology developed is only restricted to material quantity take-off from the BIM model while leaving out some other cost drivers in the actual project lifecycle cost.

On analysing these various works on the application of ontology for construction cost estimation, a major similarity observed is the implementation of rules in the ontology to facilitate reasoning for retrieving useful information which would normally be somewhat challenging to obtain from an ordinary BIM model. Also, in order to develop these ontologies, these researchers have invested some time in formalising the domain knowledge relating to cost estimation although the developments have mostly only focused on specific work aspects in construction (e.g. labour cost, tiling). The few studies which covered the development of ontology-based cost estimation for almost all construction work packages (Liu, Li, *et al.* 2016, Abanda *et al.* 2017) have adopted existing standard rules of measurements for cost estimating in developing the ontology structure since these standards are generally accepted as guidelines in the industry. For instance, Abanda *et al.* (2017) looked into the development of ontology-based cost estimation based on New Rules of Measurement (NRM) standards in the UK construction industry. Perhaps their intention was to satisfy the ‘formality’ clause in the ontology definition since NRM can be regarded as a common understanding and consensus in the construction industry for cost estimating. Similarly, Liu, Lu, *et al.* (2016) adopted the Chinese national specification for cost estimation code (GB 50500 specification) for bill of quantities (BoQ) as their reference specification in the development of an ontology to support construction cost estimation. They have integrated automated reasoning using certain construction conditions to enhance the reasoning process. The rationale of these researchers being to develop independent catalogue that can be used by different software and also to facilitate uniformity.

Although these researchers have covered great aspects of ontology-based cost estimation for construction, they have mostly focused on the onsite construction methods. There has been limited work published on the development of ontologies for offsite construction cost estimation for facilitating process analysis and informed decision-making. Also, there are limitations in the current classifications of the OSM domain with various inconsistencies as observed from the review in chapter 2. This needs to be addressed in order to enable formalisation of the estimating process using an ontology. In summary, much of the focus has been on the application of ontologies for cost estimation of the onsite construction methods and the development of platform-independent cost modelling systems for OSM is yet to be properly explored. This study will look into the approach to enabling the development of an ontology, based on the ABC modelling method specifically tailored to suit the analysis of various OSM methods.

4.6.2 Existing ontologies in OSM domain – Review of related work on ontology development for OSM

The review of existing literature in the OSM domain was conducted to reuse terminologies and existing knowledge classification. The review also considered the possibility of extending some of the existing ontologies relevant to the research problem. Ontologies such as ifcOWL ontology generated from the IFC standards (Pauwels and Terkaj 2016), Building Topology Ontology (BOT) (Holten and Ferdinand 2020) describing the topology of buildings, and Building Product Ontology (BPO) (Wagner and Uwe 2019) for describing building products, are very useful for modelling the AEC domain information in a Linked Building Data format. However, BOT and BPO ontologies were purposely implemented as lightweight ontologies to promote reuse and do not include specific DfMA concepts for offsite manufacturing which is a challenge. Also, El-Gohary and El-Diraby (2015) developed the Construction PRO-cess Ontology (IC-PRO-Onto), a domain ontology for representing construction and infrastructure process knowledge by capturing the most fundamental concepts in the domain. Given this, some of the high-level terminologies from the IC-PRO-Onto such as ‘Process’, ‘Sub-Process’, ‘Activity’, etc. will be considered for reuse. However, as no ontology is all-inclusive, other process related terminologies to suit the objectives of the study will be investigated.

Similarly, while MASON (Lemaignan *et al.* 2006) provides the core concepts of manufacturing, extending it to include the complexities and depth of analysis of buildings, and, more so, offsite buildings, creates a substantial challenge with redundancy and complexity. It is necessary that any extension of an ontology leads to a result that is lightweight, efficient, and conceptually coherent, in order to support adoption and implementation. As argued by Kalemi et al. (Kalemi *et al.* 2020), ontologies in complex domains that attempt to be all-inclusive often are not optimal for purpose: a prominent example in construction is the development of BOT as a way of addressing ifcOWL's complexity. This supports the notion that there is no "perfect" ontology and no "optimum" classifications or concept hierarchies (El-Gohary and El-Diraby 2015).

4.7 Analysis of knowledge representation languages for modelling OSM domain knowledge

Based on the review of informal, semi-formal and formal knowledge modelling methods, it is evident that a careful selection of modelling method to meet the objectives of the modelling exercise needs to be undertaken. The use of object-oriented languages both formal and semi-formal is useful in providing a foundation for visualising the knowledge-based system. For the purpose of this study, the production process of OSM methods needs to be captured in order to facilitate detailed analysis of the process while also automating these tasks. BPMN, UML and IDEF0 languages are informal/semi-formal modelling methods where knowledge captured can be converted into a formal one suitable for modelling in the KBS. These languages can be used to generate computer-readable and executable models, it supports the modelling of object-oriented software systems (Kim *et al.* 2003). BPMN given its ease of use and advanced expressiveness is more suitable for capturing the activities of the production line of various OSM methods. However, there is also a need to design and visualise the structure of the proposed KBS systems before formal modelling in an ontology. UML class diagram is one of such languages which is used in modelling the structure and design of software systems in order to allow for analysis of the functionality (Hause 2006) and mainly used for specifying a software system which mainly serves to specify, visualise, construct and document the artefacts of a system (Hause 2006). A combination of BPMN and UML would be applied in this study.

In terms of formal modelling of OSM knowledge to support automated process analysis. One of the important decisions required of any ontology developer is the choice of language and the decision is majorly influenced by the expressiveness of a language and the inference mechanism supported by the ontology language (Corcho *et al.* 2003). Web-based ontology languages such as DALM, OIL. OWL offers standards for sharing and publishing ontologies in the WWW. However, OWL offers greater expressiveness and machine interpretability through the provision of additional vocabularies along with its usual formal semantics by combining the expressive power of DAML+OIL (W3C 2004). OWL-DL also offers the level of inferencing needed for building cost estimating rules to support automated reasoning in the ontology. Therefore, OWL is considered suitable to support the modelling of the OSM ontology and its expressiveness is especially critical for linking the concepts of OSM product which in many cases are interlinked, however, still independent on their own.

4.8 Chapter Summary

This chapter provides a critical review of informal, semiformal and formal knowledge representation standards used in supporting the development of KBSs. A critical analysis of informal/semiformal modelling methods of knowledge modelling was done and languages such as BPMN, IDEF0 and UML meets most of the selection criteria relating to the objectives of the study. However, a combination of BPMN and UML will be adopted for the study given the richness of the language and ease of communication. OWL-DL presents the most suitable formal language for ontology development and also supports the rule language SWRL hence will give the level of expressiveness needed for the development of the knowledge-based process analysis model capable of generating various data from a process such as cost and time. The next chapter will provide details on the development of a research framework representing the high-level structure of knowledge based on existing taxonomies from the literature review presented in chapter 2, and also the ABC model to be adopted in this study based on the review from chapter 3. Additionally, a conceptual model will be presented which is intended to represent the architecture of the KBS to be developed in this study.

CHAPTER 5: RESEARCH FRAMEWORK AND CONCEPTUAL MODEL DEVELOPMENT

5.1 Introduction

An extensive review of the concepts related to the study's purpose of developing an automated knowledge-based process analysis system for OSM methods has been covered in the previous chapters. In this chapter, a synthesis of the knowledge gathered from literature review will be carried out in order to develop the research framework to be used to guide the data collection phase for the offsite production workflow (OPW) ontology. Given that ontologies are supposed to represent a shared conceptualisation of the knowledge in a domain, the reuse of existing taxonomies and classification systems is necessary for fulfilling this criterion. However, OSM knowledge is still in the developing stage and yet to reach a general consensual classification approach for its products and processes. In this chapter, a conceptual framework of OSM classification system will be developed based on the review of literature and existing standards in the construction industry from Chapter 2. This will be used as the major taxonomies to form the foundation for the knowledge modelling in the OPW ontology. Another framework will be developed to represent the process modelling structure for implementing the ABC method for OSM based on the review from Chapter 3 and would form the basis of the rules in the OPW ontology. Lastly, a conceptual model will be presented which will represent the architecture and system interactions of the proposed KBS (OPW ontology) to be developed in this study.

5.2 Generic classification system for OSM – A framework

The literature review from Chapter 3 revealed the differences in the classifications and taxonomies used of OSM systems and methods. By synthesizing the data retrieved from previous studies for the purpose of comparing evidence to generate a new construct, it is established that various factors influence how OSM is classified. This includes materials type, production methods, product types and sizes, and structural configuration. By observing the various classifications closely, it is determined in this study that these factors can be grouped under three high-level concepts which are (i) based on the product (ii) based on process (iii) based on people (Figure 5.1). The classification system in Figure 5.1 summarises the different approaches previously reviewed and should help achieve consistency in terms of the use of agreed vocabularies/terminologies and also to enhance communication.

This classification framework is based on existing knowledge of OSM and aggregating the knowledge to eliminate duplications and inconsistencies. One major advantage of classifying in this approach is the ability to make the classification robust enough and suitable for different purposes. For instance, the knowledge of OSM may be needed for various purposes such as cost estimating of OSM components, process analysis, risk management, scheduling, production sequence planning, and many others. OSM-related keywords have been used in the definitions and classifications due to the rationale behind the development of structured knowledge. The aim is to use a set of approved vocabularies by the experts in the field in order to aid communication which is also a requirement for ontology developments to avoid unnecessary creation of new terms. This framework will be used to guide the data collection phase of the study. A further explanation of the categories in the framework is outlined in sections 5.2.1, 5.2.2, 5.2.3.

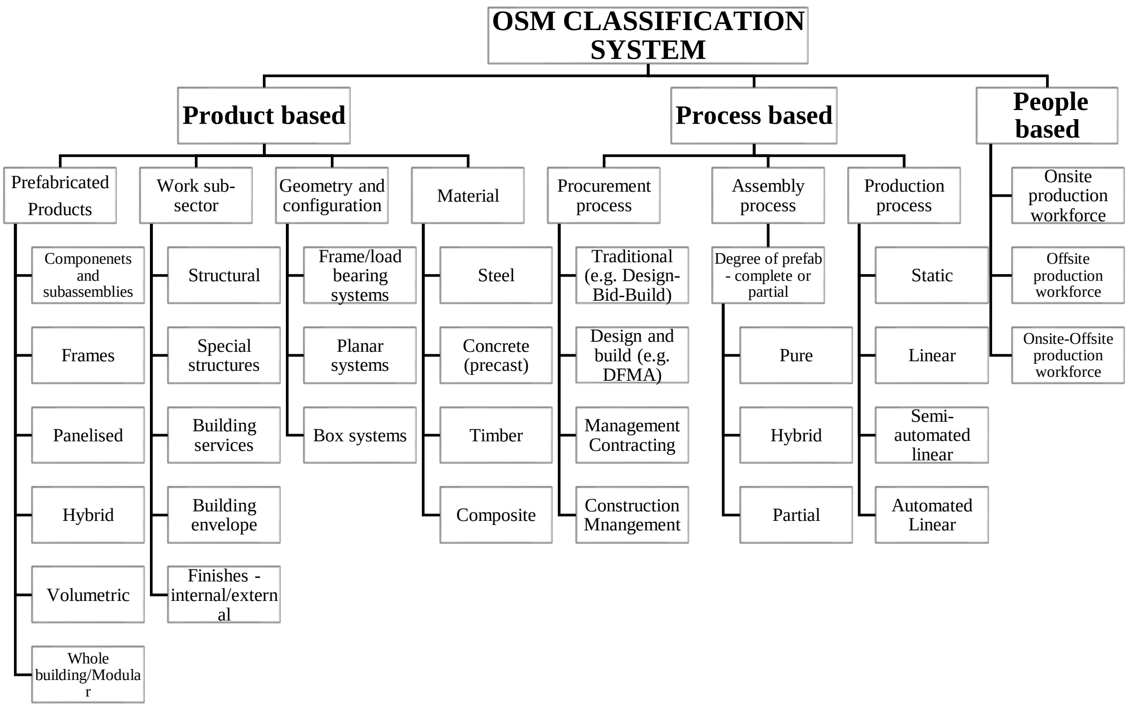


Figure 5.1: Generic Classification of OSM Domain

5.2.1 Product-based classification

The product-based classification for OSM is according to the characteristics and types of the end/finished product of an offsite manufacturing process, which include: the types of prefabricated elements, component materials, geometry and sector of work for a product (Table

5.1). This classification is useful for identifying types of offsite manufactured products and grouping them for specific purposes. For instance, the product-based classification will be useful for elemental costing purposes to attribute properties to each offsite element or component. As an example, a prefabricated product typically has a material type, geometry and also fall under a specific work sub-sector (e.g. a panelised offsite product made from timber has a plane geometry, and can either be grouped as a structural element – e.g. load-bearing wall, or building envelope – e.g. curtain walls). Accordingly, the knowledge of offsite products is enriched by defining the relationships between the various properties and the influence on the final cost of such a building element. In this case, the taxonomies in this group will help in estimating the resource cost of activities in the ABC model and for attributing estimating rules based on different attributes of each OSM element or component.

Table 5.1: Definition of concepts in the product-based classification

Class	Subclass	Instances	Description
Prefabricated Products	Components and sub-assemblies	Bricks, tiles, window, lighting, door furniture etc.	Factory manufactured items that are produced offsite and certainly not considered for onsite production.
	Frames	Beams, columns, bracings etc.	Load-bearing structures that transfer vertical and/or lateral load to the foundation.
	Panelised	Wall panels, floors panels etc.	Two-dimensional building components that do not enclose a usable space and may include several other sub-assemblies that constitute part of a building.
	Hybrid	Roofs	A mix of two or more sub-categories and usually a combination of the volumetric and panelised sub-categories.
	Volumetric	Toilet pods, plant room units, kitchen spaces, stair shaft and building service risers and lifts, shower rooms etc.	Three-dimensional building parts that enclose a usable space but do not independently form a building itself.
	Whole building	Retail outlets (shops and stores), office blocks and motels	They enclose usable spaces and make up the actual structure and fabric of the building. Usually a low rise complete building which may be fully finished or partly finished
Work sub-sector	Structural	Columns, beams, foundations, walls etc.	Primary physical parts of a building
	Building services	Pods, Lifts, plant room etc.	Systems installed in buildings to enhance functionality
	Building envelope	Façade systems, roof systems	The exterior of a building which serves as physical separator between the interior and exterior of a building
	Finishes	Plaster, paints etc.	The final surface of a building element

	Special structures	Unique structures e.g. stadia	Structures that require engineering creativity and specialist design, analysis and construction
Geometry and configuration	Frame system	Beams and columns	Load-bearing structures
	Planar system	Slab, floors, wall panels etc.	Two-dimensional components that may be straight, curved or angled
	Box system	Kitchen and bathroom pods etc.	Three-dimensional modules that do not support vertical loads itself.
Materials	Steel	Lightweight steel etc.	A metal part containing iron as a primary material
	Concrete (precast)	Self-compacting concrete, lightweight concrete etc.	Comprising of a mixture of cement, aggregate and water where components are manufactured in a central plant and later brought to the building site for assembly.
	Timber	Bamboo, Oak, plywood, softwood etc.	Wood suitable for engineering purposes.
	Composite	Fibre-reinforced polymer (FRP), PVC polyester etc.	Comprising two or more constituent materials with significantly different physical or chemical properties

5.2.2 Process-based classification

OSM can also be classified based on its processes including the procurement process (i.e. the sequence of design to production and whether the design approach attempts to integrate the ease of manufacture and efficiency of assembly or to address conventional construction design concerns), the assembly process (i.e. the extent in which manufactured components are complete for assembly) or production process (i.e. the methods employed in producing the manufactured components such as the use of innovative technologies and amount of skilled/unskilled labour required) (Table 5.2). For instance, an OSM project can be procured via a traditional design-bid-build approach where the subcontractor or specialist contractor undertakes production in a way similar to the onsite approach (i.e. static production method). Alternatively, production can be carried out sequentially on a line with the use of robotics stationed at strategic points to hasten the process (i.e. an automated linear production). In a situation where the advantages of modularisation are more desirable, all components can be factory manufactured with only the assembly done onsite (i.e. pure prefab). Describing OSM in this manner is advantageous for purposes such as planning and scheduling of the production and assembly processes. The understanding of the activities related to each production method is necessary when using the ABC method for generating data on processes. Hence, the knowledge related to this category of OSM classification will be modelled in the OPW ontology to facilitate reasoning on the impact of the choice of OSM production method on cost.

Table 5.2: Definition of terms in the process-based classification

Class	Instances	Description
Procurement process	Traditional – design-bid-build	Where the client appoints consultants to design the development and then a contractor to construct the works, the contractor has little or no influence on the design.
	Design and build - DFMA	A single contractor to design and build the work and the contractor has a say in the design process. The contractors have little or no influence on the design.
	Management Contracting	A management contractor contracts and manages the work to other work contractors to construct the work.
	Construction Management	A construction manager to serve as a representative of the client in coordinating all work contracts and other trade contractors
Production process	Static	A process where prefabricated elements are manufactured in one position, and materials, services, and personnel are brought to the fabrication point.
	Linear	Production process is sequential and carried out in a discrete number of individual stages.
	Semi-automated linear	Based on the same principles of conventional linear production as non-automated lines, but tend to have more dedicated stages
	Automated linear	Linear production with sequential stages that are automated
Assembly process	Pure prefab	All activities carried out in a controlled environment (either offsite or onsite) with only assembly and installation done onsite.
	Hybrid prefab	Comprising of both onsite and offsite prefabricated components assembled together. For instance, an onsite factory-produced element joined together with an offsite purchased structural element to make a complete structure.
	Partial prefab	A mix of offsite factory-produced components and onsite cast insitu components.

5.2.3 People-based classification

This category provides information on the degree of prefabrication and category of workforce required for offsite product manufacture i.e. whether products are manufactured/assembled using onsite or offsite labour, or a combination of both (Table 5.3). The choice of production/assembly process influences the type/characteristics of the workforce required. If a higher degree of prefabrication is sought, the amount of work that needs to be finished off in the factory will be higher and thus, require more onsite activities and workforce, and a few workforces onsite for just assembly. This classification system may be used in carrying out tasks such as risk assessment or health and safety analysis both onsite and offsite, as well as generating onsite/offsite labour cost for offsite manufactured products. In this case, the categories of workers needed for the production, information such as their skills, wages, etc would be modelled under this classification in the OPW ontology in order to trace labour consumption to activities performed in any OSM production method.

Table 5.3: Definition of terms in the people-based classification

Class	Instances	Description
People	Offsite operatives	Involves transferring building operations from site to factory using factory located personnel which could range from skilled operatives to casual workers, production managers and supervisors etc.
	Onsite workers	Involves the production of building elements at the site before erecting to its actual location using site-based personnel. This includes crane operators, installation operative, site managers etc.
	Onsite-offsite workers	Involves a mix of both offsite and onsite production and assembly team. This may include support staff in charge of overseeing both onsite and offsite works such as operation manager, etc.

5.3 Framework for lean based ABC modelling for OSM methods

A comparison of the cost drivers used in construction and manufacturing sectors has been analysed in Chapter 3, and how these relate to the OSM method of construction (see section 3.5). According to Xu *et al.* (2011), the cost drivers for a manufacturing process can be categorised into material cost, machining/production cost and assembly cost. This however does not reflect some critical aspects of the OSM method. Factors such as transportation, storage, packaging, etc. are major contributors that determine the final cost of a building and have been identified by researchers (e.g. Baldwin et al. 2006 and Pasquire et al. 2005) in the construction field. Learning from these research studies, a conceptual framework to represent the cost drivers for the OSM method in line with the ABC method is illustrated in (Figure 5.2). However, the labour cost relating to the production and assembly of the products are separated into direct and support costs so as to allow for the breakdown of the cost into value-adding, non-value adding and necessary non-value-adding aspects of the process based on the lean technique for process analysis.

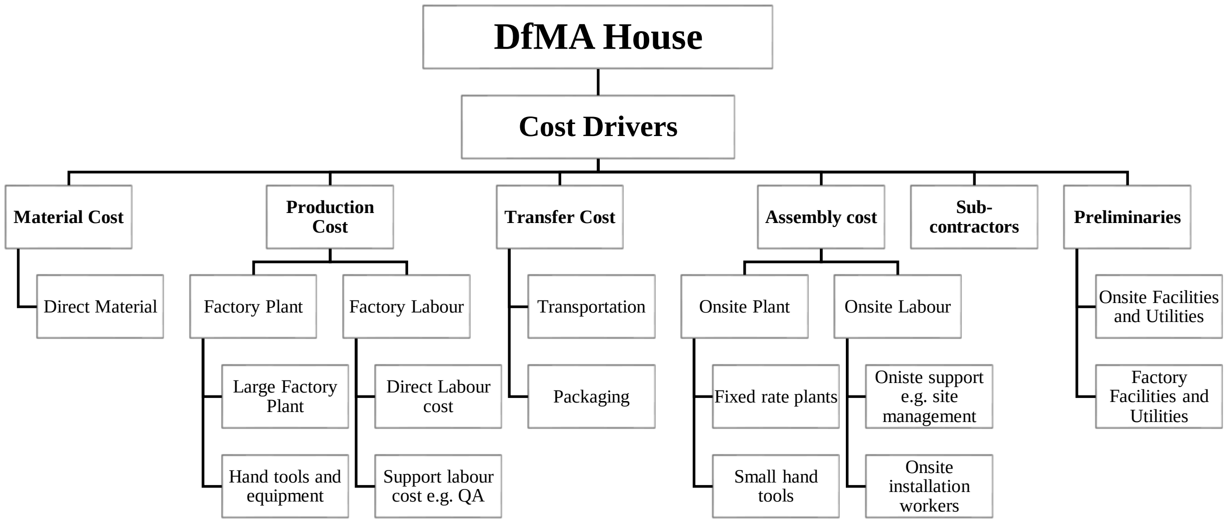


Figure 5.2: Cost drivers for OSM DfMA house

Also, previous studies have outlined best practices on steps to follow in using the ABC method for modelling the cost of a process. Since ABC is mostly used in tracing and allocating overhead cost in of activities, some researchers in the manufacturing sector (Akyol *et al.* 2007, Kim 2017, Lou *et al.* 2017) are of the opinion that direct material and direct labour cost can be easily calculated and there is no need for assigning these costs. Other researchers (e.g. Kim and Ballard 2001) who have implemented ABC in the construction sector are of the opinion that direct labour cost needs to be covered in the scope of ABC for construction processes in order to be able to capture non-value-adding activities embedded in the direct labour hours. Otherwise, the opportunity for continuous improvement through the identification of areas of profit/loss, or waste reduction may be missed.

The recommendation by Kim and Ballard (2001) will be implemented in this study. Figure 5.3 illustrates the framework for assigning and determining the production cost of the DfMA product that will be implemented in this study. The cost for OSM methods will be divided into material cost and process cost (relating to the activities involved in the process). The cost of any OSM product will thus be determined by summing up the cost of direct material and the cost of each activity consumed (such as VA, NVA and/or NNVA activities). Figure 5.3 represents the basis for setting the rules in the OPW ontology to implement the ABC modelling method. The direct material cost can be easily traced to the individual cost objects (e.g. walls, floors etc). However, the indirect cost needs to be assigned to the products.

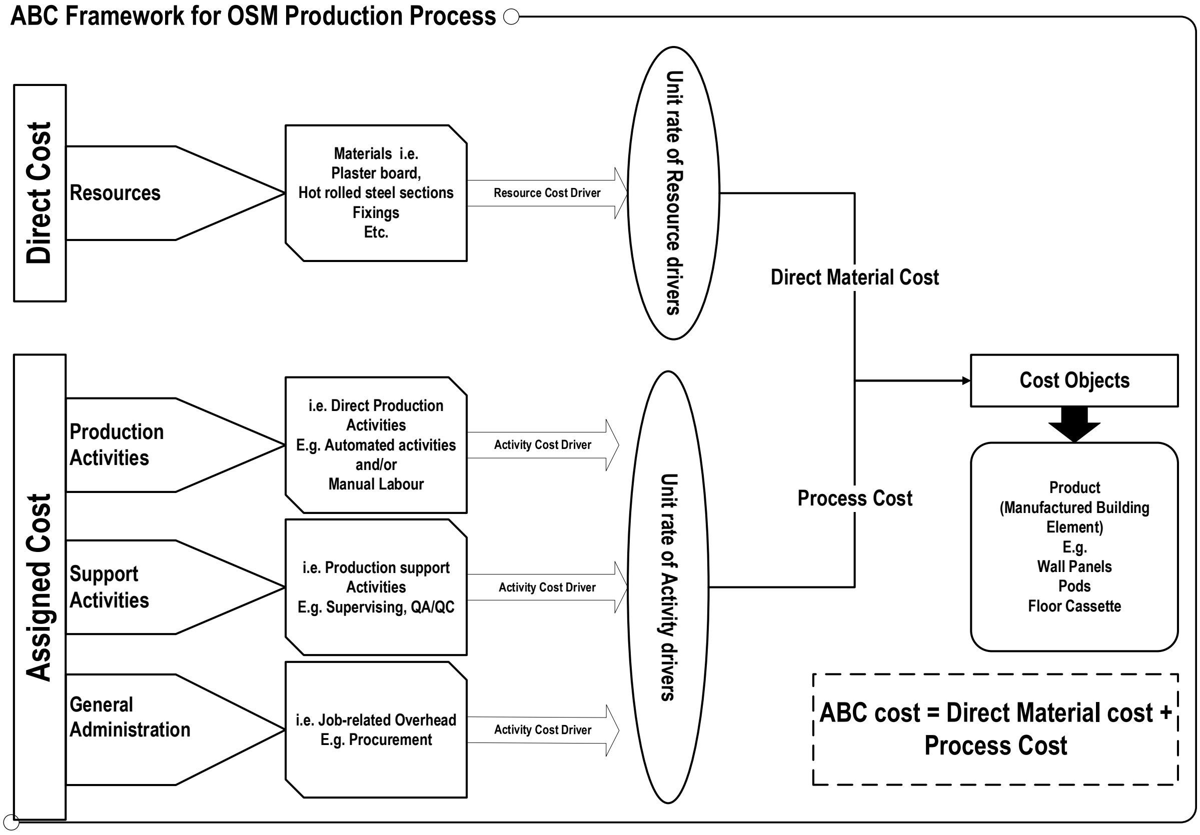


Figure 5.3: Framework for ABC modelling OSM production process

5.4 Conceptual model for the proposed OSM process workflow (OPW) ontology

Lastly, a conceptual model is developed to represent the system architecture and interactions of the proposed tool (the OPW ontology). The review conducted in Chapter 4 concluded that the use of the ontology language OWL for knowledge modelling offers better expressivity and flexibility thus enabling the richness of the semantics of the knowledge to be modelled. The ontology development tool Protégé has been selected for the modelling exercise for this study (see section 6.7.2) and this tool supports OWL and SWRL.

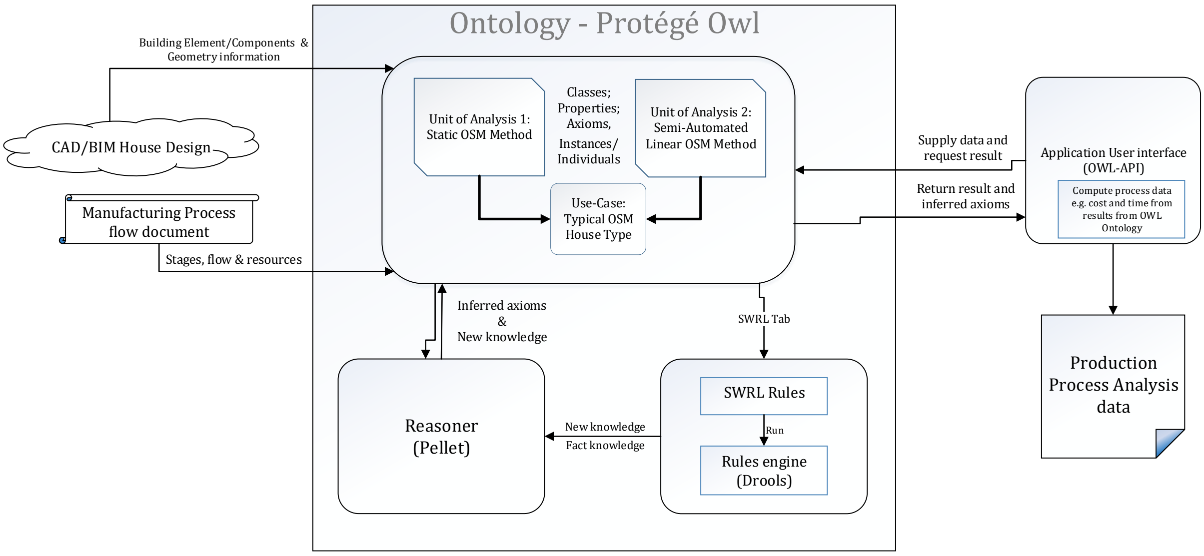


Figure 5.4: Conceptual model representing the architecture of the OPW ontology

5.5 Chapter Summary

Two conceptual frameworks and one conceptual model have been developed in this chapter to help in fulfilling the overall goal of the study which is the development of a process analysis tool for analysing OSM methods. The first framework is a classification system for OSM which covers aspects such as the product delivered using OSM, the various processes involved in the OSM method and the categorisation of the workforce required to complete an OSM project. This classification system would serve as the basis for structuring the knowledge in the proposed OPW ontology. The second framework captured the major cost drivers in the OSM method required for modelling the cost of the production process based on the ABC method. This framework will be used to guide the rule development in the OPW ontology n order to automate the analysis of the activities involved in various OSM methods. Lastly, a conceptual model is presented which represents the architecture and interactions of the proposed tool and the sources of data that will be used to generate results from the tool. Since this study is only limited to the production phase of a DfMA/OSM project, aspects such as design and assembly are not included in the model. The next stage is to develop a research design in fulling the objectives of the study and the next chapter will provide some analysis and justifications on the research methodology and strategy chosen for this study.

CHAPTER 6: RESEARCH METHODOLOGY

6.1 Introduction

In the previous chapter, two conceptual frameworks were presented to serve as a foundation for building the knowledge in the proposed ontology. These frameworks need to be further expanded and developed to enable a low-level analysis of OSM processes and this will be done through the collection of additional data. Therefore, in this chapter, a suitable research design will be examined to enable an empirical investigation of the research problems for the purpose of realising the objectives of the study. Choosing a research methodology is most times dependent on what type of questions are posed in the research (Yin 2009). This chapter will start by systematically analysing the research problem in order to identify a suitable methodological strategy for carrying out observations. Also, since academic research is directly or indirectly underpinned by a philosophical assumption underlying the research process (Ahmed *et al.* 2016), attempts will be made to explain the philosophical standpoint of the study and how the objectives and research questions match with the strategies that have been selected.

The following sub-sections are discussed: an analysis of the research problem and strategies used to address the problems, an overview of the research strategy used for developing the informal/semiformal knowledge model, and finally, an outline of the methodology selected for formal computational knowledge modelling in the ontology.

6.2 Research Philosophical Position

Philosophical views are used to denote certain assumptions and beliefs that guide a person's understanding of nature (the existence of a being) and building knowledge of such nature (Schuh and Barab 2008). A paradigm is defined as a set of perceptions and beliefs held by a discipline that guides their approach to discovering and questioning (Neuman 2014, Fellows and Liu 2015). This guides the common saying that "*questions of methods are secondary to questions of paradigm*" (Guba and Lincoln 1994) as the beliefs of individual researchers often influence their choice of methodology selection in approaching a research problem (Creswell 2009). The basic beliefs of a research paradigm are categorised into three fundamental questions which enable a paradigm to be analysed. These are the ontological, epistemological and methodological questions that guide a research enquiry (Guba and Lincoln 1994). An illustration of how these three aspects inform the research process is shown in Figure 6.1. named the research 'onion' by Saunders *et al.* (2009).

The first question usually asked in a research enquiry development is the ontological assumption about the nature of reality. This is followed by the epistemological assumptions of how to build the knowledge around such reality, and lastly, the methodological assumptions in selecting suitable methods for investigating the reality (Morgan 2007). The ontological and epistemological beliefs and assumptions are considered essentials in any research as the guide and inform all subsequent research activities (Fellows and Liu 2015).

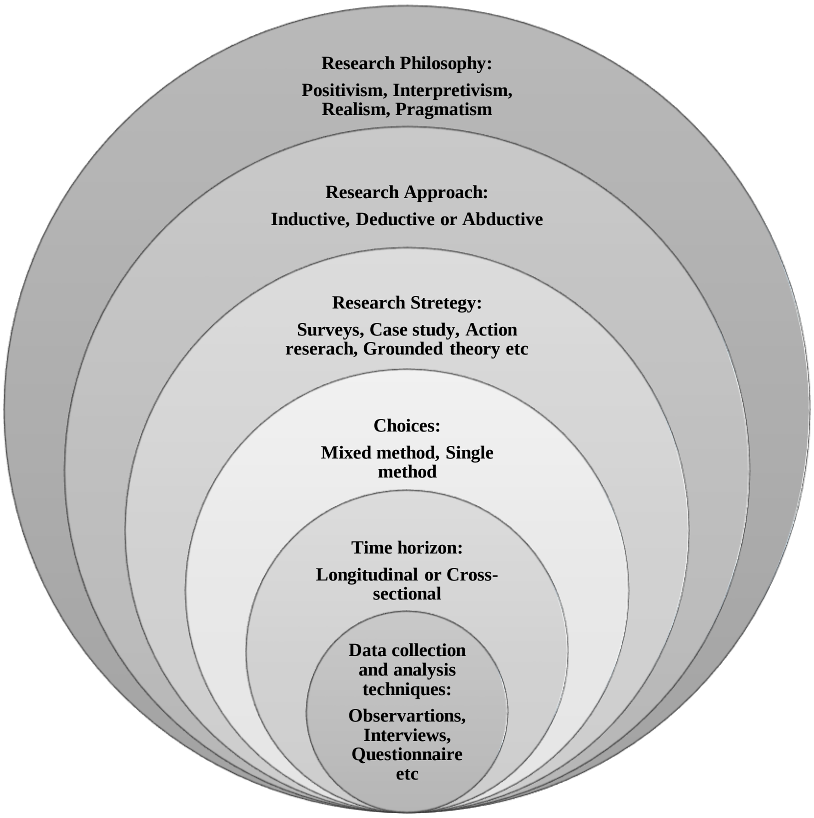


Figure 6.1: Research process (Adapted from Saunder et al. 2009)

Ontology is used to refer to the theory and existence of a being (nature) and the nature of reality (Guba and Lincoln 1994). Ontological questions are asked to ascertain what exists in a real world and the characteristics (physical and abstract structure) of such existence (Willis 2007, Schuh and Barab 2008). Epistemology on the other hand refers to the theories of knowledge, the nature of such knowledge and how it is possessed by individuals (Giacobbi *et al.* 2005). This is associated with how knowledge can be created, acquired and communicated between people (Willis, 2007, Scotland, 2012). An individual's epistemological stance hence represents how he/she chooses to understand the existence of a being.

In this study, the nature of the reality (ontological question) with regards to OSM is that the knowledge relating to OSM processes are fragmented, and based on individual company's approaches thereby inhibiting a wider acceptance due to lack of structured data to support decision making on the various competing OSM methods. A proposed solution is to systemise such knowledge to allow for consensus in the process of modelling OSM knowledge to enable data retrieval for support analysis of the processes involved. Therefore, the approach to understanding this reality will be guided by the epistemological stance taken in the study. Generally, epistemological concepts are viewed from two main perspectives, which are the positivist and interpretivist positions (Bryman 2012). A positivist adopts the objective epistemological standpoint with the belief that a reality can be measured and understood without any human intervention thus, avoiding subjectivity and supporting a natural science approach where emphasis is laid on objectivity. The interpretivist position is leaned towards an individualised and context-specific view of knowledge where a reality is constructed through social interaction with the environment (Giacobbi *et al.* 2005). An interpretivist advocates for an emphatic understanding of situations hence, judgements are considered subjective (Creswell 2009). Both philosophical underpinnings are usually matched with the quantitative and qualitative data collection methods respectively.

However, more recently the pragmatist and critical realist philosophical positions have emerged and have been widely held by researchers. The pragmatic position argues that a continuum holds between the dichotomous views of the positivist and interpretivist positions. A pragmatist believes that knowledge acquisition is not a single straightforward procedure and thus should not be committed to a single laid out philosophy but rather based on what works which could mean a combination of suitable methods, techniques and procedures that matches the research problem (Creswell 2009). This is referred to as a 'pluralistic' method by Giacobbi *et al.* (2005). The pragmatic approach to research is perceived as a means of finding practical solutions to contemporary problems with the belief that there is no single reality thus opting for theories and methods deemed suitable given a particular context (Giacobbi *et al.* 2005). The realist position on the other hand holds the position that a reality exists (an external reality) independent of the researcher's mind (Sobh and Perry 2006). A realist, therefore, acknowledges the real world and a person's view of it. Thus, the view of the reality can be relative in time. Therefore, a realist research approach believes results to be contextual and the aim is to develop a 'family of answers' that covers different contexts of a reality through triangulation of different methods (Sobh and Perry 2006).

In order to gain an understanding of how to systemise OSM knowledge to allow for automated reasoning on such knowledge for process analysis and retrieval of process data, the realist epistemological position which holds that there is an external reality and allows for the method chosen to fit the subject matter has been selected for the study. The research paradigm adopted for the study is inspired by the research problem and questions which necessitates an understanding of the subject in its context. Hence, the author holds a realist position which is considered to be somewhat in the middle as opposed to the extreme ends of the positivist and interpretivist positions. Owing to this, a combination of different methods (mostly qualitative) with the combination of various data collection techniques deemed suitable at a point in time is used in this study.

6.3 Research Approach

Based on Figure 6.1, the next stage after having selected a philosophical standpoint is to implement a research approach. A research approach can be defined as the path of conscious scientific reasoning to knowledge acquisition (Spens and Kovács 2006) and the structure of a research study depends on the approach taken (Awuzie and McDermott 2017). Accordingly, there are three approaches to carrying out a research study and the acquisition of knowledge: deductive, inductive and abductive methods. These three methods follow different paths for acquiring knowledge about a phenomenon, however, with the same goal of advancing knowledge.

6.3.1 Deductive Approach

This approach involves moving from general to specific. This approach is intended for testing an existing theory, it commences with a generalisation (an established theory) and the researcher seeks to determine if the theory applies to a specific instance (Spens and Kovács

2006). Hence, why this is called a theory-testing approach. The deductive method stems from a positivist philosophical world view from applied science thus empirical testing of such theories is required in order to avoid bias due to researchers' interference (Hyde 2000).

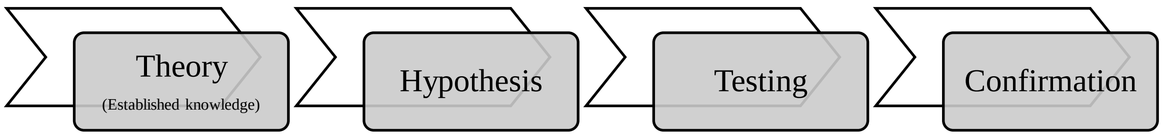


Figure 6.2: Deductive Research Process

The deductive methods start from a strong theory with the aim to test if the theory applies to a specific instance through empirical research. The theoretical framework is thus built-in form of a hypothesis and then testing and observation before reaching a conclusion to corroborate or falsify the theory as illustrated in Figure 6.2 (Spens and Kovács 2006).

6.3.2 Inductive Approach

The inductive method takes the opposite form of a deductive method and approaches reasoning from a specific case to a general theory i.e. from facts to theory thus named a theory-building approach (Hyde 2000). This method is a theory development process in which a researcher starts from observing specific aspects with the aim of arriving at a generalisation about the phenomenon being investigated (Spens and Kovács 2006). A collection of observations is usually required in order to arrive at such generalisation. Prior knowledge of literature is not required to commence the investigation, instead, the phenomenon is observed leading to the formulation of a hypothesis which is then used to develop a theory through logical argumentation as illustrated in Figure 6.3 (Spens and Kovács 2006). This method thus takes the interpretivist philosophical position with the researcher's mind open to different possibilities of results from the investigation (Hyde 2000).

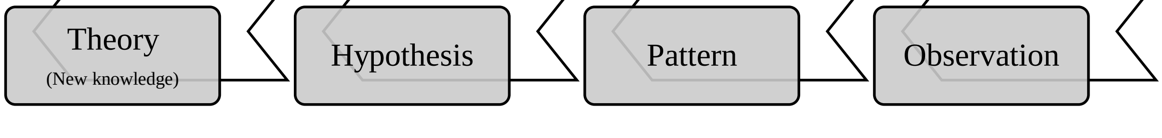


Figure 6.3: Inductive Research Process

6.3.3 Abductive Approach

The researchers in support of the abductive approach are of the opinion that research is neither purely inductive nor purely deductive (Spens and Kovács 2006), thus the researcher takes the approach of reasoning from effect to cause (i.e. explanation). This method of reasoning and acquiring knowledge may have two or more starting points such as an observation or a deliberate application of theory to explain a phenomenon (Spens and Kovács 2006) by engaging back and forth between theory and data with the aim to extend an existing theory or the develop a new one (Awuzie and McDermott 2017). The researcher thus initiates a creative iterative process by systematically combining theoretical and empirical findings (or matching framework) (Dubois and Gadde 1999) believe that previous theoretical knowledge plays an important role although may not be able to explain the phenomenon entirely, as illustrated in Figure 6.4.

A researcher using this method may borrow theories from other disciplines to explain specific issues thus, conducting the research in an overlapping manner in order to suggest new theories.

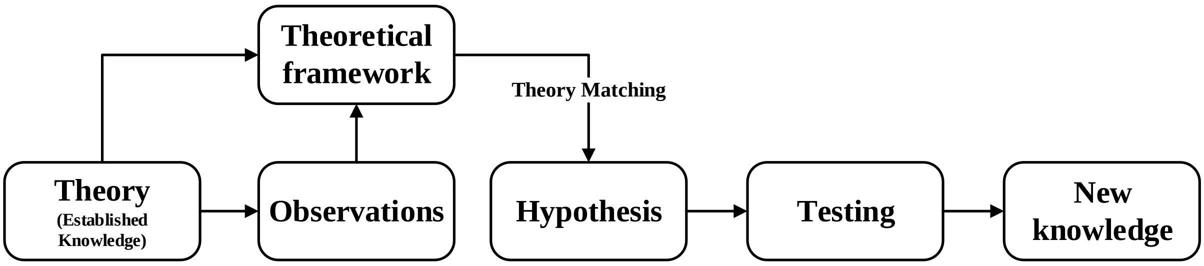


Figure 6.4: Abductive Research Process (Adapted from Spens and Kovacs 2005)

The realist position taken in this study favours the abductive reasoning approach which combines the inductive and deductive approaches by gaining insights to create new conceptual possibilities (Creswell 2009). This approach would help gain insight by using existing knowledge in the field and observations of OSM processes to generate new knowledge on how OSM process modelling should be approached. Therefore, the conceptual frameworks will be modified with results from the empirical findings and also from theoretical insight gained during the research process (Hyde 2000). The next sections outline and discuss the research strategies and research design for gathering information and collecting data, also highlights the methods for analysing the data.

6.4 Research Strategy

The next stage after determining the philosophical standpoint and the research approach is to develop a strategy for the research (see Figure 6.1). A research strategy outlines the approach that will be taken to answer the research questions and how the methodology will be implemented (Yin 2009). According to Schell (1992), research design requires a choice of research strategy, and the research approach is determined by classifying the research questions (Yin 2009, Soiferman 2010). Neuman (2014) has argued that the strategy for conducting a research study varies with regards to if the study is primarily qualitative, quantitative or a mix of both. Since this study is stemmed from a realist point of view, the research has been planned to include a combination of methods depending on the need and context at each point in the study in order to support triangulation of results and richer interpretation of the reality.

Figure 6.5 illustrates a flow chart of the research strategy/plan for this study which has guided the research design and the selection of methods, tools and techniques. For this study, the research questions have been used to guide the development of strategies with each research question matched with a suitable strategy as deemed appropriate to allow for answers to be obtained and will be outlined in the following sections.

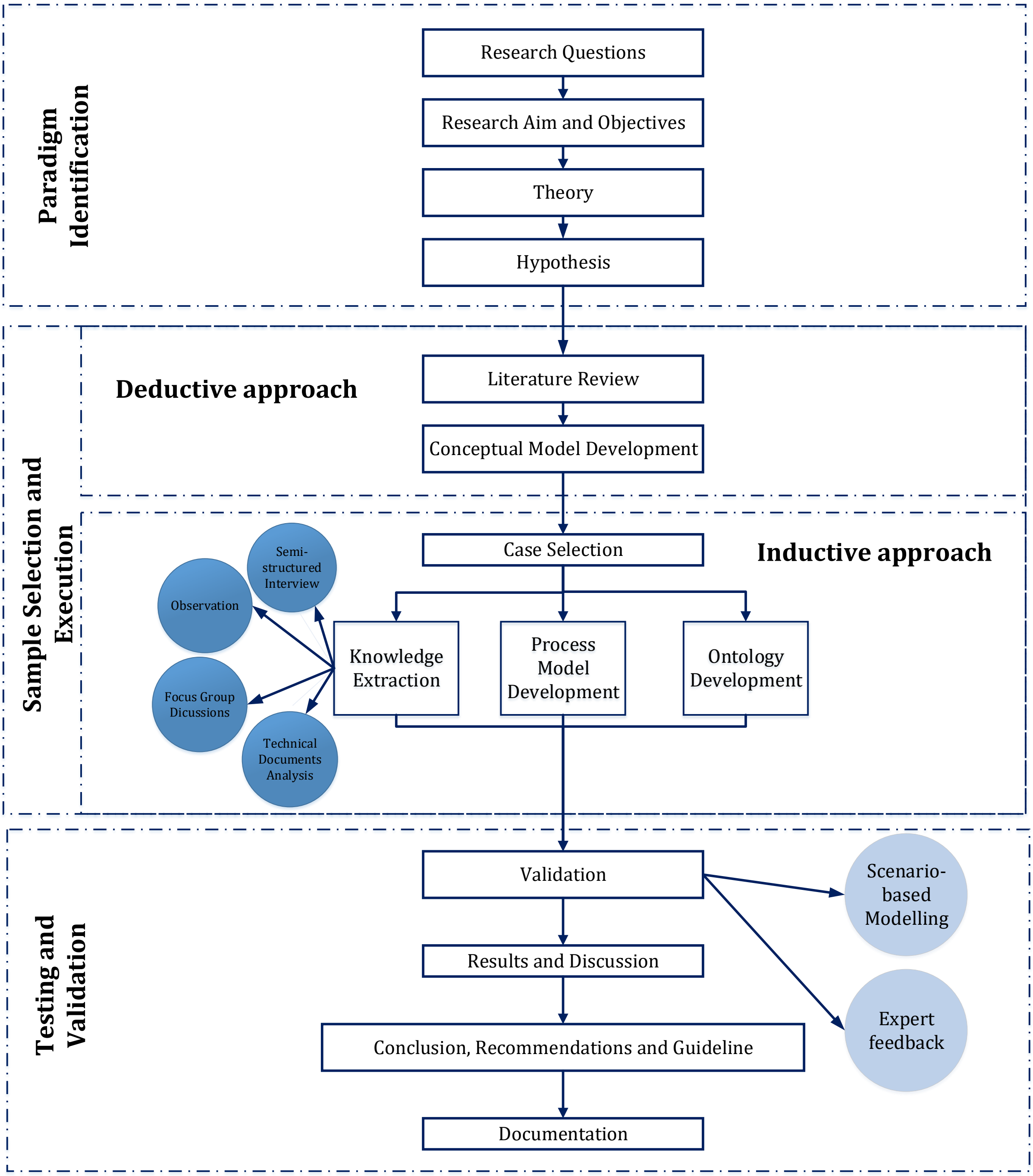


Figure 6.5: Research strategy flow chart

6.4.1 Strategy for Research Question 1

Q1: Is the current understanding and representation of the knowledge of OSM domain accurate and how best can existing knowledge be modelled for accurate representation and to support knowledge sharing and clear communication?

Due to the nature of this research question, the abductive reasoning approach was used and two strategies have been identified that will best provide the answers sought after. A critical analysis of existing literature was conducted in order to understand the historical context of OSM and identify the existing understanding of OSM in the construction industry including how OSM is be defined and existing classifications of the method. The rationale is to synthesise this knowledge for the development of a conceptual classification framework that was used as the basis for formalising OSM knowledge in an ontology. At this stage, a deductive reasoning approach was used to generate the conceptual classification framework based on previously established facts from literature about OSM. A top-down approach was adopted moving from the general knowledge to the specific in establishing what knowledge exists in the domain (Elo and Kyngäs 2008, Soiferman 2010). However, the OSM classification from literature is too high-level and unsuitable for facilitating detailed process analysis of the activities in various OSM methods. Therefore, a bottom-up approach using an inductive reasoning method was adopted for expanding the classification through primary data collection. This allowed for the classifications to be explored more specifically while expanding on the data obtained from the literature review with real-life data.

6.4.2 Strategy for Research Question 2

Q2: In what means and approach can OSM processes be analysed to provide information and allow for value-based analysis of the processes to support accurate decision-making on choices?

The analysis of existing knowledge on OSM has identified the lack of a structured approach in analysing choices as one of the critical aspects inhibiting decision-making and impacting the implementation of OSM. Also, it has been determined that OSM processes are considerably different from traditional methods and thus have different cost drivers. Therefore, a deductive approach was used to answer this question by conducting a critical review to investigate and analyse suitable methods that suit OSM process analysis to support informed decision-making. Also, since OSM is based on manufacturing concepts with similar processes, the opportunity to learn from some other industries (manufacturing industry) on how manufacturing processes are analysed was explored. A conceptual framework on OSM cost drivers based on the ABC method was developed. An inductive approach was then be used to refine the framework using expert input.

6.4.3 Strategy for Research Question 3

Q3: In what means can the knowledge of OSM processes be formalised and modelled for the purpose of systemising and automating process analysis of OSM methods considering the current data and information-driven advances in the construction industry?

Given the volume of data required to carry out the ABC modelling and the lean based value system analysis methods, the analysis of current literature has identified the use of knowledge-based modelling tools and techniques as a useful means for facilitating knowledge capture, formalisation, and sharing using experts systems to facilitate automated reasoning. Therefore, a deductive approach is used to critically analyse the existing literature on informal, semiformal and formal knowledge modelling methods in order to determine a suitable one for use in this study for systematising OSM knowledge for automated and structured process analysis.

6.4.4 Strategy for Research Question 4

Q4: Are there major differences in the process performance when using non-standardised and standardised OSM methods, and what are the major causes of any differences observed?

The inductive research approach is used to provide answers to this question. A case-study design combining the use of observations, interviews, focus group discussion and document analysis was used to develop a semi-formal process model to represent the different OSM processes which were then formalised in an ontology to facilitate automated reasoning for retrieving data to support the process analysis of OSM methods. A desktop study approach was used in modelling the knowledge by capturing concepts, properties and relationships of the key OSM domain knowledge relating to their processes in order to develop the proof-of-concept OPW ontology. Therefore, data from the OPW ontology can be used to determine the answers to this question.

6.4.5 Strategy for Research Question 5

Q5: What method can be used to validate the developed decision-support tool to test the logic and to determine its fitness for purpose?

In order to answer this question, a two-stage validation method was used: internal logic and expert validation. The first method of validation involved testing the logic of the ontology. The developed OPW ontology was tested using a use-case of an actual OSM project. Various rules were invoked in order to generate results on OSM processes and products such as product type, product cost, product information, production process sequences, VA, NVA and NNVA data, etc. The second method of validation is via expert review where experts from the OSM domain examined the results from the OPW ontology for content validation.

6.5 Research Gap Identification

The realist philosophical standpoint taken in the research necessitates the need to understand the real world that exists outside of the researcher's mind. The external reality here is what other experts in the field have researched on the topic with the purpose of creating a conceptual model/framework to serve as a foundation in building knowledge around the subject. The deductive approach was thus used to explore existing knowledge about OSM and to identify gaps in knowledge. The literature review, in this case, was done not only to determine the knowledge gaps but also to build a conceptual knowledge model. The scope of the review was designed to cover three major aspects believed to be key in addressing the research objectives: (i) background and context of offsite manufacturing; (ii) process analysis methods and cost modelling models and techniques (iii) knowledge modelling methods and techniques. These are considered critical in addressing the question of 'what' data is needed for process analysis of OSM methods, as well as 'how' the data will be acquired, stored, retrieved and communicated between domain experts.

6.5.1 Literature Search Approach

The literature review in this study was conducted through four stages as illustrated in Figure 6.6: planning, screening and extraction, knowledge model development, and documentation.

Stage 1: Planning

In conducting the literature review a search method was adopted to gather relevant publications on the subject area. Firstly, some relevant keywords were identified to aid an initial rigorous search of articles from construction-related journals using the electronic database – ScienceDirect. Supplementary searches were also carried out using other popular academic databases including Google Scholar, ASCE Library, Wiley, IEEE and Scopus. To include literature of OSM regarding its applications in practice, relevant government publications, industry standards and guidelines for OSM were also gathered. Literature on KBS and KBE was also included in the search especially publications from the W3C and Stanford university where protégé was developed.

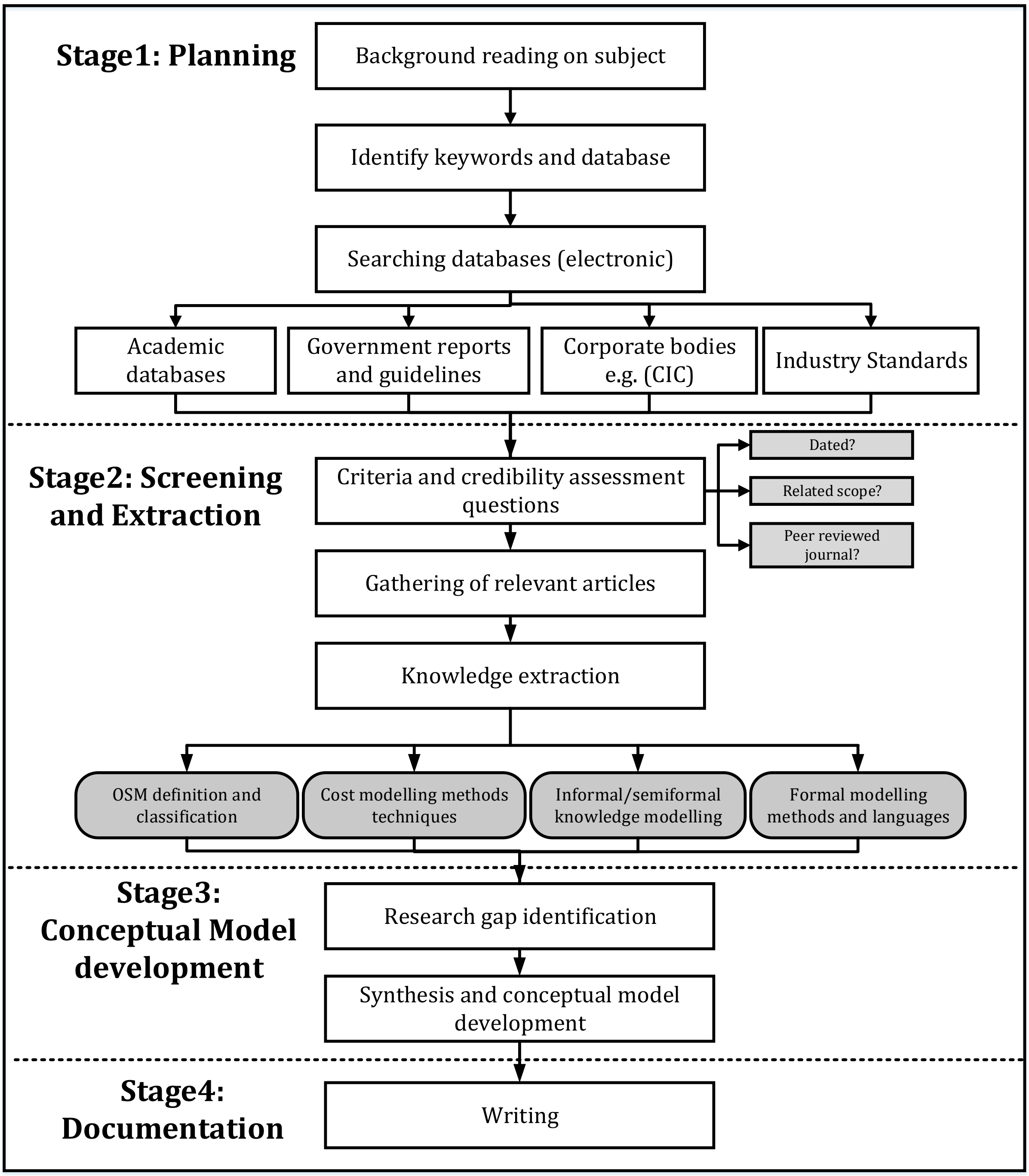


Figure 6.6: Literature search strategy

Stage 2: Screening and extraction

The initial keyword search generated thousands of articles which were very tedious to examine as a result of broad scope and the presence of several duplications from different searches. A screening exercise was thus conducted to narrow the scope, each article retrieved was skimmed through to examine their suitability to the analysis of the individual subjects. The selection criteria include aspects such as (i) the credibility of such publications i.e. whether they are published in a peer-reviewed journal or at least examined through a peer-review process, or widely recognised for industrial reports and textbooks and (ii) the date of publication and its relevance in establishing theory (iii) the type of article and the scope.

Stage 3: Conceptual model development

Having reviewed the selected publication, the gaps in knowledge were identified and conceptual frameworks of OSM classification and ABC modelling for OSM production process were developed to allow for further exploration with a suitable research methodology. The gaps identified guided the research design on what techniques and tools are suitable in exploring the gap area. The next sections will explore the data collection methods in detail.

6.6 Research Design

Research design is used to refer to the practical choices with regards to how the research is implemented. It involves the arrangements and plans set out by the researcher on how to approach the research (Ahmed *et al.* 2016). According to Yin (2009), the research design process usually follows the research strategy. This research sets out to enable a low-level detailed analysis of OSM processes. Given the nature of the data needed for this research, there is a need for in-depth study of different OSM processes so as to collect the primary data needed for the computation modelling in both the formal and semi-formal knowledge modelling methods. Thus, the research is broken down into two major aspects: Case study research and computational modelling, and research design for these stages will be examined in the following sections.

6.6.1 – Case Study Research

Case study research is defined as a form of research inquiry that requires researchers to closely observe/investigate a phenomenon in its real-life context (Schell 1992, Yin 2009). A case study research method allows an in-depth exploration of different perspectives into complex and unique issues in their real-life context (Zainal 2007, Thomas 2011). Thus, helping to answer the how and why questions i.e. questions of a process (Hyde 2000). According to Thomas (2011), for a case study to constitute a research work, two elements must be involved: (i) the subject – a phenomenon that provides the analytical frame and (ii) the object – the analytical focus that serves as a means of placing the case into a focus that develops as the case proceeds i.e. thing to be explained (analytical frame). The 'case' is also known as a 'unit of analysis', which defines the subject in a case study research (Baxter and Jack 2008). In this study, the subject (i.e. unit of analysis) are the various OSM production processes to be studied i.e. 'case', while the object involves the study of the performance of the processes that will be used to contextualise the various production process.

A combination of data collection methods can be used in this research method. A case study can be designed to include both quantitative and qualitative data to explain the process and outcome of a studied phenomenon through the use of multiple sources of evidence (Zainal 2007). Due to the nature of some of the research questions in this study, some parts of the answers are not readily available in existing literature and other published sources and are most likely to be acquired through studying the situation in its real-life context. The study requires an in-depth analysis of processes, which is heavily data reliant. The presence of data silos, typically existing in the context of construction businesses, creates complexity in the modelling processes. Therefore, a case study method was considered the best match for the research problem and questions and was chosen for this study.

6.6.2 Case study research method – Embedded single case design

There are two types of case study design: multiple and single case study designs. A single case study involves the use of only one case while a multiple case study involves a combination of two or more cases that are used to build a theory about a phenomenon. There is a general opinion that multiple case studies increase explanatory power than a single case study and researchers have suggested that using multiple methods provides more reliable evidence (Zainal 2007). However, other researchers (e.g. Hyde 2000) have pointed to the trade-off involved in each choice i.e. multiple cases result in more breadth than depth when the same resources are used. Also, Yin (1994) argued that the single case study approach is better for creating high-quality theory, and better when the aim is to shed light on a single setting

(Sarvimaki 2017). A single case study can also involve different units of analysis which is commonly referred to as the embedded single case study design (Yin 2009). A single case study with embedded units gives the researcher ability to investigate subunits within a large case and to explore and analyse data within the case study.

For this study, a single case study design has been selected as a means to conduct the exploratory research required. The standpoint is that given the nature of data required to build the knowledge model, it is more important to obtain rich content in place of the breath that can be obtained in multiple case designs. The depth required can thus only be reasonably achieved with a single case design. Moreover, the challenges with the use of OSM is that manufacturing layout and techniques do vary significantly from organisation to organisation and also influenced by other factors such as the material, product, or system of OSM adopted. Thus, using multiple case studies of different OSM cases will be complicated and may result in the capturing of only general high-level concepts which do not provide the rich set of data sought for this study. Additionally, the study is aimed at providing a 'proof-of-concept' for the use of knowledge-based systems in facilitating accurate representation and analysis of OSM processes while integrating the ABC and value analysis methods. Given this, the selection of a 'common case' serves a revelatory purpose of uncovering information and providing insight into the OSM processes that would otherwise be inaccessible due to the sensitivity of such data. Also, this common case can provide applicable data on other OSM methods and techniques if the context fits within (Sarvimaki 2017). Finally, given that the purpose of the research is to develop a proof-of-concept ontology model for OSM processes, some case study researchers (Yin 2009) are of the view that it takes only one case to prove or disprove that the research theory is achievable.

Another criticism faced by single case study design is the lack of cross-case analysis. However, the embedded unit of analysis design can be used to address this issue (Schell 1992, Yin 1994). This study intends to describe as well as explore the different production processes of OSM in order to observe their performance to support decision-making in selecting OSM methods. Therefore, there are different independent units to be studied leading to an embedded case, with the unit of analysis being the different production processes. According to Baxter and Jack (1990), the ability to analyse sub-units incorporated in a larger case separately and to analyse the case globally presents a great advantage in relating the results and validating the study. Therefore, the selected case must be able to provide data from multiple sources of evidence rather than multiple cases. In this study, two units of analysis (cases) were used in building the OPW ontology. These cases include two methods of OSM production, the static and semi-automated production processes serving as an embedded units of analysis.

Finally, case study research is criticised for not being able to provide generalizable results. While the basis for generalisation in the quantitative method is statistical generalisation, the qualitative approach takes the analytical generalisation method where the researcher's goal is to expand and generalise to theories and not to a population (Hyde 2000). The aim of analytical generalisation is to generalise a particular set of results to a broader context which is to draw broad inferences from the study that can be transferred to other contexts based on the degree of similarity between the two contexts (Flick 2014). The selected case will have the ability to support analytical generalisation where patterns and processes within the case can be used to capture lessons learned for general use of the wider industry (Yin 2016). Therefore, if the selected case proves the hypothesis correct, the theory becomes a means of identifying other cases in which the result is generalizable (Yin 2009). In relation to this study, other methods of OSM can be modelled since the knowledge structure in the ontology has been partly developed based on existing knowledge in the domain. Also, the knowledge model is flexible in that it can be specifically customised by including context specific data capturing individual manufacturer's methods, processes and products. Thus, analytical generalisation is possible.

6.6.3 Case selection – Purposive sampling method

Sampling in research is the process of determining which case, person, material or group will be involved in a research study (Flick 2007). Sampling in qualitative research is not tailored towards a formal selection of a representative part of an assumed population but rather a set-up of deliberately selected case(s) for studying a phenomenon of interest (Flick 2007). According to Nicholls (2017), qualitative sampling is more focused on quality rather than quantity thus, researchers focus mainly on getting a rich in-depth description of the phenomena under study. Therefore, selecting a case from which we can learn most, and can spend the most time in terms of accessibility is critical (Denzin and Lincoln 2000).

The purposive sampling method which allows researchers to select units/cases considered to be best suited for the research objectives and questions (Bryman 2012) was adopted for the study. The sample case study used in this study was deliberately selected to allow for detailed exploration and understanding of the phenomenon based on the research questions. Criteria for choosing the sample include (i) availability of different units of analysis - in terms of the production process involved (ii) experience of the manufacturing team (iii) data accessibility in terms of proper documentation of past projects and ability to engage with the project team.

The case study selected is based on one of the largest housing associations (HAs) located in the West Midlands region of the UK (hereafter named HAX). HAX has been procuring social housings using the traditional construction method. HAX has recently recognised the benefits of integrating house delivery within the business after an internal market research and decided to adopt OSM as a major delivery approach to align with the funding body's requirement and the national strategy to adopt Modern Methods of Construction (MMC) as well as to help to meet the housing delivery target to increase 60% of the number of houses delivered per annum. The long-term goal for OSM adoption is to continue developing the offsite products improving house delivery pace, and reducing their capital and operational costs and life-cycle carbon emissions, and improving social tenants' quality of living. Therefore, HAX intends to select the most suitable OSM method to meet their needs however, has no means of examining the performance of the competing OSM methods. This case study is selected for intellectual purpose since it is considered a typical perspective of factory house production and because it presents the opportunity for gathering information for the different units of analysis i.e. cases within a case (Denzin and Lincoln 2000), on both the static and semi-automated linear production methods.

6.6.4 Data collection strategy – techniques and methods

One major strength of the case study methodology identified by researchers (Schell 1992, Yin 1994) is the ability to deal with multiple sources of evidence. According to Schell (1992), case study research may be based on the use of multiple sources of evidence or multiple cases. The multiple sources of evidence allow for methodological triangulation to be carried out (Schell 1992). Also, there are arguments that multiple sources of evidence serve as a complement for each other and provide a more comprehensive picture of the study (Ahmed *et al.* 2016) thus reinforcing the result of the research.

The major determinant of the data collection technique is the nature of the information and enquiry required regarding the study. However, data collection techniques are more suitable for some research methodologies and objectives than others (Ahmed *et al.* 2016, Miah and Genemo 2016). The data collection techniques chosen in this study were selected to match the research objectives and questions (Figure 6.7). The next sub-sections outline the essentials of each technique used in the study.

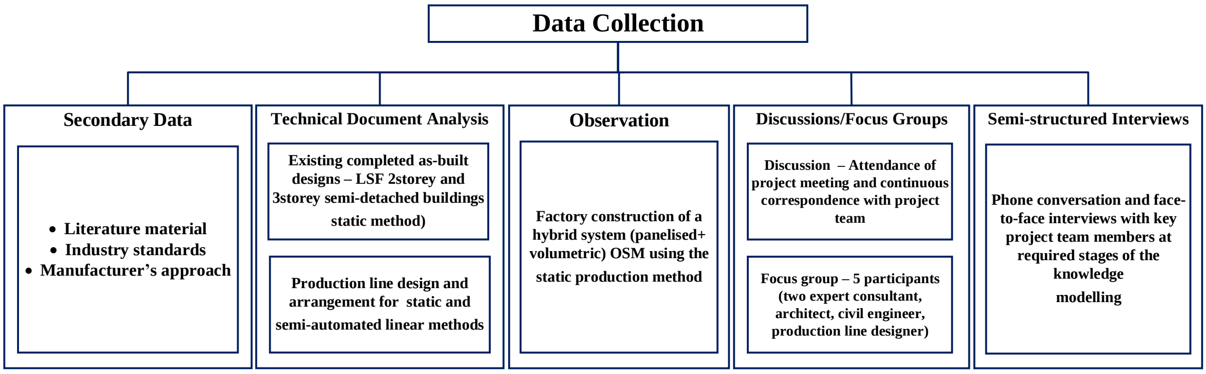


Figure 6.7: Data collection strategy

6.6.4.1 Data collection techniques and methods - Research questions 1, 2 and 3

For research questions 1, 2 and 3, the gathering of knowledge was approached through two methods: secondary data from literature review and technical document analysis as follows:

- **Secondary data (Literature):** establishing what knowledge is in existence and building on that knowledge was deemed necessary to allow these three questions to be answered. Secondary data on OSM classification, OSM cost drivers and knowledge modelling methods were gathered to develop the conceptual framework/model to enable knowledge reuse in the OPW ontology. Documents used include published academic articles, industry standards such as Uniclass and IFC classification, and rule development following W3C's guidelines.

- **Technical document analysis**: the need for this method of gathering data is to expand on the generic classifications derived from secondary sources to reflect the actual real-life OSM classifications suitable for process modelling. The documents used in the knowledge extraction stage include completed as-built design drawings to extract information on product classification using a bottom-up approach.

6.6.4.2 Data collection techniques and methods - Research question 4

Research questions 4 concerns the development of the semi-formal and formal knowledge modelling methods using a process mapping tool and an ontology formal modelling approach. Data collection to fulfil this question required fieldwork exercise. Data was collected using three methods: observations, technical document analysis, interviews and focus group discussions.

- **Technical document analysis:** the first step to gathering data on the production process was to get an understanding of the production line workflow, equipment/tools, workforce requirements and standards/protocols used in the product development stage. Highly technical and confidential documents were used at this stage to develop a preliminary process model using BPMN notations. This includes the production line design for the static and semi-automated methods of OSM production. Also, analysis of as-built design of past projects was used to further develop the conceptual classification system to capture details such as material types, products, specific components, etc. Also, a review of cost plan documents for selected projects was done to extract information on rates build-up and labour requirements for activities in the production processes.

- **Observations:** the next stage after the initial knowledge extraction was an observation process to study the production sequence of the static OSM method in order to answer some questions on the initial process map. The observations were done by visiting the sites located in the West Midlands region, UK.

- **Interviews:** interviews were also conducted with professionals from various companies involved in the project. This includes the engineering company contracted for the design of the production, the project consulting team from the HA in charge of production and resourcing for the project, the steel manufacturing company and the architectural company in charge of the DfMA aspect. This stage was crucial for gaining clarifications on the documents being analysed and to get an opportunity to probe for more explanation where required. The interviews were semi-structured to allow for free flow communication and interactions between the researcher and the participants and allowed the researcher to gain insight into the respondent's knowledge, experience, and perceptions about the context (Ahmed *et al.* 2016). The semi-structured interview method was selected because both structured and unstructured methods could not allow for the required moderate flexibility deemed suitable for the study. These sessions were recorded for analysis and future reference purposes.

- **Discussions and focus groups:** Several project meetings were held during the data collection phase which was attended by the researcher as an opportunity to meet with other companies involved in the project (Architectural, Civil Engineering, Manufacturing solutions, etc.) for a discussion session on the knowledge-based system. Additionally, as a means of reviewing and evaluating the process model developed, two focus group sessions were organised involving 5 key participants from the project (two expert consultants, one architect, one civil engineer, and one production line design engineer). The reason for this is to ensure that expert knowledge is captured in the process model and consequently the ontology is an accurate representation of the OSM business. Given the constraints imposed by the national lockdown in the UK, the focus groups were done virtually using Microsoft Teams with sessions automatically recorded for data analysis purposes.

The data collection method for research question 5 will be discussed in section 6.8.

6.6.5 Data analysis – Thematic and content analysis method

Analysing research data is critical to any research and influences the validity of the results obtained. The ability to draw valid and reasonable inferences from data is considered one of the core competency of a researcher (Ormerod 2010). Data analysis is defined as a process of converting raw data into a meaningful conclusion (Ahmed *et al.* 2016). For this study, the data collected are mainly qualitative data (from literature review, interviews, discussions, focus groups, technical documents) therefore, only qualitative data analysis methods are applicable. The process of analysing qualitative data is generally subdivided into two: (i) inductive analysis and (ii) deductive analysis.

The inductive analysis method involves deriving categories of knowledge from data as they emerge. According to Elo and Kyngäs (2008), the inductive method is well suited in a case where information about a phenomenon is minimal and the knowledge in the field is fragmented. Deductive analysis on the other hand has been encouraged when the purpose of the study is theory testing and the categories of knowledge have been derived from previously established facts (literature) about a phenomenon (Elo and Kyngäs 2008). Both the content analysis and thematic analysis methods of analysing qualitative research can be used for these two approaches. Content analysis is defined as an objective and systematic way of quantifying a phenomenon by filtering its content into fewer related categories and a suitable method for analysing data obtained for human interaction or from written documents (Miah and Genemo 2016). Thematic analysis on the other is recommended for analysing and organising textual content (Ahmed *et al.* 2016).

Both methods of analysis were used at various stages during the course of this study. The deductive approach was used in analysing literature content for the purpose of developing a conceptual model while the inductive analysis approach was adopted in analysing the data obtained from the case study through interviews, discussions, focus groups and document analysis. A three-stage process was adopted: preparation, organising and the reporting stages. The content analysis method was used for analysing data obtained from the observation, interviews, discussion and focus group transcript text. Also, used for analysing the information in the case study technical documents. This was carried out by creating a list of categories from the data, then systematically collating information from text using codes and clustering of themes.

6.7 Computational Modelling – Methods, tools and languages

6.7.1 Ontology development methodology – METH-ONTOLOGY

Ontology development requires a selection between choices of tools, methods and languages to be used in the knowledge modelling process. Most methodologies for building ontologies have been developed through the experiences of people as they develop their various knowledge-based systems (Jones *et al.* 1998) and each of the ontology methodologies has a set of laid down activities for the ontology developer to follow. For this research, 'Meth-Ontology' has been selected as the methodology to be implemented. This method is well adopted and recommended by many researchers in the field (Fernandez *et al.* 1997, Jones *et al.* 1998, Corcho *et al.* 2003, Saad and Shaharin 2016). The Meth-Ontology approach is also considered suitable for building ontology from scratch, reusing existing ontologies or re-engineering ontologies (Corcho *et al.* 2003). The knowledge model in this study was built using the approach laid down in Meth-Ontology. This approach is considered one of the most mature methods (Fernandez *et al.* 1997, Corcho *et al.* 2003) because it thoroughly analyses the lifecycle of an ontology, based on evolving prototypes, by identifying the stages in which an ontology moves through its lifetime. It also specifies activities to be completed for each stage, the techniques to be adopted in going about them and identifies the output expected of each activity. Also, the method is well focused on the maintenance phase of an ontology which is not common for other methods (Jones *et al.* 1998).

The reason for selecting this method for the study is because of the flexibility the approach gives to the ontology developer. Meth-Ontology is independent of any tool/application and gives flexibility in terms of knowledge formalisation as it does not require the use of existing ontologies from a specific application as do most other methods (Fernández 1999, Corcho *et al.* 2003). The ontology development process in this study followed three stages as outlined in the Meth-Ontology approach with a number of activities carried out for each stage: (i) project management phase; (ii) development phase and (iii) support phase (Figure 6.8).

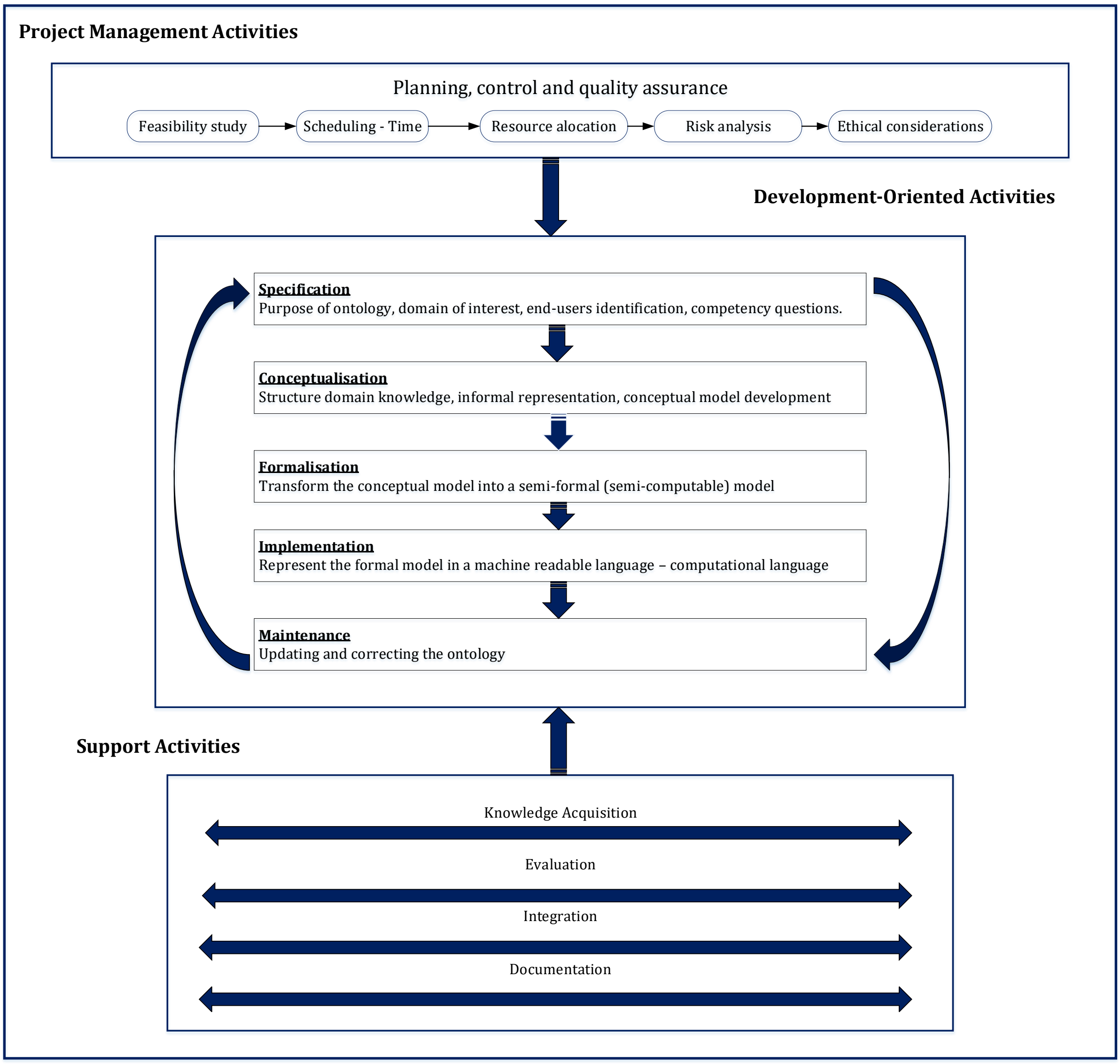


Figure 6.8: Ontology development process and life cycle (adapted from Corcho *et al.* 2003**)**

The structured method adopted in building the OPW ontology according to Meth-Ontology set out stages for the development process which are: specification, conceptualisation, formalisation, implementation, and maintenance. The following explains how these stages have been implemented in the study.

1. **Specification**: During the specification stage, the objectives and purpose of building the OPW ontology were identified which is to systemise OSM knowledge so as to enable automated process analysis and retrieval of process-related data. This was followed by determining the scope of the ontology (limited to the production phase only). The targeted audiences and the end-user requirements were also identified. In order to ensure that the ontology covers the intended needs and is fit for purpose, a set

of competency questions were developed intended for the ontology to answer by consulting with professionals from the OSM manufacturing case study. This is essential in order to help picture how the proposed system might work. A scenario-based approach was used to develop the competency questions.

Scenario – Offsite manufacturer's perspective

A manufacturer's main goal is to make profits from their business. In order to remain competitive and encourage continuous improvement of their business, an offsite manufacturing company needs to be able to evaluate their business processes to determine the best approach to deliver value to their customers. Relating to the OPW ontology, some set of competency questions were identified which the proposed ontology will be expected to answer.

The OPW ontology is expected to capture knowledge on different production processes and their corresponding resource requirements such as manpower and tool used in the different methods. This is very essential in the ABC approach that information on individual activities can be retrieved for the purpose of analysing their added value, which leads to the first competency question.

Competency Question 1: *What activities are involved in manufacturing a house using various systems of OSM (i.e. panelised, volumetric or hybrid methods) and what resources are consumed by these activities?*

Following from question 1, since the knowledge on processes involved in building a house has been modelled, some metadata could be attached to this knowledge to allow for analysis of the various OSM processes. An example of this is retrieving information on the cost and time of each activity in an OSM production process. This also will support ABC modelling method thus leading to the second and third questions.

Competency Question 2: *What is the cost of each activity performed in the factory house building process for the various OSM methods?*

Competency Question 3: *What is the time spent on each activity and in the associated workstation involved in producing a house in the various OSM method?*

Finally, the knowledge in the ontology and the metadata on cost and time can be further analysed in terms of the performance of the competing OSM methods in order to allow OSM companies to evaluate alternative ways of achieving their objectives and supporting continuous improvement. The lean value system analysis approach will be adopted in assessing and classifying the activities in the OSM production process based on the three categories: VA, NVA and NNVA. This leads to the fourth and fifth questions.

Competency Question 4: *What proportions of the activities involved in the production process of different OSM methods fall in the categories value-adding, non-value-adding and/or necessary non-value-adding?*

Competency Question 5: *What is the percentages/value of the cost and time spent on the various categories of activities in the competing OSM production methods?*

These requirements have been used to guide the OPW ontology development in terms of identifying the knowledge to be captured and modelled, and how such knowledge should be modelled in order for the ontology to be able to generate data to support informed decision-making on the various OSM methods.

2. **Conceptualisation**: Having identified the scope and objectives of the ontology, the knowledge gathering phase was initiated. The conceptualisation phase of the ontology is to represent the knowledge in the form of intermediate representation (IR) using informal or semi-formal external representation which is independent of any implementation language (Corcho *et al.* 2003) and can be easily understood by the domain expert (i.e. non-ontology experts) in ensuring that knowledge in the model is accurately represented. This was achieved using the BPMN language/notation in

modelling the various production processes for OSM methods and their activities as BPMN can be easily understood by non-experts.

3. **Formalisation**: This stage involved representing the knowledge in a semi-formal or semi-computable form. In this regard, a UML class diagram was developed and used to represent the architecture/layout of the proposed OPW ontology by representing the concepts (classes), subclasses, instances, properties (attributes), and relationships that are needed in the ontology to fulfil the stated objectives.

4. **Implementation**: The process of formally representing the ontology in a machine-readable language was facilitated in the ontology builder – Protégé. Protégé allowed for the ontology to be modelled with the chosen language for the research (OWL) and also building rules using SWRL. The reasoning was performed with the JESS reasoned supported in Protégé.

5. **Maintenance**: The last phase is continuous maintenance and update of the ontology to capture new concepts, individuals and/or relationships as deemed necessary during the course of the research.

To achieve these development activities, some other independent support activities were carried out concurrently to ensure the success of the OPW ontology development. These include knowledge acquisition at every stage of the development, integration of other existing ontologies in the domain as required, and the evaluation of the model as the knowledge is being modelled as follows.

6. **Knowledge acquisition**: Continuous acquisition of knowledge and information on OSM classification, OSM cost drivers and OSM processes was an ongoing process throughout the ontology development phase. The data collection method is outlined in section 6.6.4.

7. **Integration**: A review was conducted to consider the possibility of extending some of the existing ontologies relevant to the research area to determine if knowledge can be integrated. It is necessary that any extension of an ontology leads to a result that is

lightweight, efficient, and conceptually coherent, in order to support adoption and implementation. In this case, the existing ontologies relating to OSM do not contain the low-level factory shop floor knowledge required for the process modelling in this study. However common vocabularies and definitions sourced from literature as captured in the conceptual classification framework (Figure 5.1) were adopted at a high level for better communication.

8. **Evaluation**: This is used to refer to the verification and validation of the ontology as a technical process that validates the correctness of the ontology (Ferndndez et al. 1997). During the course of developing the OSM ontology, the ontology was being evaluated from time to time to determine the validity in terms of completeness, consistency and to avoid redundancies. This was done by running some simple queries to test if the ontology returns expected result as would an expert in the field and also test that the requirements of the competency questions are being met. Also, a reasoner was initiated to observe inconsistencies and redundancies if any.

6.7.2 Ontology development tool – Protégé

The ontology editor tool Protégé was used in developing the knowledge model. One of the core reasons for selecting this tool is that it allows for the use of different inference engines and it is platform and language independent (Corcho *et al.* 2003). Protégé provides support for life cycle activities associated with ontology development while also supporting extensibility to its architecture to allow for more flexibility and functionality to be integrated. One other reason for which protégé was considered well suited for this study is that it is domain-independent due to being an open-source independent application. Considering the requirement needed in the study for building the OPW ontology and documenting the process, Protégé features many interesting plugins – OWL, SWRL OntoViz, etc. which were handy during the ontology development and result reporting stages thus, adding more functionality to the ontology environment.

6.7.3 Ontology development language – OWL and SWRL

Web Ontology Language (OWL) is a semantic mark-up language for sharing and publishing ontologies on the World Wide Web (WWW). As identified in section 4.4.1, OWL is developed as an extension to RDF and used when there is a need to process information content rather than just presenting information to humans (W3C 2004). OWL is the selected language used in modelling the OSM ontology in this study because it facilitates greater machine interpretability through the provision of additional vocabularies along with its usual formal semantics (Corcho *et al.* 2003). OWL also allows for explicit representation of terms and relationships between such terms which is the main aim of an ontology. With this, OWL provides more expressiveness than other languages like RDF, XML, RDF Schema.

6.8 Model Validation – Use case and expert evaluation approach

The fifth research question is about testing and validating the OPW ontology. To address this question, a two-staged validation method was designed for use in the study comprising of (i) internal (logic) validation and (ii) external (expert) validation (Figure 6.9).

6.8.1 Logic Validation – Scenario-based testing

Scenario-based validation using a use case of an actual OSM project was adopted in this study. A use case is defined as a set of actions prepared by a system that provides observable results. The OPW ontology contains various integrated rules developed in order to generate results for the intended purpose. Therefore, a number of scenarios based on a sample OSM project (the use case) were tested to determine if the ontology is able to provide expected results on the competency questions (i.e. logic testing). This process is termed the internal validation method. The use-case selected is a completed project of a light steel-framed (LSF) 3bedroom semi-detached house. This use case was used in populating the ontology with instances and used to generate results for the two units of analysis in this study (i.e. the semi-automated linear and static production methods).

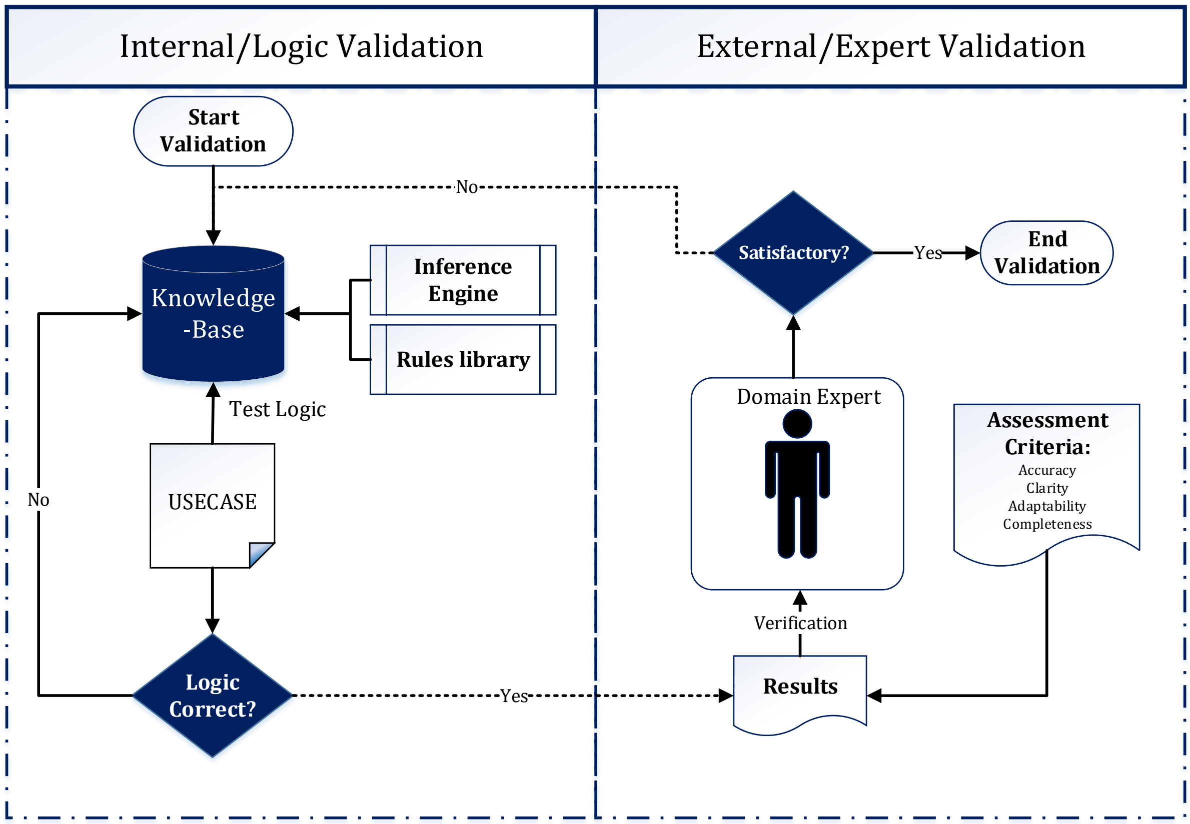


Figure 6.9: Validation Process

6.8.2 Expert Validation

The second stage validation – expert validation method was used in validating the semi-formal process models and results generated OPW ontology. First, the process models developed were evaluated by domain experts via focus group discussion to ensure that the interpretation of the production process of the units of analysis is accurate before modelling the knowledge in the ontology. This method was then later used as external validation to evaluate the final results from the ontology. Domain experts comprising representatives from the case study organisations were asked to complete a competency framework questionnaire (see Appendix B).

The result from the ontology was presented to the experts and the content validation method was used to evaluate the results. The content validity approach, also known as the validation by review commonly used in related studies (Ijomah and Childe 2007, Lucko and Rojas 2010) was used to verify how well the results from the OPW ontology represents reality, and how well suited it is to the need of industry practitioners. The criteria used in the assessment include accuracy, clarity, adaptability, and completeness of the model as used by previous researchers (Ijomah and Childe 2007).

6.9 Ethical Consideration

This research complied with Birmingham City University's (BCU) principle for ethical conduct. Major ethical considerations with regards to data collection have been identified and the research has been through BCU ethical clearance procedure. Data collected through the case study have been handled carefully in compliance with data handling policies and intellectual property protection guidelines for Birmingham City University approved in 2013. Participating individuals' details have also been handled with the highest level of confidentiality and/or anonymity and participants have been informed of arrangements for publications of research results with all issues of co-authorship and acknowledgements agreed upon.

The dignity, rights, safety and well-being of participating companies and professionals was a key consideration for the research. Informed consent was obtained at every planned discussion and meeting and participants are made aware of the aftermath use of the data. All collected data are handled with confidentiality and used for academic purposes only. An ethical form has been filled and approved for this research in compliance with the university's research policy (see Appendix A).

6.10 Chapter Summary

In summary, the critical realist philosophical viewpoint was adopted in this study which led the author to take an abductive approach to conduct the research study. The philosophical stand and approach selected favours the use of a combination of methods in achieving the objectives of the research. Thus, an embedded single case study method was the preferred research design for gathering information. Observations, interviews, document analysis, and focus group discussions were employed for gathering primary data needed for the development of OPW ontology. This was followed by the computational modelling of the knowledge in an ontology development tool – Protégé.

The OPW ontology was developed using the Meth-Ontology method and validated with a two-stage validation approach. The first stage consists of testing the logic of the model using a use case on panelised OSM system while the second stage involved an expert validation approach where an external review of the results from the ontology was carried out by domain experts. The next chapter presents the conceptualisation and implementation stage of the ontology development process following the Meth-Ontology approach.

CHAPTER 7: COMPUTATIONAL MODELLING – INTELLIGENT KNOWLEDGE MODELLING OF OSM PROCESS KNOWLEDGE

7.1 Introduction

The previous chapter explained the methodology used for the data collection for knowledge modelling in the OPW ontology. An embedded single case study design consisting of two units of analysis was selected for this study. Also, the methodology for the ontology development selected for this study is the Meth-Ontology approach. The specification phase of the ontology development has been described by setting identifying the set of objectives of the proposed ontology (section 6.7.1). The next stages in the ontology development process following the Meth-Ontology approach are the conceptualisation, formalisation and implementation phases.

This chapter will follow the Meth-Ontology procedure starting from stage 2 (conceptualisation) to stage 4 (implementation) in fulfilling the objectives of the study. This chapter will start first by explaining the conceptualisation of OSM process knowledge through detailing the production line design using a workstation arrangement of both the static and semi-automated production methods. Semi-formal representations of the OSM production process of the two units of analysis will be developed using BPMN language and notations. Also, this knowledge will be formalised and transformed into a semi-computable model through a UML class diagram in representing the architecture of the proposed system at a high level and identifying key relationships between the concepts in the proposed ontology. Finally, the knowledge will be implemented in an ontology development tool – Protégé – using computable ontology language – OWL.

7.2 Overview of DfMA business with OSM

The study aims to model the knowledge of OSM production processes from the point of material delivery to work stations to the transportation of the finished manufactured products to the site. The scope does not include the design phase of the product and assembly/installation of finished products on the construction site. Thus, it is imperative to study the manufacturing organisation and their business in order to understand the value chain as well as capturing other support or indirect activities that contribute to the production of the finished product. Figure

7.1 shows an overall generic hierarchical structure of a typical OSM business which will serve as a basis for developing the process maps/models for the units of analysis in this study.

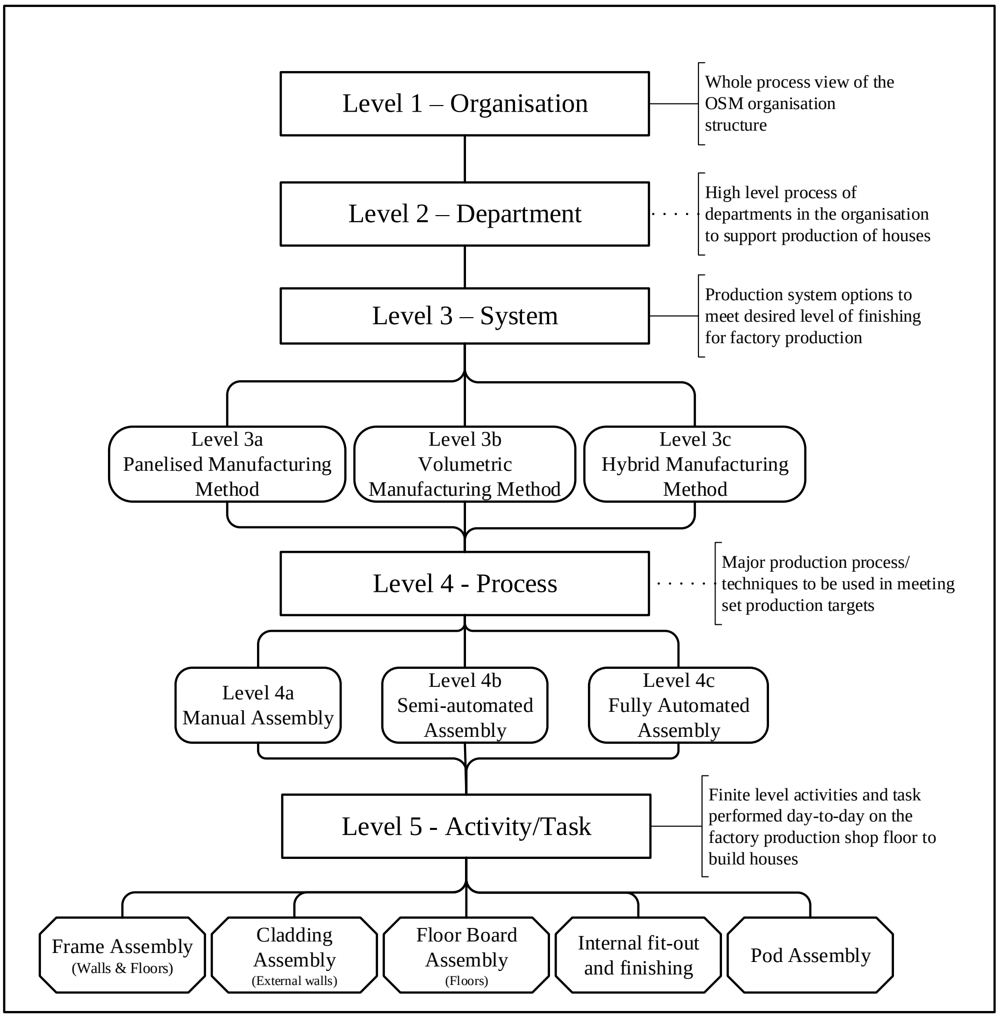


Figure 7.1: DfMA Business system hierarchy

Level 1 in the hierarchy (Figure 7.1) captures an overview of a major OSM organisation overall business process then narrows down further to the various departments in the business and the high-level individual processes involved in each department (Level 2). There are various systems of OSM houses production ranging from panelised, volumetric of hybrid systems of OSM representing the types of finished product from an OSM factory (Level 3). Information on the processes involved in these systems of OSM products will also be captured in the process map. Also, each of these OSM systems can be produced using various OSM production methods (Level 4) depending on the needs of the customer. Finally, the process of producing houses using the various OSM methods involves some major activities to be carried out on the factory shop floor (Level 5).

However, for the various OSM production methods or systems, there are differences in some aspects. For instance, the activities involved in each stage may differ depending on the equipment used, workflow arrangement, resource requirements, etc. These differences may impact the performance and efficiency of the various competing OSM methods. Therefore, the next section will develop a representation of the workflow of the two units of analysis in this study which is needed in developing the process maps to capture the activities performed in the production processes.

7.3 Conceptualisation stage – Representing OSM production processes

The end product from an OSM production line depends on the type of OSM system desired for a project. The major systems of OSM can be grouped as (i) panelised, (ii) volumetric (boxes), or even a mix of both (iii) hybrid. Regardless of the system intended, the 2Dimensional elements in form of panels will usually be produced which can then be formed into a 3Dimensional element for the volumetric product. In the panelised OSM system, the key elements (products) relating to house production are the wall, floor and ceiling. Also for the panelised systems of house production, the key stages involved are i) assemble the steel sections, ii) install the cladding, and iii) apply finishes to the internal side of the panels. In the case of the volumetric system, the finished panels need to be assembled into pods before transporting to the site therefore the fourth stage of pod assembly would be required (see Figure 7.1).

7.3.1 Workflow of static OSM production method

The static production method for house building as done in HAX factory is used as a reference in this study and will be described. In the static system, the production is done in silos with various team members working on different types of products in a gang (Figure 7.2). The frame and cladding assembly production processes are done in one station (Station 1) thus provisions are made for raw material storage and storage of finished products (the panels) close to the station. Once the assembly is completed, the products are moved to the internal fit-out and finishing station (Station 4 and 5) where the required level of finishing is applied. The work is carried out mostly by factory operatives and causal workers. However, specialist trades are needed for some finishing work and are required to move from one station to another to render services on products. Some panels may be transferred to the pod assembly stations (Stations 2 and 3) if the volumetric or hybrid product is required. Finished batches of building elements are then moved to a temporary storage area in the factory and later transported to the site.

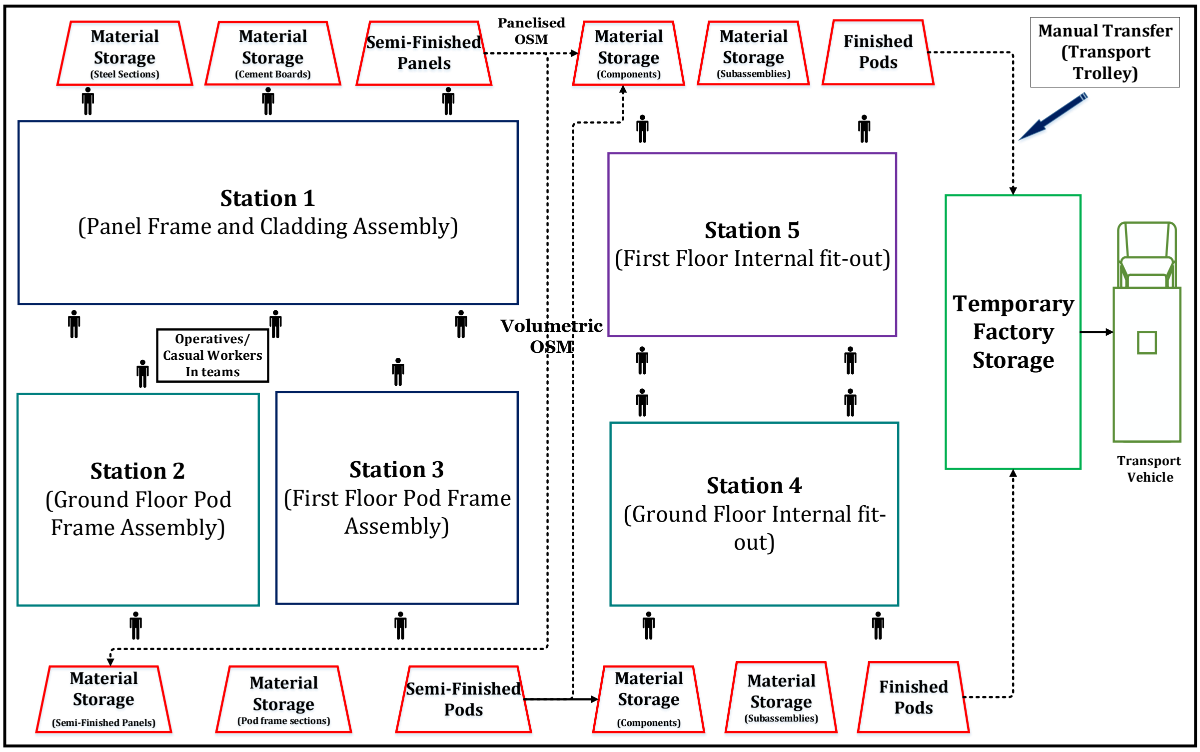


Figure 7.2: Static production workflow

7.3.2 Workflow of semi-automated linear OSM production method

The semi-automated linear method for factory house building was designed and simulated by the production engineering company for HAX as an alternative to the static method in order to compare the value-added with the automation of some key tasks and the use of a more structured workflow (Figure 7.3). This comprises two automated lines for frame and cladding assembly (Line 1 and Line 2) consisting of automated machines and various robotic arms. The last stage involving internal fit-out is to be done manually (Line 3, 4 and 5). Compared to the static method, production is done on an assembly line with dedicated stages/stations. The production line in this method operates with constant work cycles to allow for synchronous flow supported by operatives located at strategic positions. Each station has a dedicated number of production teams and the unfinished products/units are moved in various dedicated interconnected stages. The products move on a conveyor system and are picked up by fork-lift or trolleys to be loaded on transport vehicles. The batch manufacturing method is used instead of a singular house build method where the tool is set up for a particular batch type of frame at a time. Also, this method requires an area for stockpiling where materials are held in a holding area. Finished batches of building elements (the product) are moved to a temporary storage area in the factory and later transported to the construction site.

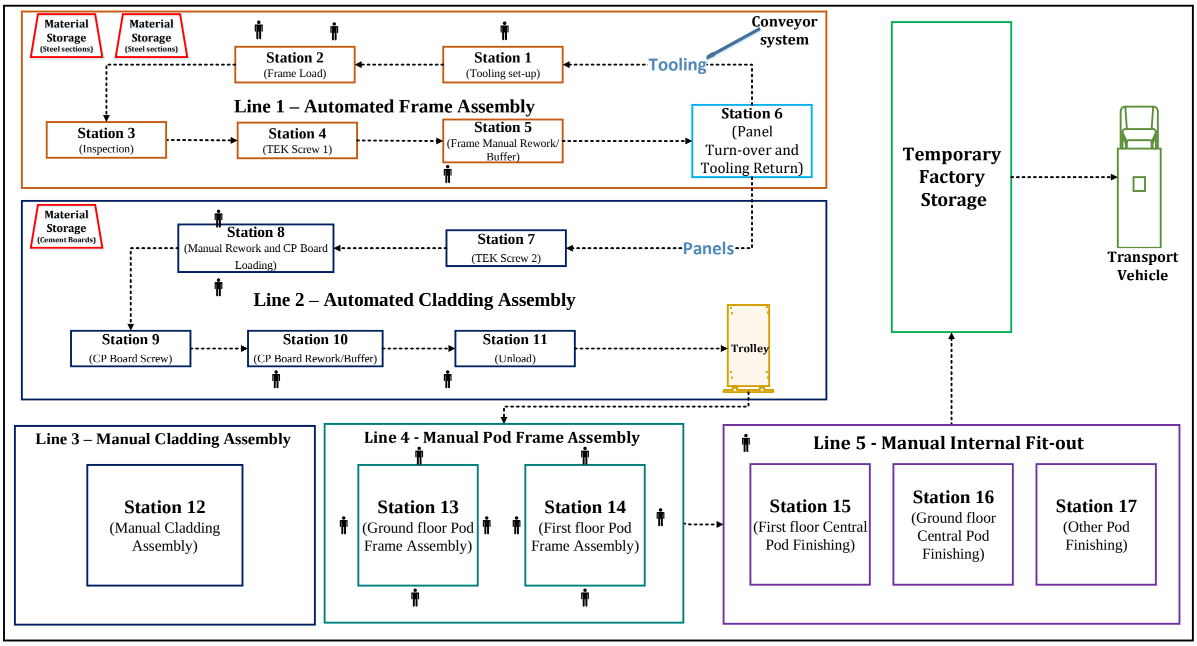


Figure 7.3: Semi-automated linear production workflow

7.4 Conceptualisation stage: Process Mapping Using BPMN language/notations

The next step in the conceptualisation of OSM production process knowledge is to model the activities in each workstation of both units of analysis and to capture the sequences of these activities from the start to finish of the product development in the factory. The process modelling using BPMN notations is done in a series of nested diagrams where each diagram represents the different levels of details of the DfMA Business system hierarchy (as illustrated in Figure 7.1).

7.4.1 Understanding BPMN Notations/Language

The main elements of the BPMN language are illustrated in Figure 7.4. The events notation is used to denote various consequences at different stages in a process. The process could be started manually by a user or anyone involved in a business. The message start event is used when the process is started from a message which is mostly emails or a web service. The timer start event is used to represent a cyclical pattern of events which could be on a daily, weekly, monthly, etc basis. Intermediate events are events that occur during the execution of a process. The message intermediate event represents exchanges between two pools. The timer intermediate denotes a flow restriction such as a task that can only be done after a particular time. The signal event represents the transfer of signals between systems in a process. Similarly, the end events are used to denote the termination of a process which also be initiated with a message (message end event) or a signal indicator (signal end event).

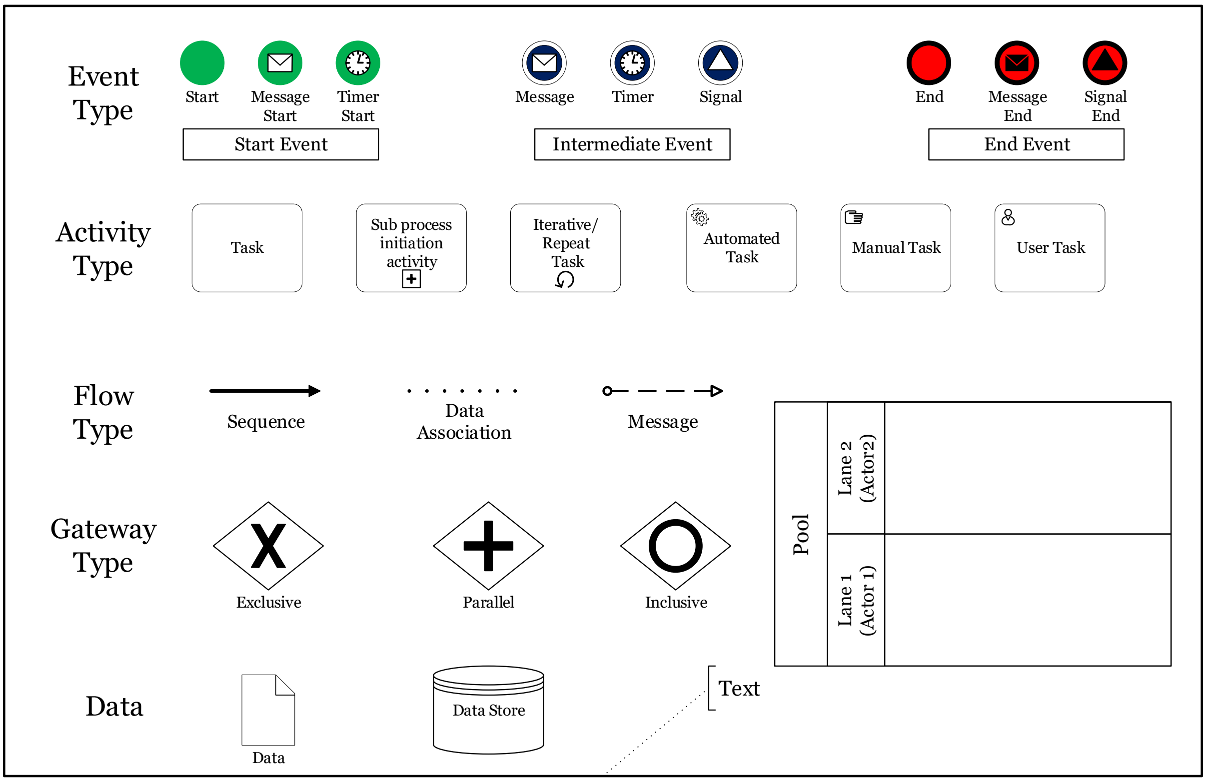


Figure 7.4: Major notations for BPMN language

The process workflow is shown using connectors (flow). Connectors can be used to denote activity sequence flow, message flow between parties/systems and data (artefact) association with a process. The gateways are used to divert the flow of the process. The activities are represented in different types. A manual task represents activity performed without any automation or use of workflow. A service task (automated task) represents activities done automatically. A user task represents works performed by a user of a system (such as office staff). The sub-process denotes a process that is collapsible and involving several other tasks. The loop task involves activities that are often done repeatedly or iterative in nature. The gateways are used to control convergence and divergence of the process sequence. The exclusive gateway causes the flow to be diverted in only one direction such as a decision point. The inclusive gateway causes a process flow to take one or more paths depending on a condition. The parallel gateway causes the process to slit into multiple flows and can be used to denote activities done in parallel. Pools represent an organisation, separate organisations or external relationships. The swim lanes represent different aspects of a particular organisation such as the teams, departments, individuals, etc. within a process and their interactions.

7.4.2 Process Mapping of OSM production process knowledge (Level 1)

As illustrated in Figure 7.2 and Figure 7.3, each production line in an OSM production method contains various workstations, and some activities will be performed in these workstations. In order to analyse the performance of the units of analysis, these activities need to be identified to enable formalisation of the knowledge in the ontology. Appendix D – contains the breakdown of the process maps for various stages involved in the factory house building process for the two units of analysis (static and semi-automated methods). Both the production activities and support activities involved in the OSM product development stage are captured. This is represented by first capturing the high-level procedures/processes from the organisation (Level 1), to the departments in the organisation (Level 2) and then the factory shop floor activities (Level 5) based on the business hierarchy (see Figure 7.1). This will allow allocation of direct cost and overhead cost in analysing the processes.

As an example, the BPMN notation is used to represent the manual process for assembling a volumetric pod in the factory (Figure 7.5). The process map captures individual activities performed on the factory shop floor and also information on the workforce required and the flow of activities. Additionally, equipment used in the process are identified as well as the documents necessary to complete these tasks. The activities have been coded using some numbering for unique identification of the tasks and easy communication.

The time taken to complete each activity is also observed and recorded and has been separated into four categories (i) process time (relating to working directly on a product), (ii) waiting time (relating to activities that involve waiting), (iii) loading time (relating to moving materials, partially completed products or completed products around the factory) and (iv) inspection time (relating to quality or health and safety). These four categories constitute the overall cycle time for each activity. For instance, for an activity involving loading and waiting, the cycle time is calculated by summing up the loading and waiting time. This data will then be formalised in the ontology to enable automated reasoning and computation of process data.

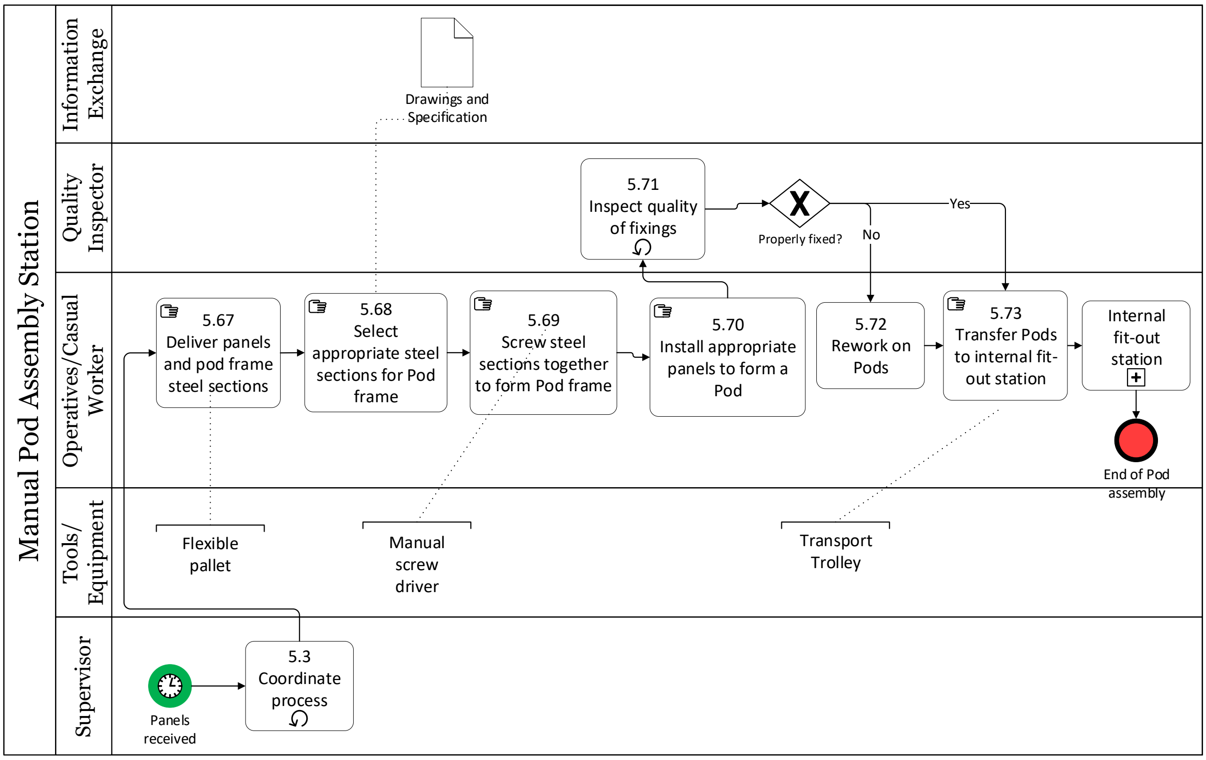


Figure 7.5: Manual Volumetric Pod Assembly Process Map

7.5 Formalisation Stage: Semi-formal representation of OSM Process knowledge

The third phase of the ontology development process is to formalise the knowledge into a semi-computable model. A UML class diagram (also known as a structural diagram) is one of such language that helps to represent and visualise the structure of a system, in this case, the OPW ontology by showing various aspects; (i) concepts – both classes and subclasses (ii) their properties (attributes) (iii) operation and (iv) the relationships between instances of a class (Figure 7.6). The UML class diagram presents the architecture of the OPW in a semi-formal representation by showing a high-level view of the knowledge structure. The top compartment shows the name of the major concepts/class relevant to the OPW ontology, the second/middle compartment displays some of the major attributes (i.e. named properties) of the class and the last/third compartment is used to input some operations (rules or codes) related to the class.

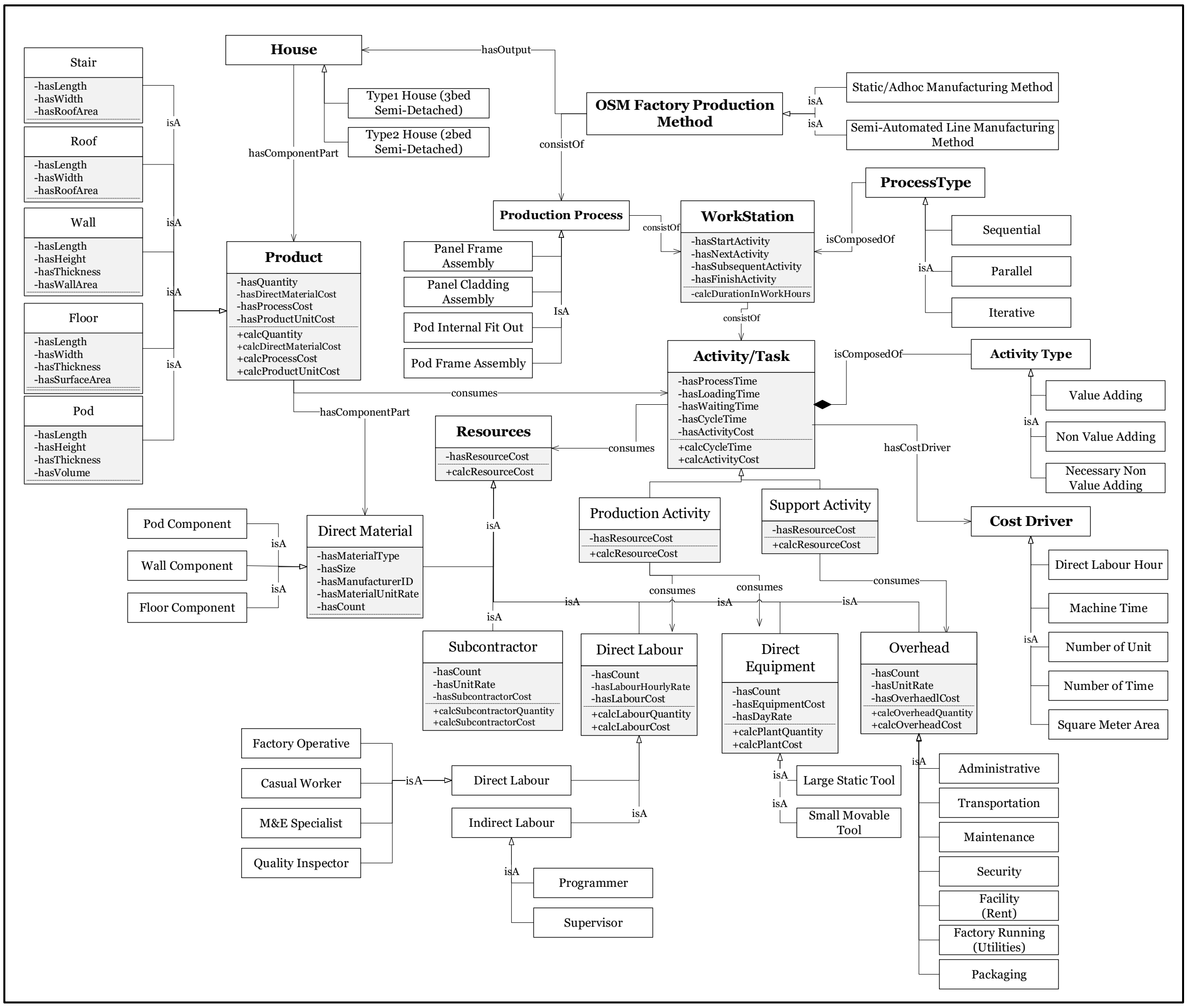


Figure 7.6: Semi-formal knowledge representation in UML Class Diagram

For the OPW ontology (Figure 7.6), there are 10 major classes (Level 1 denoted with bold text) required to formalise the production process knowledge of the offsite methods. These include concepts such as (i) OSMFactoryProductionMethod – for classifying all types of production systems (ii) Production Process – for classifying the processes involved in each method, (iii) WorkStation – for capturing the categories of activities in each station (iv) ProcessType – relating to the workflow of events in the production process, (v) Activity Type – for classifying the activities using the VSA method (vi) Activity – for classifying the different types of activities performed on the factory shop floor, (vii) Resources – relating to resources consumed in the processes (viii) Product – relating to the finished product/output from the production line and (ix) House – for classifying the final product after assembly at the destination point, which is onsite, (x) Cost Driver – relating to the cost drivers of each activity performed in the production process of the products.

The subclasses of the major classes are represented (Level 2) with the *isA* relationship to denote a parent-child relationship. Some relationships between the various classes are also represented. The key attributes/properties needed to include semantics in the ontology include data properties such as Cost, Time, Distance, Length, Width, etc., and object properties such as *hasComponentPart*, *consume*, *isComposedOf*, *hasOutput*, etc. These attributes of the instances of a class will enable classification and reasoning on the knowledge in the ontology.

As an example, an OSM production method (OSMProductionMethod) '*consistOf*' production processes (ProductionProcess), and each production process (ProductionProcess) '*consistOf*' various workstation (WorkStations). There are different sequences of events in each workstation (ProcessTypes) which could be parallel, sequential, or iterative in nature. Also, each workstation (WorkStation) '*consistOf*' activities (Activity), and these activities (Activity) '*consume*' resources (Resources) which can be labour, plant/equipment, materials, or overhead. The cost of the activities is driven by some factors (CostDriver), and activities can be classified as VA, NVA or NNVA (ActivityType). Finally, the output of any production method (OSMProductionMethod) is the products from the finished production line (Product).

7.6 Implementation Stage: Formal development using the OPW ontology using OWL and SWRL

The implementation stage of the ontology requires the formalisation of the knowledge in an ontology language. This is important in order to achieve two things, the form (syntax) and content (semantics) evaluation. The correct form is needed to enable automatic reasoning on the knowledge and the tool chosen for this study is Protégé ontology builder/editor which is based on the formal representation standard – OWL2.

7.6.1 Creating taxonomies – Classes and subclasses in the OPW ontology

Defining the class hierarchy in an ontology is an important aspect of knowledge modelling to allow reasoning in the KBS. Classes in ontology are also known as concepts and are used to represent sets that contain individuals by describing the requirements for membership of such classes. When using OWL2 formal representation, all classes and subclasses in the ontology are categorised under a SuperClass named 'Thing' (see Figure 7.7). For the OPW ontology, there is a need to model the knowledge of the competing production methods by describing the processes involved, the resources consumed and the output from the process (i.e. the products). The high-level classes and subclasses presented in the UML class diagram (see Figure 7.6) have been further expanded to contain more subclasses as illustrated in Figure 7.8.

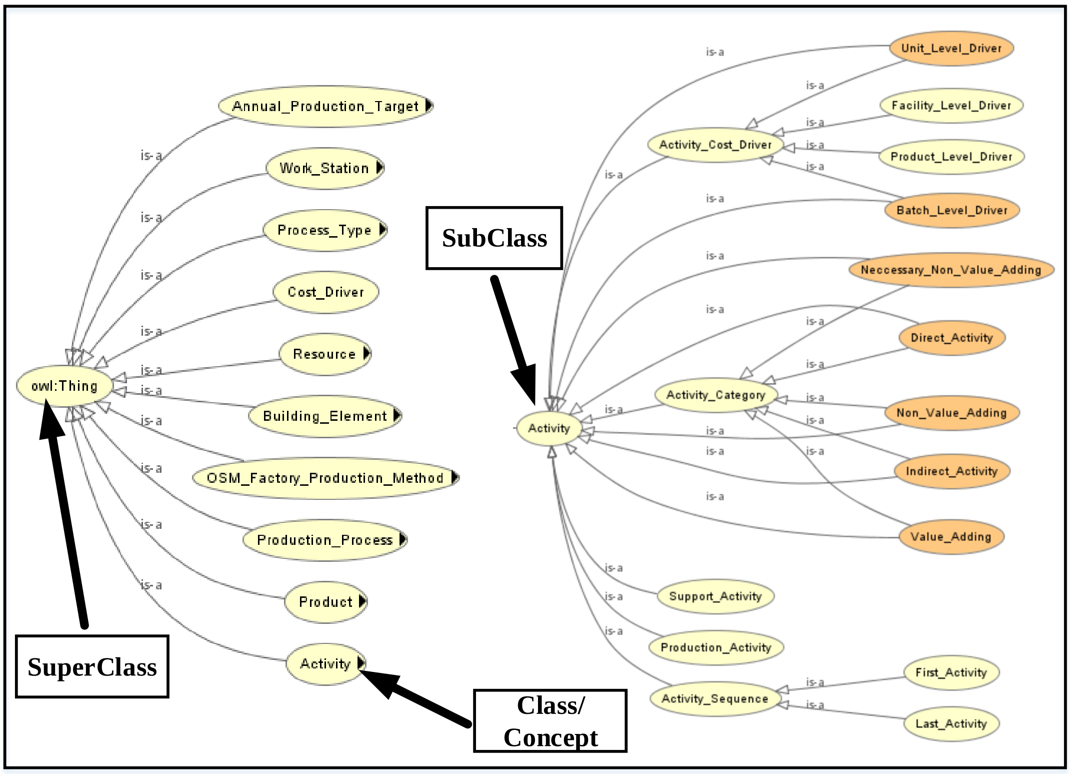


Figure 7.7: OPW ontology taxonomies showing the parent-child relationship

Because OWL classes are assumed to overlap which means that an individual can be an instance of more than one class, the ontology has been modelled to separate different classes where necessary by asserting disjointness of one class from another class. For instance, an individual under the class activity cannot be classified as both a direct labour and an indirect about. That is, a Programmer is different from a Quality Inspector. Also, an activity can only be one of the following (i) value-adding (ii) non-value adding (iii) necessary non-value adding.

These classes, attributes, and relationships will enable retrieval of data on the instances modelled in the OPW ontology to support analysis of the production workflow of the units of analysis. The structure of the OPW ontology developed is published on the web for sharing, and reuse of the production knowledge relating to OSM.[1]

[1] The OPW ontology can be accessed from: https://edlirak.github.io/oho-pro/index-en.html

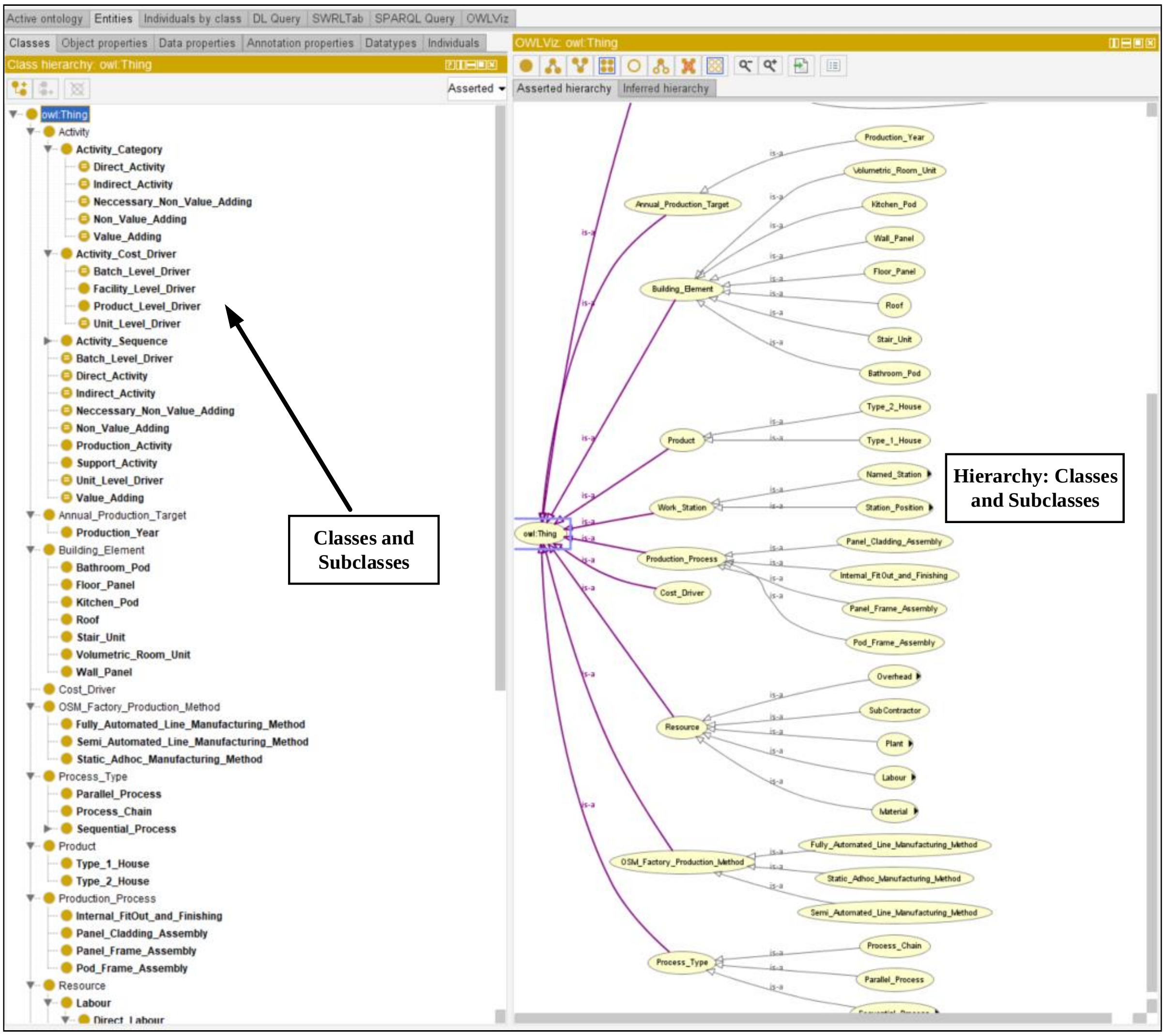


Figure 7.8: OWL Implementation for the OPW Ontology: Classes and Subclasses

7.6.2 Properties (attributes) in the OPW ontology

Properties in OWL are used to represent relationships are classified as either object properties or datatype properties. Object properties link an individual to another individual while datatype properties link an individual to a data value such as integer, string, float, etc. Both types are properties needed in the ontology and have been used to support reasoning and rule development for the OPW ontology.

The object properties used in the OPW ontology are described in Figure 7.9. The relationships identified in the formalisation stage of the ontology development with the UML class diagram (see Figure 7.6) have been implemented as object properties in the OSM process ontology. For instance, the object property '*consume*' links class 'Activity' to class 'Resource' i.e. Activity *consume* Resources. Inverse properties have also been defined in the ontology for better semantics to allow for a reverse expression to be made as shown in Figure 7.9. The inverse property of ‘*consume*’ is thus ‘*isConsumedBy*’ which applies to the classes participating in the ‘*consume*’ relationship. For instance, an expression can be made as follows: ‘Resource’ *isConsumedBy* ‘Activity’.

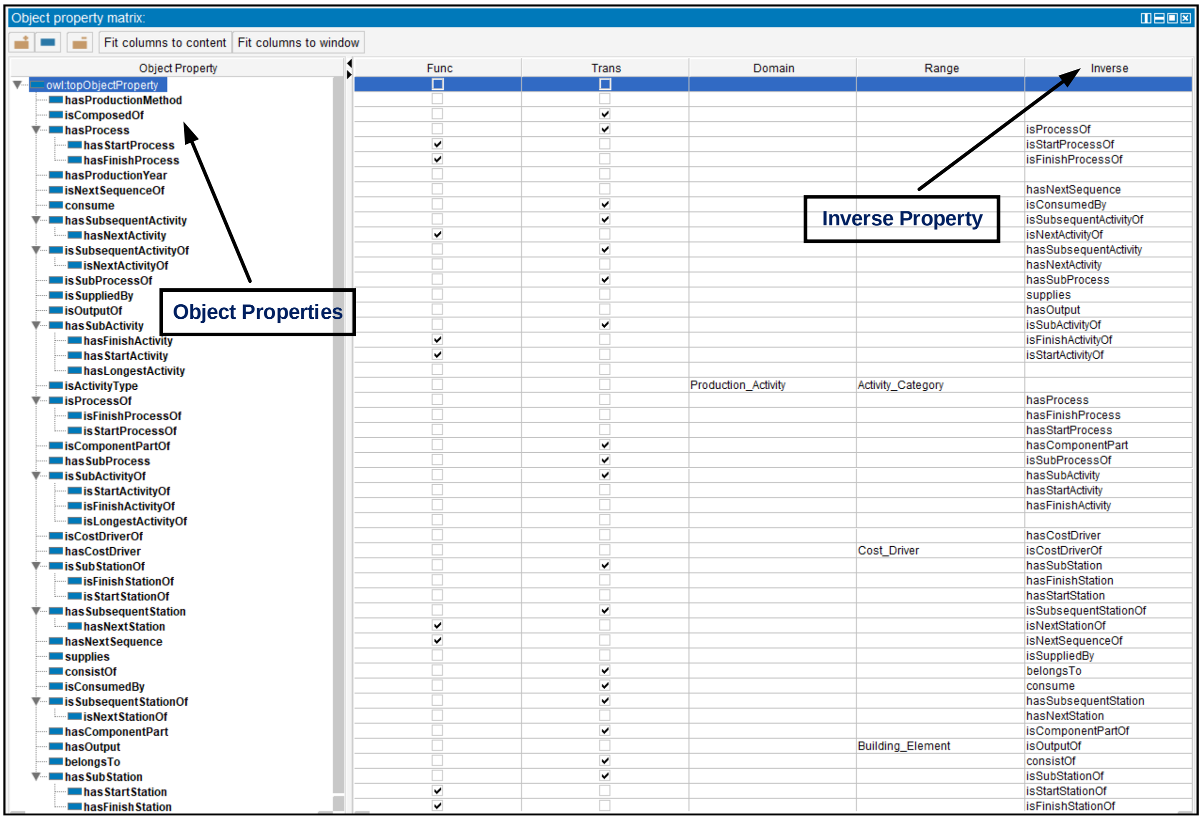


Figure 7.9: Object Property Matrix showing property types and restrictions as modelled in Protégé.

OWL2 also allows certain restrictions to be assigned to properties defined in an ontology. An example of this is specifying the boundaries of the properties by defining the domain and range. Therefore, the domain of a property specifies the initial class while the range of the property specifies the second class. This concept was implemented in the OPW ontology for some properties in order to create restrictions. For instance, the object property *hasComponentPart* has a domain class ‘House’ and has a range class ‘Product’. This implies that the property *hasComponentPart* can only be used to link an individual from the classes ‘House’ and ‘Product’ i.e. an OSM house (which could be any house type) is composed of component parts ranging from various products from the production line (such as walls, floors, stairs, etc.).

Datatype properties have also been defined in the OPW ontology to model the attributes of individuals/instances of a class. For instance, data relating to cost and time needs to be associated with individuals in the class 'Activity'. The datatype properties used in the OPW ontology are illustrated in Figure 7.10. Similar to the object properties, datatype properties can also have restrictions specified. Some of the restrictions defined are involving the domain and range of the data properties. For instance, the property *hasMaterialCount* has a range of the value type xsd:integer, thus implying that materials can only be counted in whole numbers.

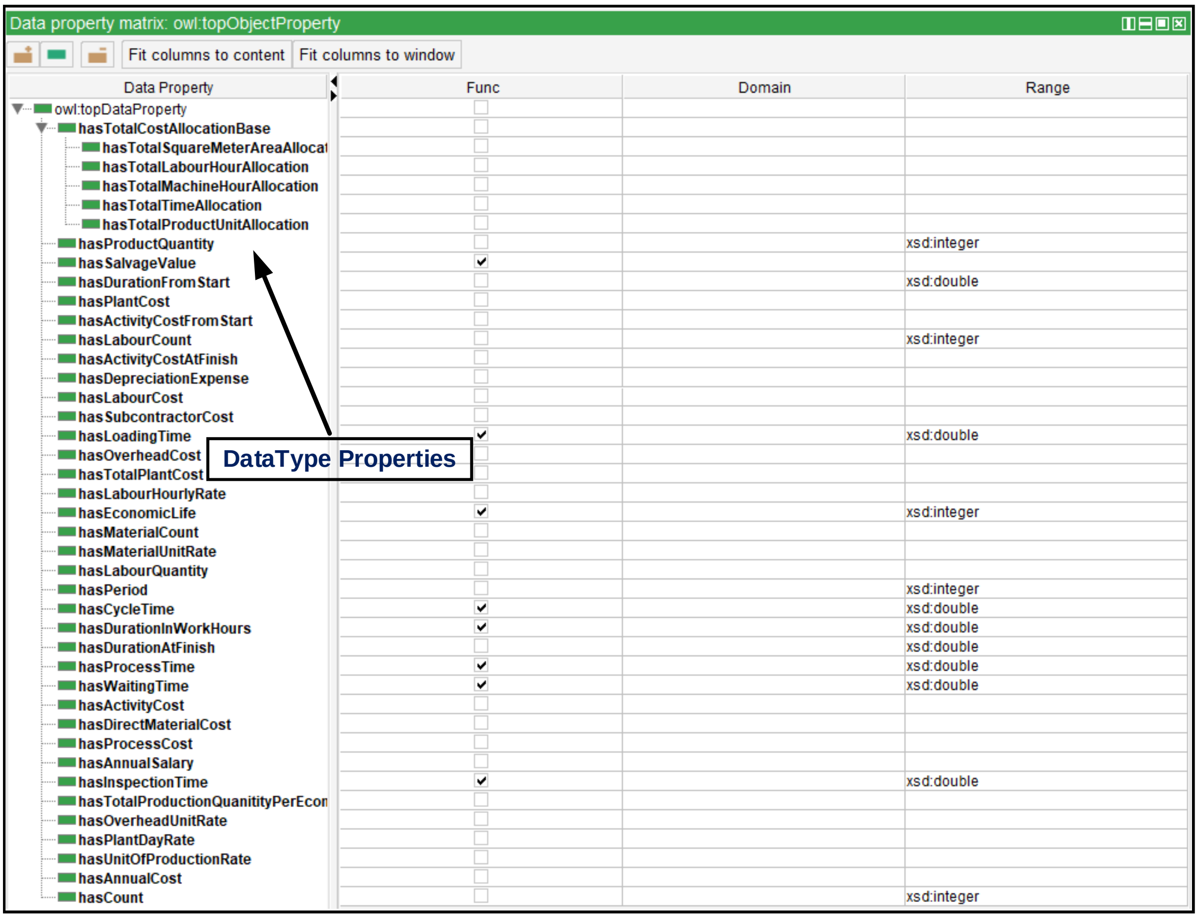


Figure 7.10: DataType Property Matrix showing property types and restrictions as modelled in Protégé.

Lastly, the final type of restrictions assigned to both the data and object properties are defining the characteristics of such properties. OWL2 supports the following types of properties in an ontology – Functional, Inverse functional, Transitive, Symmetric, Asymmetric, Reflexive, and Irreflexive properties. All object properties can have various characteristics while datatype properties can only have the functional characteristic.

The functional characteristic is used when an individual can only participate once in a relationship or can only have one value of a particular property. This characteristic is applicable to both the object and data property types and has been implemented in the OPW ontology as illustrated in Figure 7.9 and Figure 7.10. For instance, the object property *hasNextActivity* is a functional property which implies that an individual participating in this relationship can only have ONE relationship with another individual via the property *hasNextActivity* (i.e. an activity in a production sequence can only have ONE other activity in the sequence directly next after that activity). Similarly, the datatype property *hasProcessTime* is a functional property thus, an individual can only have ONE datatype property via *ProcessTime*. In literal terms, an activity can only have one process time. The inverse functional property is used to characterise the inverse of a data property as being functional.

The transitive property type is used to indicate inheritance relationship such that if an individual from Class A is related to an individual from Class B, and an individual from Class B is related to an individual from Class C via the same property, then the property holds true for individuals from Class A and C (i.e. the individual from class A is related to the individual from class C). An example of the implementation of this in the OPW ontology (see Figure 7.9) is with the property *belongsTo* denoted as a transitive property. This implies that IF an individual from the class 'Activity' has a relationship *belongsTo* with an individual in class 'WorkStation', and an individual in class 'WorkStation' has a relationship *belongsTo* with another individual in class 'ProductionProcess', THEN the individual in class 'Activity' also *belongsTo* the class 'ProductionProcess'.

The other property characteristics have not been used in the OPW ontology as they do not apply to the objectives specified for the ontology.

7.6.3 Restrictions in the ontology – Creating class definitions

In an OWL ontology, restrictions also known as axioms are used to denote constraints to a class. Restrictions are also created in order to describe individuals based on the relationship they participate in so as to enable reasoning and classification in the ontology. OWL2 supports three types of restrictions, the quantifier restrictions in form of an existential or universal restriction, the cardinality restriction in form of minimum, maximum or exact, and the hasValue restriction.

The Existential restriction represents the class of individuals that participate in at least one relationship along a specified property and is also referred to as ***some**ValuesFrom* (denoted by *some* ∃). The Universal restriction represents the class of individuals that only have relationship along a given property to other individuals of a specified class and referred to as ***all**ValuesFrom* (denoted by *only* ∀). In the OPW ontology, the existential restriction have been used to define and categorise individuals in the class 'Activity' into VA, NVA and NNVA as illustrated in Figure 7.11. As an example, the class 'Necessary_Non_Value_Adding' have been described in the OPW ontology as a class of individuals that must be an 'Activity' and must have the object property *hasInspectionTime* ***some*** value that is xsd:double. '**Some**' means that for an individual (i.e. an activity) to be classified as Necessary-non-value adding, it must have some *InspectionTime* attributed to it.

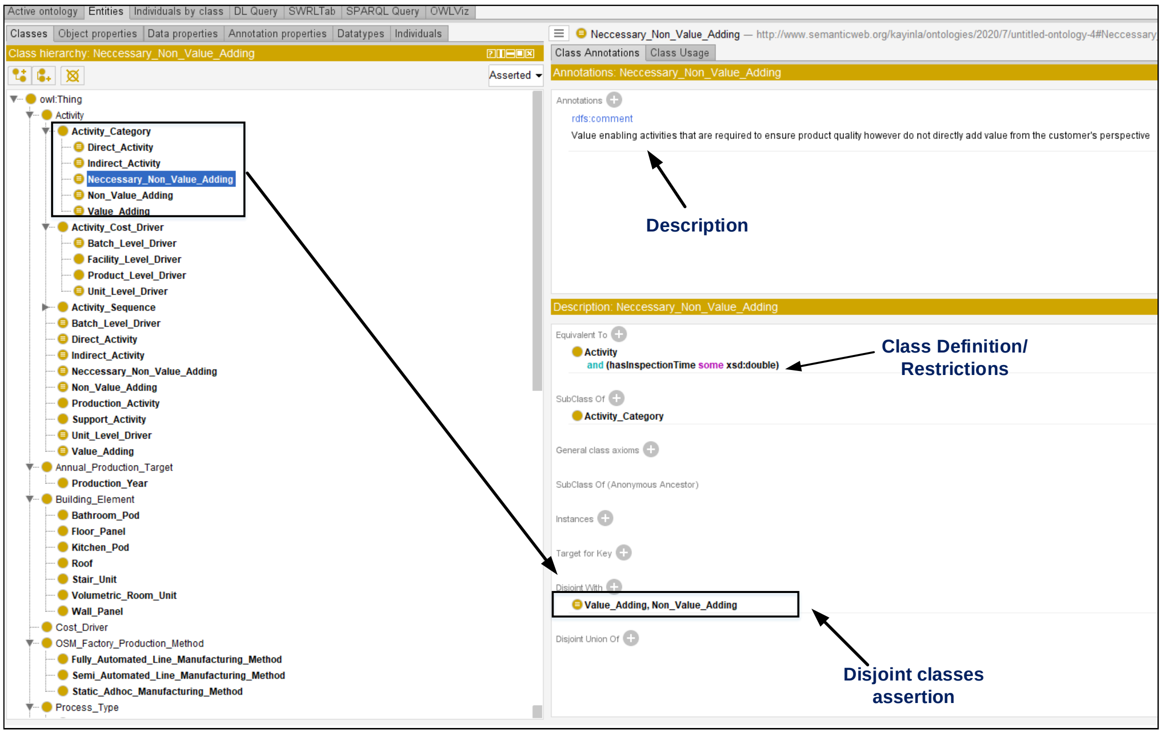


Figure 7.11: Modelling restriction and defining classes in the OPW ontology

7.7 Rule Development – Semantic web rule language (SWRL) Rules

So far, the knowledge implementation in the ontology with OWL has defined the major classes, subclasses, attributes, and axioms relevant to the OPW ontology. However, as identified from the literature review, the OWL is unable to create some expressions especially when it relates to computing values. OWL is based on the open-world assumption (OWA) due to being originally focused on the semantic web, which is an infinite repository based on unlimited resources and knowledge. Hence, OWL has limited expressions in some cases, which is why SWRL rules are needed to allow for these expressions to be included in the ontology. Therefore, some process rules need to be integrated into the OPW ontology to enable the computation of process-related data. Some SWRL rules have been included in the OPW ontology to allow for mathematical expressions such as calculating cost, time, and also supporting reasoning in the ontology. As the OPW ontology is aimed at answering some set of competency questions, the rule development has been focused on these questions. Figure 7.12 illustrates the implementation and integration of rules in the OPW ontology, these rules will be further expanded and explained in the following sections.

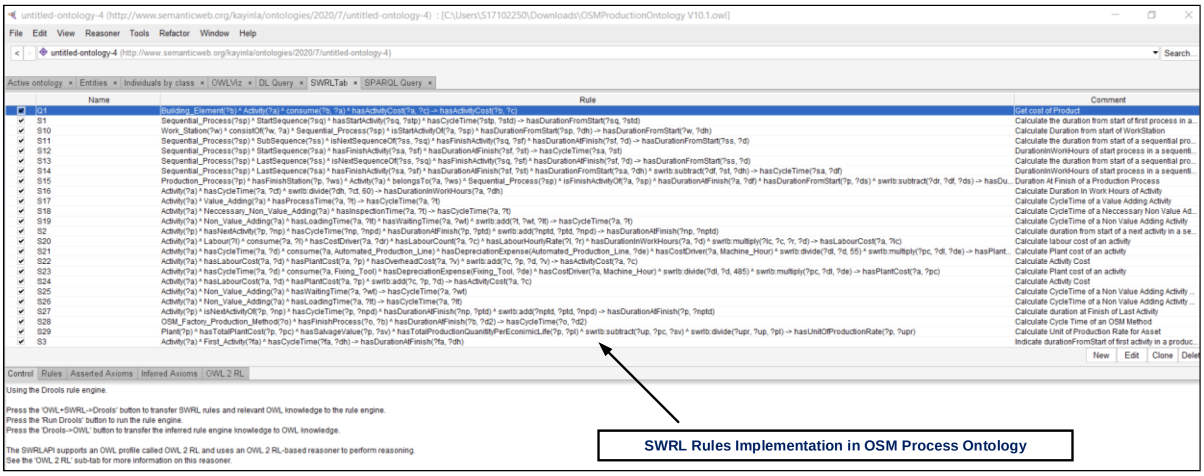


Figure 7.12: SWRL development in the OPW Ontology

7.7.1 SWRL Rules – Time-based rule implementation in the OPW ontology

In analysing the performance of the units of analysis in regards to time as the key proformance indicator (KP1), there is a need to generate certain information from the ontology such as the time spent on activities, work stations, and on a production line in total. Data on the duration of each activity as gathered from the case study has been modelled directly into the OPW ontology as asserted knowledge. Also, some activities are classified under the class 'ActivitySequence' as either a 'StartActivity' or 'FinishActivity' to denote their position in the process. Some SWRL rules have been implemented in the OPW ontology in other to convert the asserted duration from minutes to hours *(durationInWorkHour)* for each activity (Table 7.1), and to indicate the time at finish/end *(durationAtFinish)* of each individual activity as they occur in the production process (Table 7.2). This information will allow the development of the rules further in identifying time taken for different production methods.

Table 7.1: SWRL rule to calculate the duration of an Activity in Hours

Rule 1: *Calculate Duration In Work Hours of Activity*
Activity(?a) ^ hasCycleTime(?a, ?ct) ^ swrlb:divide(?dh, ?ct, 60) -> hasDurationInWorkHours(?a, ?dh)

Table 7.2: SWRL rule to assign the finish time of activities in a process

Rule 2: *Indicate Duration at Finish of First Activity in a production process*
Activity(?a) ^ First_Activity(?fa) ^ hasCycleTime(?fa, ?dh) -> hasDurationAtFinish(?fa, ?dh)
Rule 3: *Calculate Duration at Finish of Last Activity in a production process*
Activity(?p) ^ isNextActivityOf(?p, ?np) ^ hasCycleTime(?p, ?npd) ^ hasDurationAtFinish(?np, ?ptd) ^ swrlb:add(?nptd, ?ptd, ?npd) -> hasDurationAtFinish(?p, ?nptd)
Rule 4: *Calculate Duration at Finish of the Next Activity in a production process*
Activity(?p) ^ hasNextActivity(?p, ?np) ^ hasCycleTime(?np, ?npd) ^ hasDurationAtFinish(?p, ?ptd) ^ swrlb:add(?nptd, ?ptd, ?npd) -> hasDurationAtFinish(?np, ?nptd)

Activities in the OPW ontology represent the most finite level of the day-to-day tasks carried out on the factory shop floor. However, these activities largely occur not as a standalone entity, but rather in multiples in a workstation. Also, activities in each workstation can be carried out either sequentially, or in parallel depending on the production plan. For the purpose of the case study, the BPMN diagrams mapping the activities in each production process (see Appendix D) have been used as a guide in modelling the activities in each workstation. Having modelled the knowledge on the activities in each OSM method and implemented rules for calculating the time for each activity, it is now possible to calculate each sequence of activities in a workstation.

To achieve this, each set of activities in a process is classified under the class ‘StartSequence’, ‘SubSequence’, or ‘LastSequence’. This is to enable the identification of the step-by-step process involved in the production process. Consequently, each sequence represents the set of activities carried out in each workstation which could be carried out as either sequential or parallel activities. However, given the challenges with SWRL where some mathematical expressions such as deriving a summation of various values are not supported, the approach taken is to transfer the value of the *durationAtFinish* of the last activity in the sequence as the *durationFromStart* of the next activity in the sequence and so on to generate the rotal time taken in each production process. The following SWRL rules were developed in the OPW ontology to calculate the *durationFromStart* in minutes (Table 7.3) of the processes (sequential and parallel).

Table 7.3: SWRL rule to assign the start time of activities in a process

Rule 5: *Indicate the duration from start of first process in a sequential process*
Sequential_Process(?sp) ^ StartSequence(?sq) ^ hasStartActivity(?sq, ?stp) ^ hasCycleTime(?stp, ?std) -> hasDurationFromStart(?sq, ?std)
Rule 6: *Indicate the duration from start of a sub/mid process in a sequential process*
Sequential_Process(?sp) ^ SubSequence(?ss) ^ isNextSequenceOf(?ss, ?sq) ^ hasFinishActivity(?sq, ?sf) ^ hasDurationAtFinish(?sf, ?d) -> hasDurationFromStart(?ss, ?d)
Rule 7: *Indicate the duration from start of a last process in a sequential process*
Sequential_Process(?sp) ^ LastSequence(?ss) ^ isNextSequenceOf(?ss, ?sq) ^ hasFinishActivity(?sq, ?sf) ^ hasDurationAtFinish(?sf, ?d) -> hasDurationFromStart(?ss, ?d)
Rule 8: *Indicate the Finish Activity in a parallel process*
Parallel_Process(?pp) ^ hasLongestActivity(?pp, ?lp) -> hasFinishActivity(?pp, ?lp)

Now that the ontology is able to assign start and finish time of all activities in a sequence and also to the work stations where these activities are perfomed, the next step is to calculate the *cycleTime* of each process in the production line from the already derived value of *durationsFromStart*. The *cycleTime* represents the overall time taken to complete a set of activities in a process either sequential or parallel. The set of activities performed in a workstation forming a process are identified as either sequential or parallel processes. Also, these processes are classified based on the time of occurrence in a chain as ‘Start Sequence’ (to denote the first process in a production line), ‘SubSequnece’ (to denote mid processes in a production line) or ‘LastSequence’ (to denote the last process in a production line). Also, the object property *hasNextSequence* is created to allow identification of the flow of processes in an OSM production method. Table 7.4 presents the SWRL rules for calculation the cycle time of processes on a production line.

Table 7.4: SWRL rule to calculate the cycle time of processes in a work station

Rule 9: *Calculate cycleTime of a StartSequence in a sequential process*
Sequential_Process(?sp) ^ StartSequence(?sa) ^ hasFinishActivity(?sa, ?sf) ^ hasDurationAtFinish(?sf, ?st) -> hasCycleTime(?sa, ?st)
Rule 10: *Calculate cycleTime of a SubSequence in a sequential process*
SubSequence(?sp) ^ hasNextSequence(?sp, ?sn) ^ hasDurationFromStart(?sp, ?st) ^ hasDurationFromStart(?sn, ?st1) ^ swrlb:subtract(?dh, ?st1, ?st) -> hasCycleTime(?sp, ?dh)
Rule 11: *Calculate cycleTime of a LastSequence in a sequential process*
Sequential_Process(?sp) ^ LastSequence(?sa) ^ hasFinishActivity(?sa, ?sf) ^ hasDurationAtFinish(?sf, ?st) ^ hasDurationFromStart(?sa, ?dh) ^ swrlb:subtract(?df, ?st, ?dh) -> hasCycleTime(?sa, ?df)
Rule 12: *Calculate the cycleTime of a parallel process*
Parallel_Process(?pp) ^ hasFinishActivity(?pp, ?lp) ^ hasCycleTme (?lp, ?ds) -> hasCycleTime(?pp, ?ds)

Having developed the rules for calculating the duration/time spent on processes performed (either sequential or parallel classified under the class 'ProcessType') in each workstation on a production line, it is now possible to assign the cycle time in each workstation by aggregating the cycle time of the processes performed in the work stations. The values of *cycleTime* obtained are assigned to the individuals under the class 'WorkStation'. Also, a workstation in the factory production process consists of at least one activity carried out in that workstation as part of the production process. Work stations also follow a defined sequence similar to how activities are performed. For instance, the activities in the class 'FrameLoad' station would occur before the activities in the class 'TEKSrew1' station, while the activities in the class 'TEKSrew1' station have to be completed before activities in class 'TEKSrew2' station and so on. The following SWRL rules are used to calculate the cycle time in each workstation.

Table 7.5: SWRL rule to assign the cycle time of work stations in a production line

Rule 13: *Calculate durationFromStart of WorkStation in a production process*
Work_Station(?w) ^ consistOf(?w, ?a) ^ Sequential_Process(?sp) ^ isStartActivityOf(?a, ?sp) ^ hasDurationFromStart(?sp, ?dh) -> hasDurationFromStart(?w, ?dh)
Rule 14: *Calculate Cycle Time in a Work Station*
Work_Station(?w) ^ consistOf(?w, ?a) ^ Sequential_Process(?sp) ^ isSubActivityOf(?a, ?sp) ^ hasCycleTime(?sp, ?dw) -> hasCycleTime(?w, ?dw)

Similarly, since OSM production processes comprise one or more workstations, the cycle time of the various processes can be calculated by aggregating the cycle time of the workstation in the processes. The class 'Production Process' in the OPW ontology represents the high-level key stages involved in a factor house building method. For the purpose of this case study, these are grouped under five processes (see Figure 7.1) which include (i) panel frame assembly, (ii) panel cladding assembly, (iii) pod frame assembly (iv) floorboard assembly and (v) internal fit-out and finishing processes.

The panel frame and cladding assembly process could be done using the manual method or the semi-automated method on a production line. Therefore, the time involved with these two methods needs to be estimated to allow for process analysis. The following SWRL rules have been developed in order to calculate the *cycleTime* involved in each of the production processes (Table 7.6).

Table 7.6: SWRL rule to calculate the cycle time for OSM production stages

Rule 15: *Calculate DurationFromStart of an OSM Production Process*
Production_Process(?p) ^ hasStartStation(?p, ?ws) ^ Activity(?a) ^ belongsTo(?a, ?ws) ^ hasDurationFromStart(?ws, ?ds) -> hasDurationFromStart(?p, ?ds)
Rule 16: *Calculate DurationAtFinish of an OSM Production Process*
Production_Process(?p) ^ hasFinishStation(?p, ?ws) ^ Activity(?a) ^ belongsTo(?a, ?ws) ^ Sequential_Process(?sp) ^ isFinishActivityOf(?a, ?sp) ^ hasDurationAtFinish(?a, ?df) ^ hasDurationFromStart(?p, ?ds) ^ swrlb:subtract(?dr, ?df, ?ds) -> hasDurationAtFinish(?p, ?dr)
Rule 17: *Calculate Cycle Time of an OSM Production Process*
Production_Process(?p) ^ hasDurationFromStart(?p, ?wf) ^ hasDurationAtFinish(?p, ?wl) ^ swrlb:subtract(?df, ?wl, ?wf) -> hasCycleTime(?p, ?df)

Finally, in order to analyse a process based on the lean technique of VSA, the process waste in any process must be quantified by identifying the VA, NVA and NNVA aspects (refer to section 3.2.1). In the OPW ontology, each of these classes of activities has been defined by creating restrictions using the Existential definition - ***some**ValuesFrom* denoted by *some* ∃ (see section 7.6.3). Since the duration of each activity is already modelled in the ontology and the activities can be automatically classified by the reasoned based on the class definition, it is possible to calculate the cycle time of each category of activities. Therefore, The following SWRL rules have been developed in the OPW ontology to calculate the *cycleTime* of the various categories of activities in an OSM production process (Table 7.7).

Table 7.7: SWRL rule to calculate the cycle time for various activity categories

Rule 18: *Calculate CycleTime of a Non Value Adding Activity with Waiting Time Only*
Activity(?a) ^ Non_Value_Adding(?a) ^ hasWaitingTime(?a, ?wt) -> hasCycleTime(?a, ?wt)
Rule 19: *Calculate CycleTime of a Non Value Adding Activity with Loading Time Only*
Activity(?a) ^ Non_Value_Adding(?a) ^ hasLoadingTime(?a, ?lt) -> hasCycleTime(?a, ?lt)
Rule 20: *Calculate CycleTime of a Non Value Adding Activity*
Activity(?a) ^ Non_Value_Adding(?a) ^ hasLoadingTime(?a, ?lt) ^ hasWaitingTime(?a, ?wt) ^ swrlb:add(?t, ?wt, ?lt) -> hasCycleTime(?a, ?t)
Rule 21: *Calculate CycleTime of a Neccessary Non Value Adding Activity*
Activity(?a) ^ Neccessary_Non_Value_Adding(?a) ^ hasInspectionTime(?a, ?t) -> hasCycleTime(?a, ?t)
Rule 22: *Calculate CycleTime of a Value Adding Activity*
Activity(?a) ^ Value_Adding(?a) ^ hasProcessTime(?a, ?t) -> hasCycleTime(?a, ?t)

7.7.2 SWRL Rules – Cost-based rule implementation in the OPW ontology

Since the knowledge involving the *cycleTime* of activities, workstation and various production processes can now be retrieved from the ontology, another application of the OPW ontology is to analyse and compare the resources consumed in various processes based on the cost incurred in the product development process. Also, this will enable analysis of the waste in the process in terms of cost incurred in performing the various types of activities i.e. VA, NVA, and NNVA In order to achieve this, some SWRL rules have been implemented in the ontology to enable retrieval of cost-related data for the various resources consumed by each activity in a factory production process also known as the process cost.

However, in the ABC modelling method, the cost driver is a major factor that drives the cost up or down and plays an important role in estimating the cost of activities. Therefore, a class 'CostDriver' was modelled in the OPW ontology which consists of various cost drivers identified for the purpose of this study. Based on the ABC framework used in this study (see Figure 5.3), the process cost of performing an activity comprises the cost of (i) labour (direct or indirect), (ii) plant/equipment and (iii) administrative overhead. Therefore, SWRL rules will be developed to enable estimating the cost of these resources in the OPW ontology.

Estimating the cost of labour is a straightforward one since the OPW ontology already includes knowledge of the labour requirements for each activity and also information on the hourly rates for each labour category. Also, knowledge of the duration of each activity is present in the ontology. Therefore, the following rules have been implemented in the OPW ontology to generate and assign labour costs to activities in a production process or work station (Table 7.8).

Table 7.8: SWRL rule to calculate the Labour cost of an activity

Rule 23: *Calculate Labour Cost of an Activity in a Production Process*
Activity(?a) ^ Labour(?l) ^ consume(?a, ?l) ^ hasCostDriver(?a, ?dr) ^ hasLabourCount(?a, ?c) ^ hasLabourHourlyRate(?l, ?r) ^ hasDurationInWorkHours(?a, ?d) ^ swrlb:multiply(?lc, ?c, ?r, ?d) -> hasLabourCost(?a, ?lc)

In terms of the plant/equipment cost. The straight-line depreciation method has been adopted for this study. This is because the effect of depreciation relating to the major plants in the production line and other small movable equipment needs to be considered in generating the plant cost for each activity performed in the production process. Some data type properties have been implemented in the OPW ontology to allow for estimation of labour cost using the straight-line method. This includes properties such as (i) *hasEconomicLife* – denoting the economic life span of equipment (ii) *hasSalvageValue* – denoting the value of the equipment at the end of its economic life (iii) *hasPeriod* – denoting the year of production (iii) *hasTotalPlantCost* – denoting the total cost of all plant/equipment at the year of purchase (iv) *hasAllocationBase* – denoting the total hours per period (v) *hasAllocationRate* – denoting the rate of using the plant per hour in a period (vi) *hasTotalProductionQuantityPerEconomicLife* – denoting the total number of products to be produced during the economic life of the plant (vii) *hasDepreciationExpense* – denoting the cost of plant per period.

Information such as the salvage value and the expected life span of the equipment were obtained from the partner engineering company that designed the production line for the case study. The following step-by-step rules have been implemented in the OPW ontology to generate the cost of equipment for activities in a production process (Table 7.9).

Table 7.9: SWRL rules to calculate the plant/equipment cost of performing an activity

Rule 24: *Calculate Depreciation Expense for an Asset in a given year*
Plant(?p) ^ hasTotalPlantCost(?p, ?pc) ^ hasSalvageValue(?p, ?sv) ^ hasEconomicLife(?p, ?el) ^ swrlb:subtract(?up, ?pc, ?sv) ^ swrlb:divide(?de, ?up, ?el) -> hasDepreciationExpense(?p, ?de)
Rule 25: *Calculate Unit of Production Rate for Asset in a period (rate of plant per unit)*
Plant(?p) ^ hasDepreciationExpense(?p, ?de) ^ Production_Year(?y) ^ hasProductionYear(?p, ?y) ^ hasProductQuantity(?y, ?q) ^ swrlb:divide(?upr, ?de, ?q) -> hasUnitOfProductionRate(?p, ?upr)
Rule 26: *Calculate Cost Pool for each activity (Total Allocated Cost)*
Activity(?a) ^ hasAllocationRate(?a, ?r) ^ Plant(?p) ^ consume(?a, ?p) ^ hasCostDriver(?a, Machine_Hour) ^ Production_Year(?y) ^ hasProductQuantity(?y, ?q) ^ hasProductionYear(?p, ?y) ^ swrlb:multiply(?tc, ?q, ?r) -> hasTotalCostAllocationBase(?a, ?tc)
Rule 27: *Calculate Allocation Base of Activity*
Activity(?a) ^ Plant(?p) ^ hasDurationInWorkHours(?a, ?d) ^ consume(?a, ?p) ^ hasCostDriver(?a, Machine_Hour) ^ hasProductionTimePerPanel(?p, ?t) ^ swrlb:divide(?ab, ?d, ?t) -> hasAllocationBase(?a, ?ab)
Rule 28: *Calculate Allocation Rate of Activity machine time per hour*
Activity(?a) ^ Plant(?p) ^ consume(?a, ?p) ^ hasCostDriver(?a, Machine_Hour) ^ hasUnitOfProductionRate(?p, ?ur) ^ hasProductionTimePerPanel(?p, ?t) ^ swrlb:divide(?ar, ?ur, ?t) -> hasAllocationRate(?a, ?ar)
Rule 29: *Calculate Plant cost of an activity*

Activity(?a) ^ hasDurationInWorkHours(?a, ?d) ^ Plant(?p) ^ consume(?a, ?p) ^ hasCostDriver(?a, Machine_Hour) ^ hasAllocationRate(?a, ?r) ^ swrlb:multiply(?ac, ?d, ?r) -> hasPlantCost(?a, ?ac)

It is now possible to calculate the process cost of activities since the OPW ontology includes data on the cost of labour and plant for all activities performed in the production stage of a house. However, in terms of the process cost, some activities consume both labour and plant (i.e. activities involving a mix of machining and manhour), while some require only manual labour (manhour) or plant (i.e. automated machining in a case where the activity is performed in an automated production line without any human intervention) only. Therefore, the rules developed in the OPW ontology have been implemented to cater to such dynamics.

Table 7.10: SWRL rules to calculate the process cost of activities

Rule 30: *Calculate Process Cost of Activities involving Labour and Plant*
Activity(?a) ^ Production_Activity(?a) ^ hasLabourCost(?a, ?d) ^ hasPlantCost(?a, ?p) ^ swrlb:add(?c, ?p, ?d) -> hasActivityCost(?a, ?c)
Rule 31: *Calculate Process Cost of Activities involving only Plant*
Activity(?a) ^ Production_Activity(?a) ^ hasPlantCost(?a, ?d) -> hasActivityCost(?a, ?d)
Rule 32: *Calculate Process Cost of Activities involving only Labour*
Activity(?a) ^ Production_Activity(?a) ^ hasLabourCost(?a, ?d) -> hasActivityCost(?a, ?d)

Finally, the cost of activities performed in the product development stage can bow be retrieved from the OPW ontology. Therefore, it is now possible to aggregate these costs and assign the cost to the products (building elements/components) that consume the activities in order to generate the cost of each product. This approach using the ABC method has been implemented in the OPW ontology to assign both the direct activity cost (class 'ProductionActivity') and the overhead activity cost (class 'SupportActivity'). In this case, the cost of the product (cost object) is the cost of the direct material and the process cost makes up the cost of an item (cost object). This leads to the final rule (Table 7.11) for estimating the cost of a product.

Table 7.11: SWRL rules to calculate the cost of a product the production process

Rule 33: *Calculate and assign Cost of a Product*
Product(?b) ^ Activity(?a) ^ consume(?b, ?a) ^ hasActivityCost(?a, ?c) -> hasActivityCost(?b, ?c)

The rules implemented in the OPW ontology now make it possible to analyse the two units of analysis focused on in this study. Data on the cost and time of producing different products in both the manual/static and the semi-automated linear methods of production can be retrieved from the ontology to enable analysis of the two competing methods of production. Also, the process waste involved in both methods can be calculated and used as a means of evaluating the performance of the production workflow of each method as well as for monitoring the effect of changes made in the processes.

7.8 Chapter Summary

This chapter described the conceptualisation, formalisation, and implementation stages of the OPW ontology. In this chapter, the business process of a typical OSM company has been described by studying the processes at different levels in the organisation while focusing on how it supports the production of building products on the factory shop floor. The workflow arrangement of the two units of analysis considered in this study (the static and semi-automated linear production methods) has also been described. The process maps of the production methods are modelled using the BPMN language integrating key aspects in a process such as resources and information flow including the actors in the processes, documents generated or consumed during the processes, and major tools/equipment needed to complete some of the processes.

Also, the development and implementation of the OPW Ontology in Protégé have been discussed. Firstly, a conceptual model illustrating the structure of the ontology was developed using a UML class diagram, this was then formally implemented in an ontology using OWL2 by describing 10 major classes relevant to the OPW ontology and also the development of properties (object and data type), axioms, and attributes in the ontology. Some process rules relating to estimating the cost and time of OSM processes have been developed and explained in this chapter. The next chapter will present the testing and validation of the knowledge modelled in the OPW ontology by means of a use case of an actual OSM project.

CHAPTER 8: TESTING, EVALUATION AND VALIDATION OF ONTOLOGY – USE-CASES OF 3BED SEMI-DETACHED HOUSE TYPE

8.1 Introduction

In this chapter, the knowledge implemented in the OPW ontology is evaluated and tested by experimenting with the set of competency questions expected for the ontology to answer. A two-stage validation approach is also adopted by first testing the internal logic of the ontology using a use case of a real-life scenario of an already completed 3Bed semi-detached house (hereafter known as Type 1 House). The use case is devised to provide a proof-of-concept of the capability of the OPW ontology in supporting evaluation and analysis of OSM methods to support informed decision-making on choices. The internal logic validation process was done using SPARQL and SQWRL query languages supported by Protégé to retrieve information from the knowledge base. This was followed up with external validation by domain experts to access the results from the tool and its implications. This chapter also provides some further statistical analysis on the data from the experimental results in comparing the performance of the units of analysis. A root cause (RC) analysis is also carried out to determine the causes of process waste in the house building process for OSM methods.

The chapter is presented in three parts. Part one presents the experimental results and answers generated from the OPW ontology based on the competency questions, part two presents further analysis of the time, cost and value analysis comparisons for both methods of production, and part three presents a root cause analysis of the sources of process waste in OSM production methods.

8.2 Overview and description of Use Case - Panelised System OSM

The use case selected for testing the ontology is a case of a 3BED semi-detached house type (hereafter House-Type 1). House-Type 1 is made of light steel-framed (LSF) solution using the panelised system of OSM (drawings are reproduction for academic purposes only). The production system used in this project is the OSM panelised solutions comprising of 2-Dimensional end products. For the factory production, the external frame of the house is divided into a total of 32 panels which are the output from the production process. This consists of 20 external clad panels and 12 internal panels for the party walls (Figure 8.1 and Figure 8.2).

For clarity purposes, these panels are named based on their positioning in the building when looking (taking reference) from the front side of the building (Table 8.1).

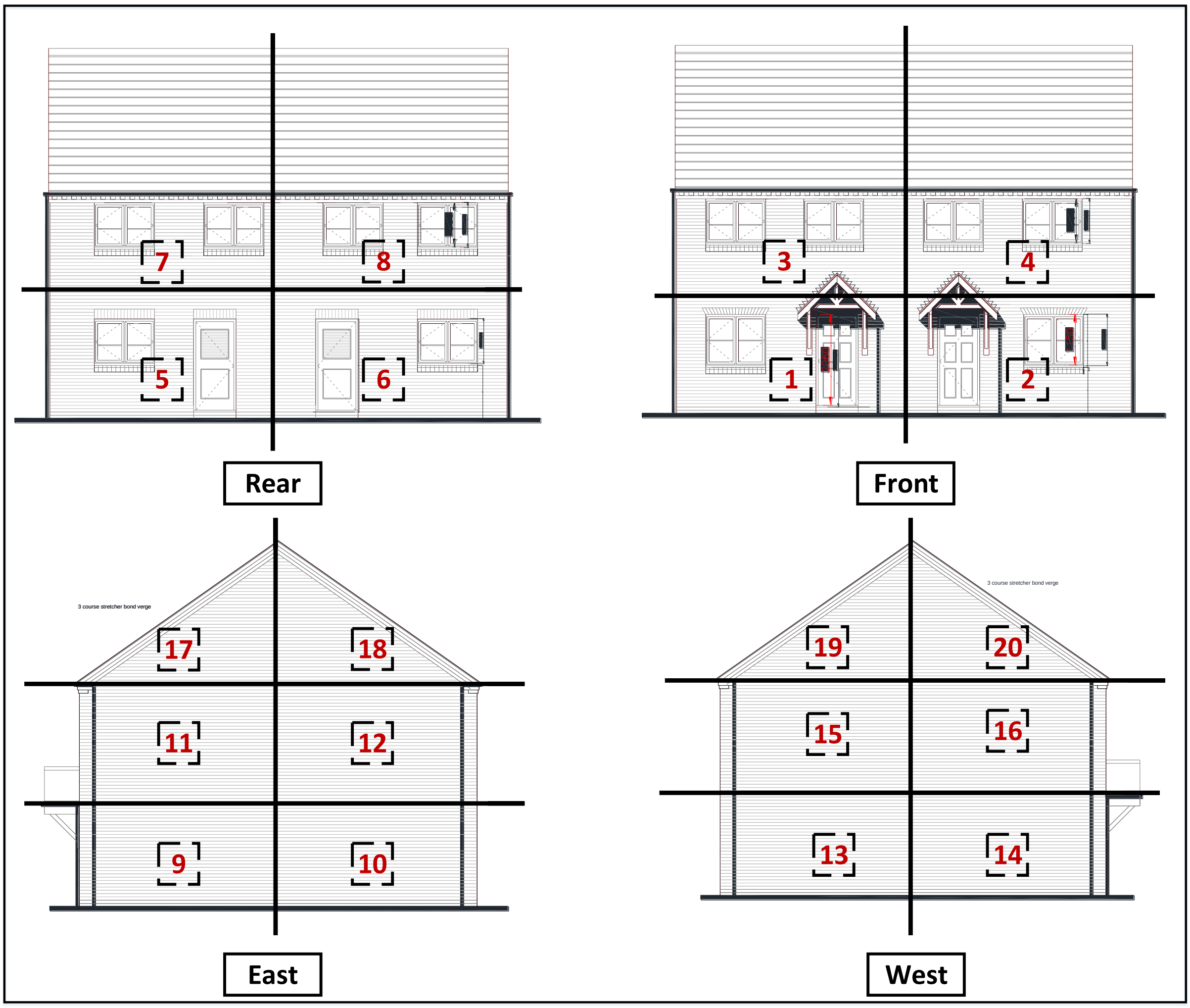


Figure 8.1: Twenty Clad Panels from the Production Line

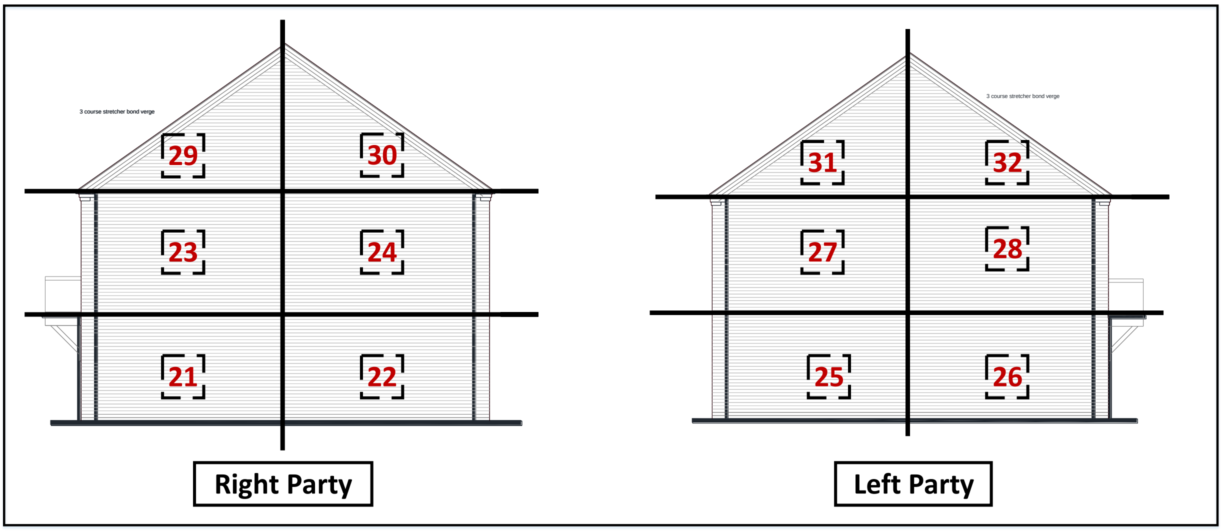


Figure 8.2: Twelve Internal Panels from the Production Line

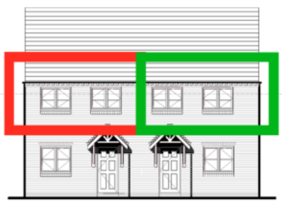
Table 8.1: Naming convention for wall panels in Type 1 house

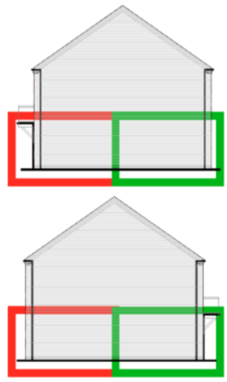
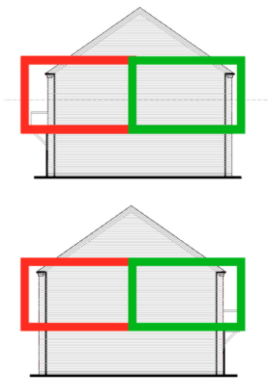
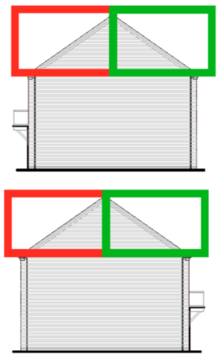
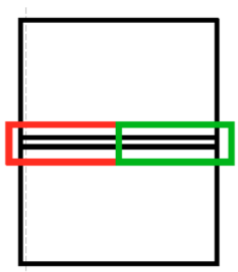
Group	Element	Wall Panels	Ref
BuildingElement	WallPanel	• Lower Front Left Panel • Lower Front Right Panel • Upper Front Left Panel • Upper Front Right Panel	1 2 3 4
		• Lower Rear Left Panel • Lower Rear Right Panel • Upper Rear Left Panel • Upper Rear Right Panel	5 6 7 8
		• East Lower Gable Left Panel • East Lower Gable Right Panel • East Upper Gable Left Panel • East Upper Gable Right Panel • West Lower Gable Left Panel • West Lower Gable Right Panel • West Upper Gable Left Panel • West Upper Gable Right Panel	9 10 11 12 13 14 15 16
		• East Left Apex Panel • East Right Apex Panel • West Left Apex Panel • West Right Apex Panel	17 18 19 20
		• PW East Lower Gable Left Panel • PW East Lower Gable Right Panel • PW East Upper Gable Left Panel • PW East Upper Gable Right Panel	21 22 23 24

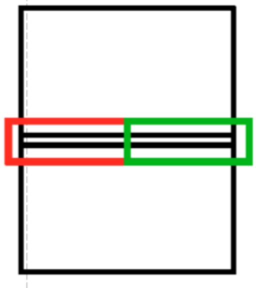
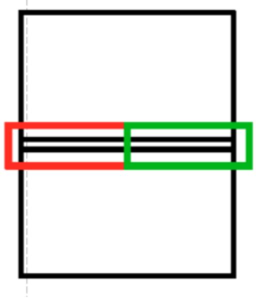
		• PW West Lower Gable Left Panel • PW West Lower Gable Right Panel • PW West Upper Gable Left Panel • PW West Upper Gable Right Panel • PW East Left Apex Panel • PW East Right Apex Panel • PW West Left Apex Panel • PW West Right Apex Panel	25 26 27 28 29 30 31 32

As the house type is semi-detached, some of the panels are similar or identical for ease of production and are typically flipped around during the production process in order to maintain the correct positioning of components such as doors and windows. Therefore, for the purpose of modelling the knowledge in the OPW ontology, these panels were asserted to be the same as their opposite panels in identifying the instances of the house type (Table 8.2). The naming convention also follows the position of the various panels. For instance, GF represents the ground floor, FF represents the first floor, LSF represents light steel frame. Therefore, the Instance 3BED_GF_Front_LSF_01 can be interpreted as an instance of a wall panel of 3Bed house type, located on the ground floor front, light steel frame panel with number code 01.

Table 8.2: Identifying individuals/instances for the OSM process ontology

Ref	Panels	Instances	Position
1 2	• Lower Front Left Panel • Lower Front Right Panel	3BED_GF_Front_LSF_01	
3 4	• Upper Front Left Panel • Upper Front Right Panel	3BED_FF_Front_LSF_02	
5 6	• Lower Rear Left Panel • Lower Rear Right Panel	3BED_GF_Rare_LSF_06	

7 8	• Upper Rear Left Panel • Upper Rear Right Panel	3BED_FF_Rare_LSF_07	
9 10 13 14	• East Lower Gable Left Panel • East Lower Gable Right Panel • West Lower Gable Left Panel • West Lower Gable Right Panel	3BED_GF_Gable_LSF_03	
11 12 15 16	• East Upper Gable Left Panel • East Upper Gable Right Panel • West Upper Gable Left Panel • West Upper Gable Right Panel	3BED_FF_Gable_LSF_04	
17 18 19 20	• East Left Apex Panel • East Right Apex Panel • West Left Apex Panel • West Right Apex Panel	3BED_Roof_Gable_LSF_05	
21 22 25 26	• PW East Lower Gable Left Panel • PW East Lower Gable Right Panel • PW West Lower Gable Left Panel • PW West Lower Gable Right Panel	3BED_GF_PartyWall_LSF_08	

23 24 27 28	• PW East Upper Gable Left Panel • PW East Upper Gable Right Panel • PW West Upper Gable Left Panel • PW West Upper Gable Right Panel	3BED_FF_PartyWall_LSF_09	
29 30 31 32	• PW East Left Apex Panel • PW East Right Apex Panel • PW West Left Apex Panel • PW West Right Apex Panel	3BED_Roof_Gable_PartyWall_LSF_10	

8.3 Populating instances/individuals in the OPW ontology

Individuals in the ontology also known as instances are used to represent the lowest level of granularity in the domain described. In the OPW ontology, the instances under the class ‘Product’ in the ontology represents specific building elements that are derived from the production process. While the instances under the class ‘House’ represent the complete house after assembly on the construction site (Figure 8.3). Similarly, the activities performed on the factory shop floor are modelled as instances of the class ‘Activity’. The modelling of these activities has been guided by the BPMN process map (see Appendix D) which represents the finite level tasks performed on the factory shop floor were populated as activities under the subclasses ‘ProductionActivity’ and ‘SupportActivity’ (Figure 8.4). Consequently, following the ABC methodology for cost estimating, the instances in class ‘Products’ are related with instances in class ‘Activity’ i.e. each building element is associated with the activities consumed in producing it.

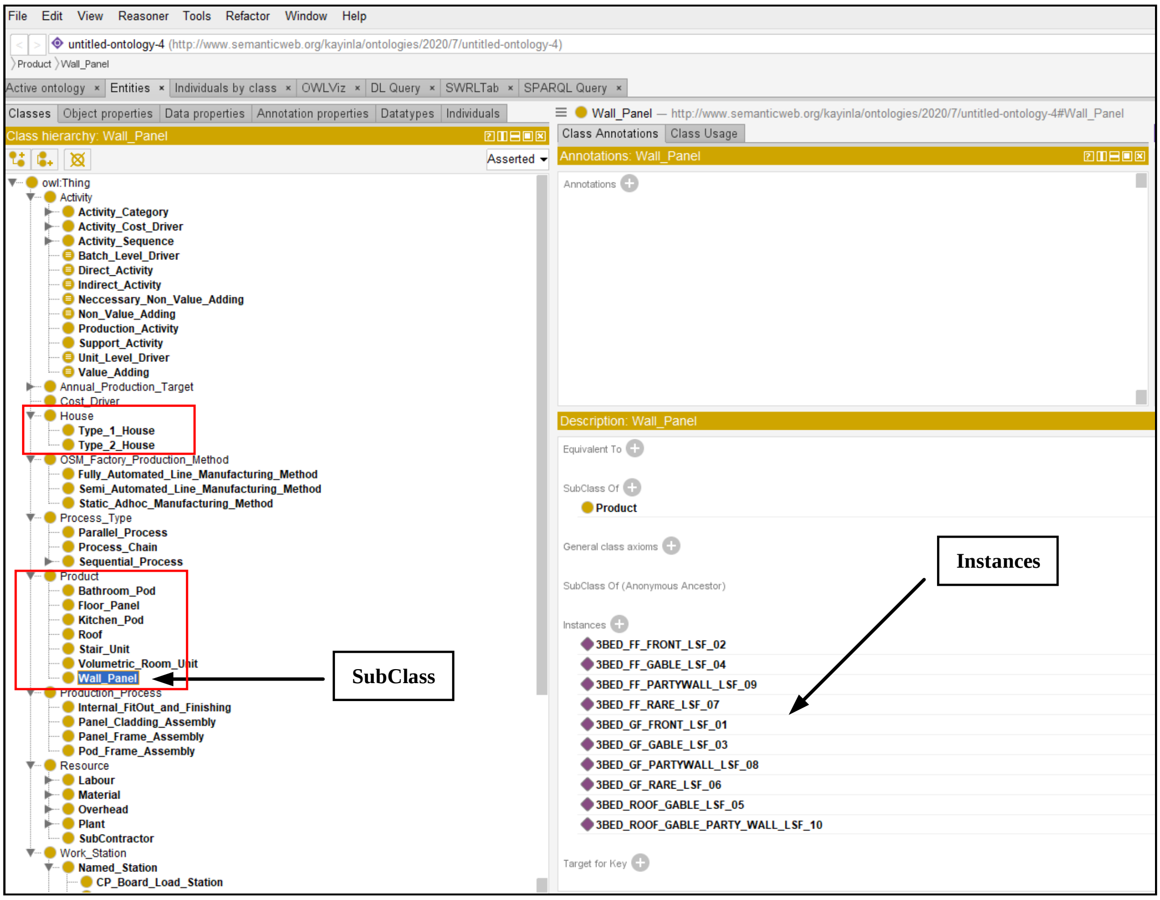


Figure 8.3: Instances of Type 1 House - 3BED Semi-Detached

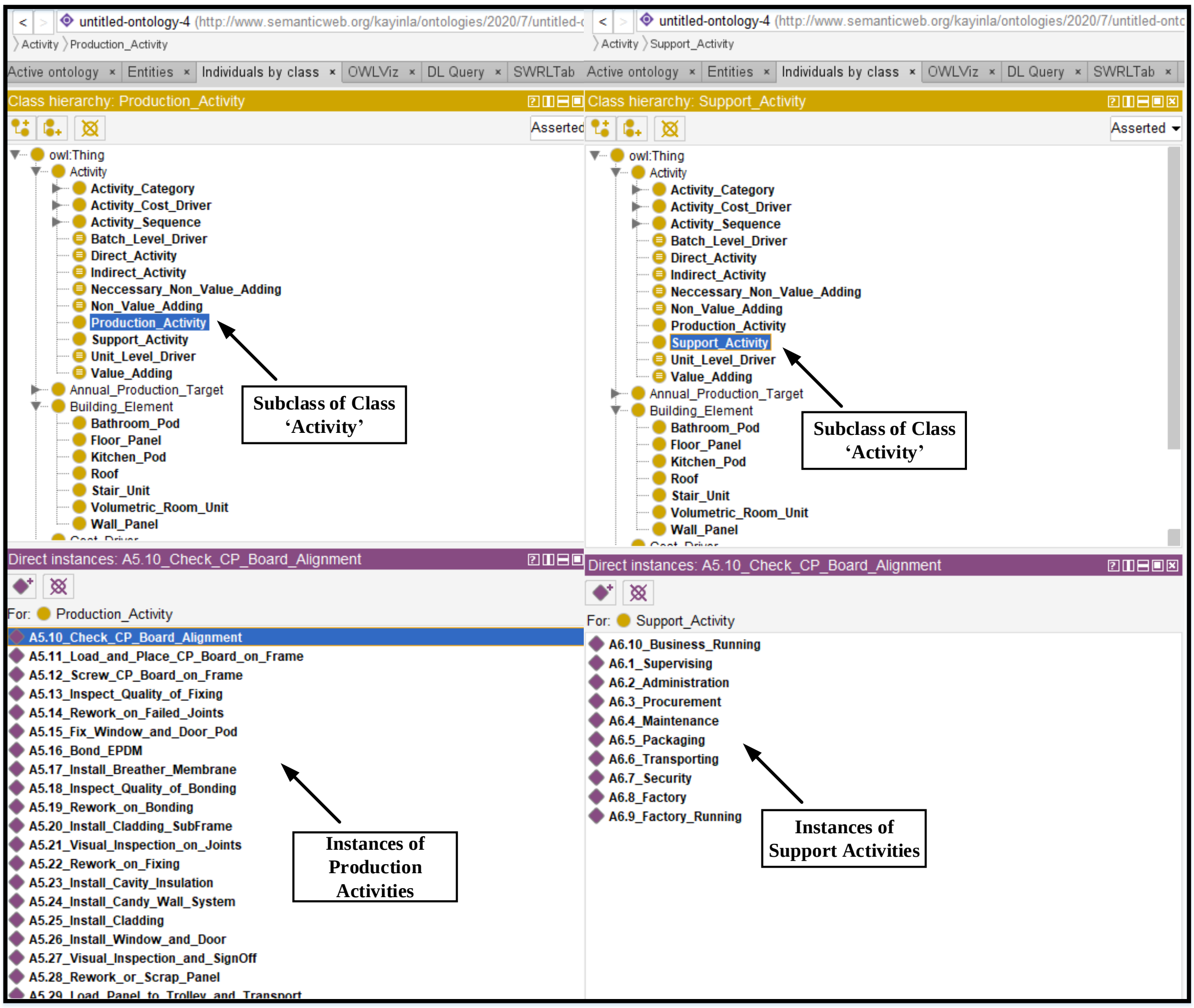


Figure 8.4: Instances of class ‘Activities’ in THE OPW ontology

In preparation for reasoning and retrieving knowledge from the OPW ontology, these instances are assigned some slots/values to describe the properties and attributes of the instance. For example, specifying the object properties such as the cost driver of the activities, asserting what activity comes before or after, or stating the work station where the activity belongs. Similarly, some data properties have been specified such as the time of the activity, the labour rate per hour, the plant cost per hour, etc. (Figure 8.5).

As the objective is to analyse the processes, a comparison of two units of analysis (the static and the semi-automated methods of production), for a like-to-like comparison between the two methods, the workflows for wall panel production for the House-Type 1 have been chosen for demonstration in this thesis. The static method is based on an actual production process while the semi-automated method in the case study is based on a detailed scheme containing simulations of actual production information and detailed workflow incorporating automated stages of sub-assemblies.

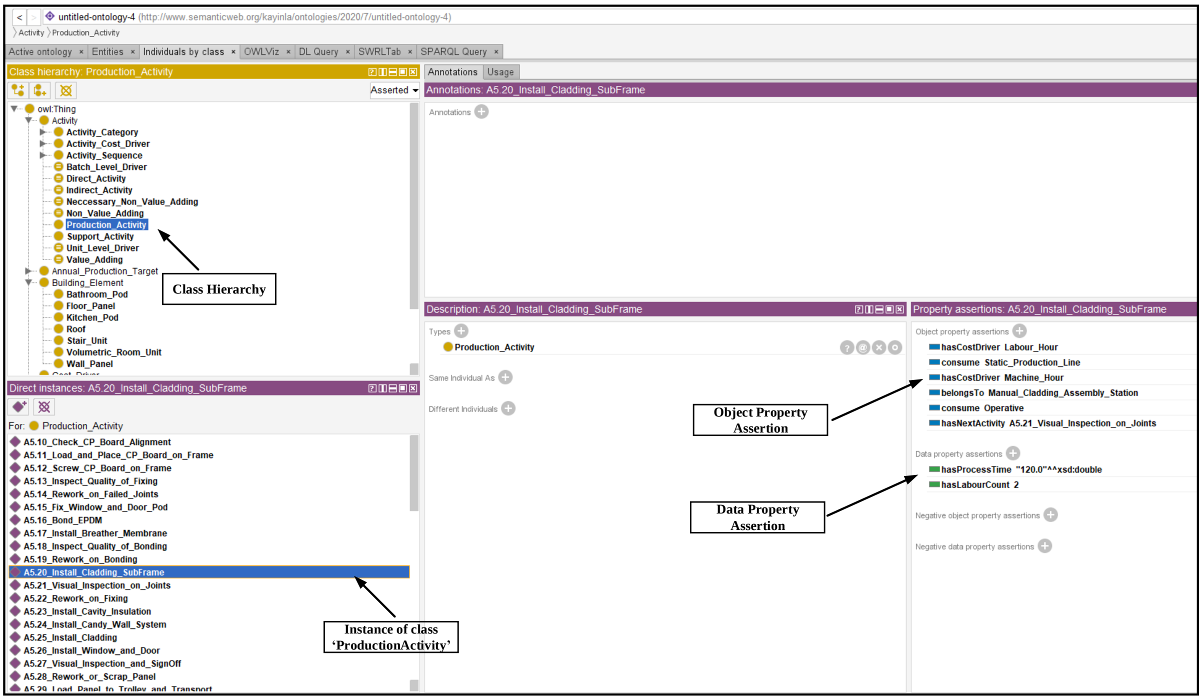


Figure 8.5: Assigning properties to instances in the OPW ontology

8.4 Testing the OPW ontology – Internal validation of logic through reasoning and knowledge retrieval

As the ontology is developed to answer a set of competency questions to meet the objectives of the study, it is necessary to develop queries to help retrieve information on these questions from the knowledge base. Hence, why the knowledge base has been instantiated in preparation for the actual implementation. SPAQRL is the query language used for this purpose to manipulate linked data such as the knowledge in an ontology and to generate results required from users in the form of a triple pattern. SPAQRL represents a collection of RDF statements that match the query with a set of data and returns information based on the already inferred or asserted knowledge in the ontology. SQWRL, on the other hand, allows for pattern matching specification to be generated from an ontology. These languages are available in Protégé and supported by the tool.

8.4.1 Experiment 1 – Competency Question 1: Querying the ontology for process-based information

The first competency question involves retrieving information on activities involved in an OSM production process of various building elements (products from the factory), and the resources consumed by these activities.

> ***Competency Question 1:*** *What activities are involved in manufacturing a house using various systems of OSM (i.e. panelised, volumetric or hybrid methods) and what resources are involved in each process?*

In order to fulfil this requirement, some object properties were created in the ontology to link instances within the ontology. To avoid duplication, these properties were made transitive so has to create a chain of information and relationships. The object properties *'belongsTo'* and *'consume'* were used for this purpose. This allows the expression 'Product' *consumes* 'Activitiy' and 'Activitiy' *consume* 'Resource' to be established in the OPW ontology.

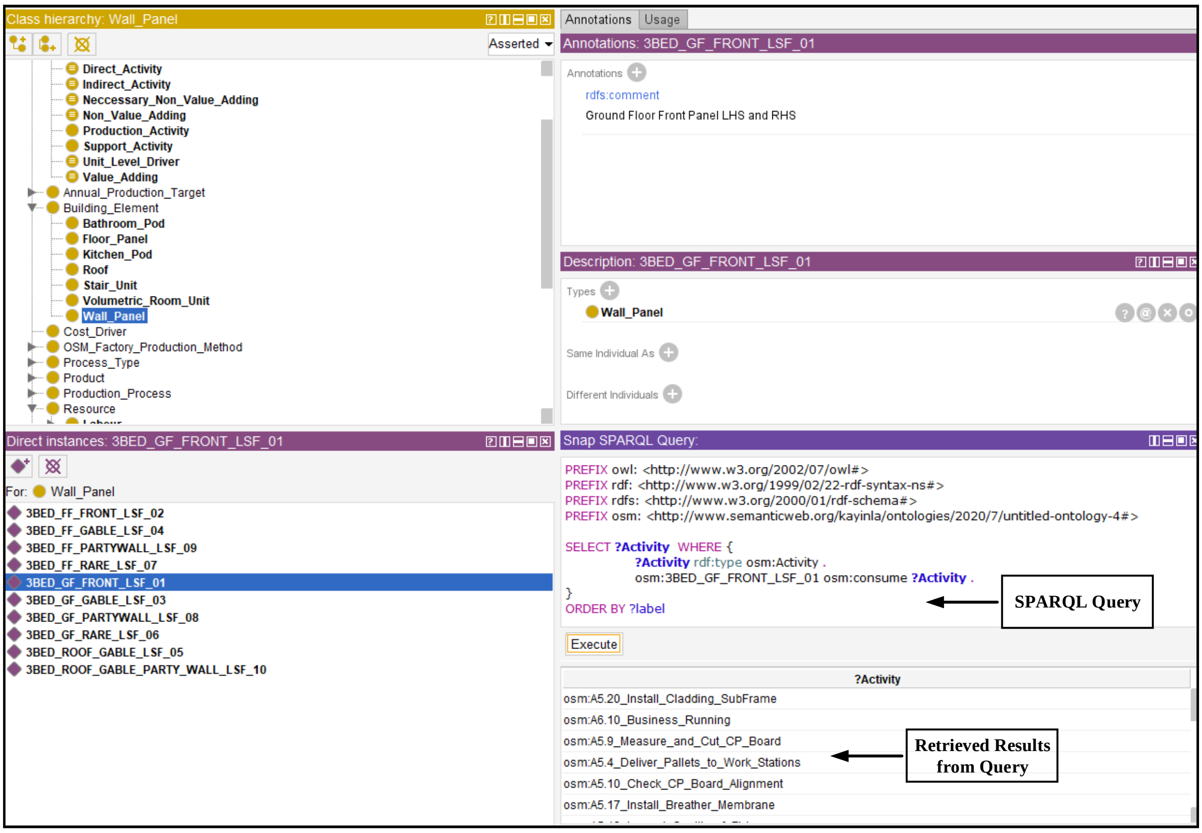


Figure 8.6: SPARQL Query Result - Activities involved in a wall panel production

For demonstration, a query was developed to retrieve information on the activities involved in the production of a wall panel using the instance of '3BED_GF_Front_LSF_01' (Figure 8.6) and also to obtain information on the resources consumed by these activities (Figure 8.7). Also, it is possible to retrieve information on the activities involved in a production process when using either the static method of production or the semi-automated method of production. Similarly, information on the activities performed on a specific workstation has been retrieved from the ontology and the sequence of how these activities are performed through the object property '*hasNextActivity*', or '*isNextActivityOf*'.

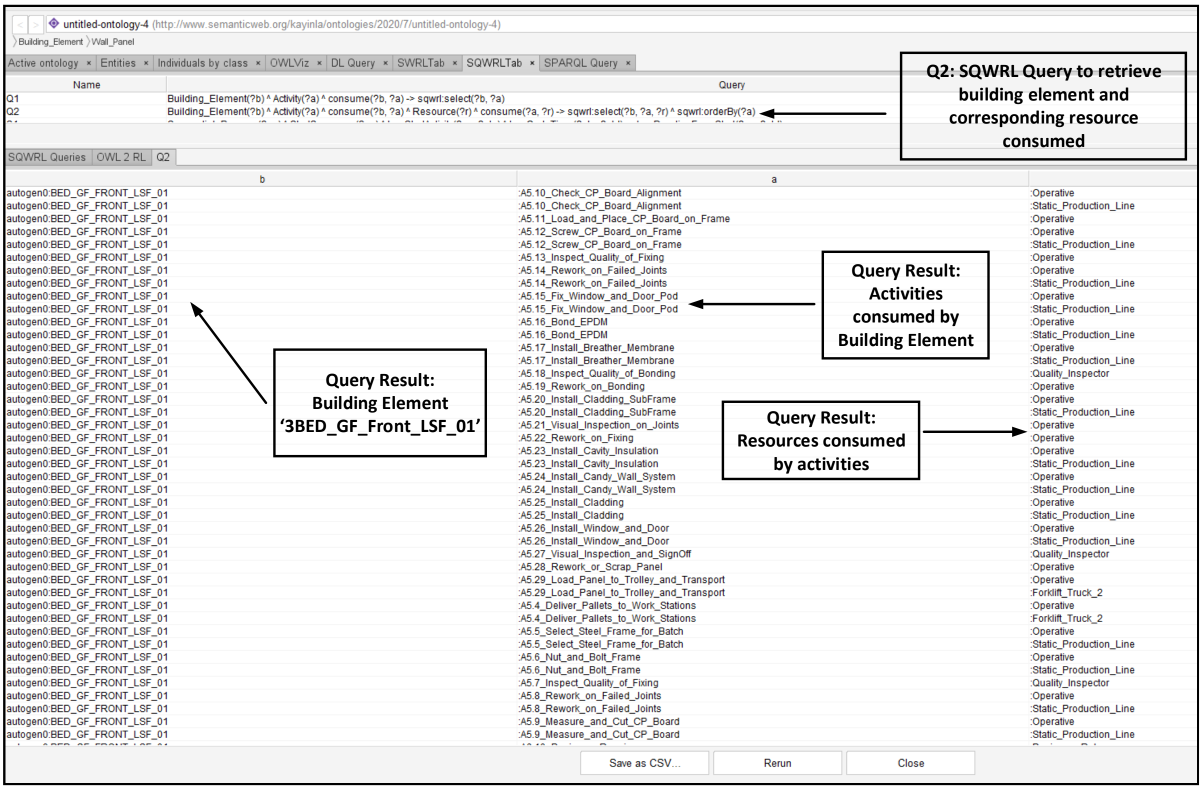


Figure 8.7: SQWRL Query Result – Resources consumed by building element

8.4.2 Experiment 2 – Competency Question 2: Retrieving cost information of products

Apart from retrieving general information from the OPW ontology regarding processes, methods, activities, resources, and products, involved in the product development stage, the ontology is also able to initiate some computations to support the ABC method. The second competency question relates to retrieving information on the cost of activities involved in an OSM production process and linking these with the various building elements that consume the activities.

Competency Question 2: *What is the cost of each activity performed in the factory house building process for the various OSM methods?*

The building elements are in turn related to a specific house type through the object property *'hasComponentPart'* thus allowing for the cost of each product to be computed (see Chapter 7 for SWRL rules). The data property relating to this is the *'hasActivityCost'* which is computed by summing up the cost of resources consumed by activity through the properties *'hasLabourCost'*, *'hasPlantCost'*, and *'hasOverheadCost'* depending on the resources applicable to each activity. The activity costs thus form the process costs involved in producing any product from the OSM methods. The data properties (*'hasLabourCost'*, *'hasPlantCost'*, and *'hasOverheadCost')* are computed with the help of SWRL rules and are then fed back into the knowledge-base as inferred properties (Figure 8.8).

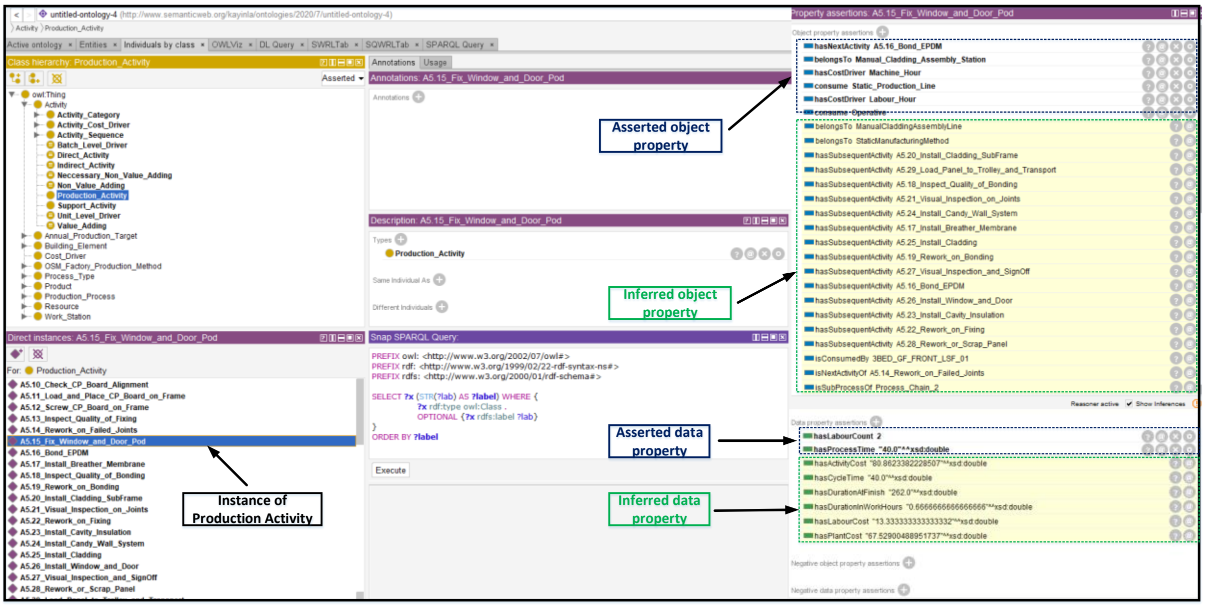


Figure 8.8: Reasoning Result – Asserting properties in the ontology to obtain cost information

To test the ontology, a query was developed to retrieve information on the cost of activities involved in the production of a type of wall panel with the static method of production, using the instance of '3BED_GF_Front_LSF_01' (Figure 8.9). The query result returned the activities and the collected cost of each of the activities. This allows for the comparison of costs for different panels based on the activities they consumed, and also, based on the method of production.

Similarly, another query result (Figure 8.10) returns the breakdown of the activity cost into labour and plant costs. The labour cost involves the cost of man-hour spent working on the activities while the plant cost includes the cost of small movable tools (such as forklifts) and large static tools (production line equipment). It is worth noting that some activities only have the plant cost and this is mostly applicable to activities performed using the semi-automated linear method where the activities are automated and requires no human intervention.

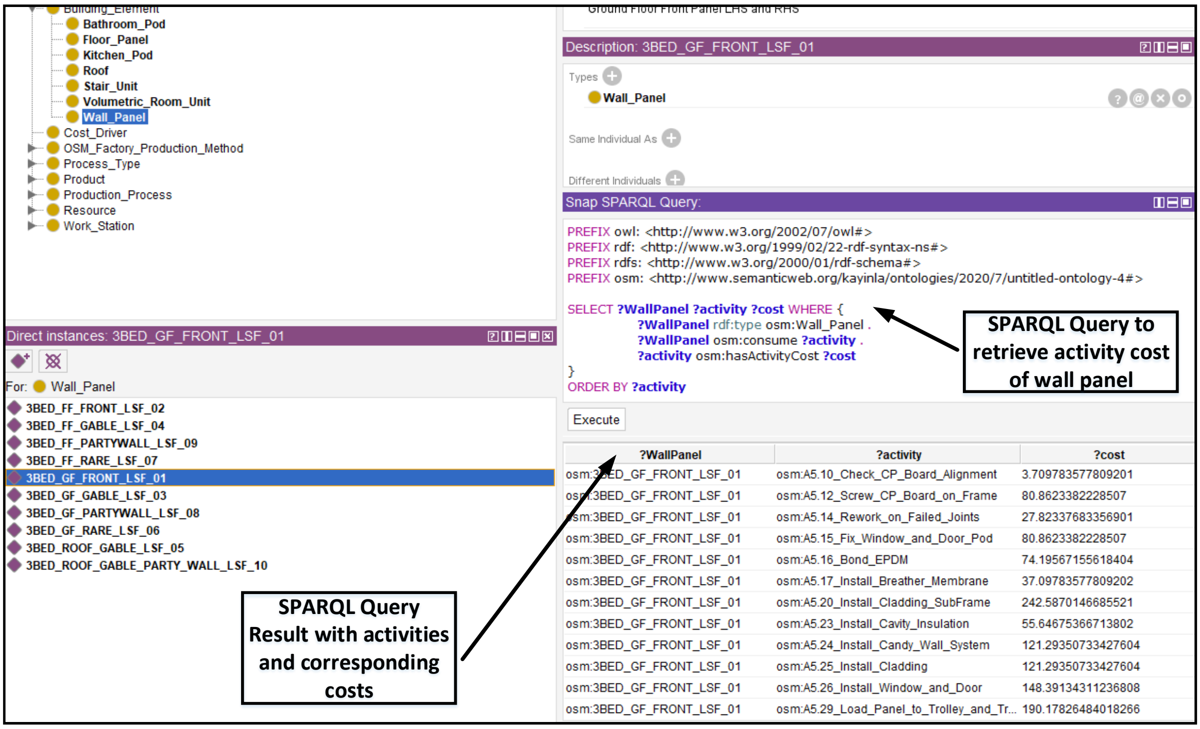


Figure 8.9: SPARQL Query Result - Activities cost of an instance of wall panel

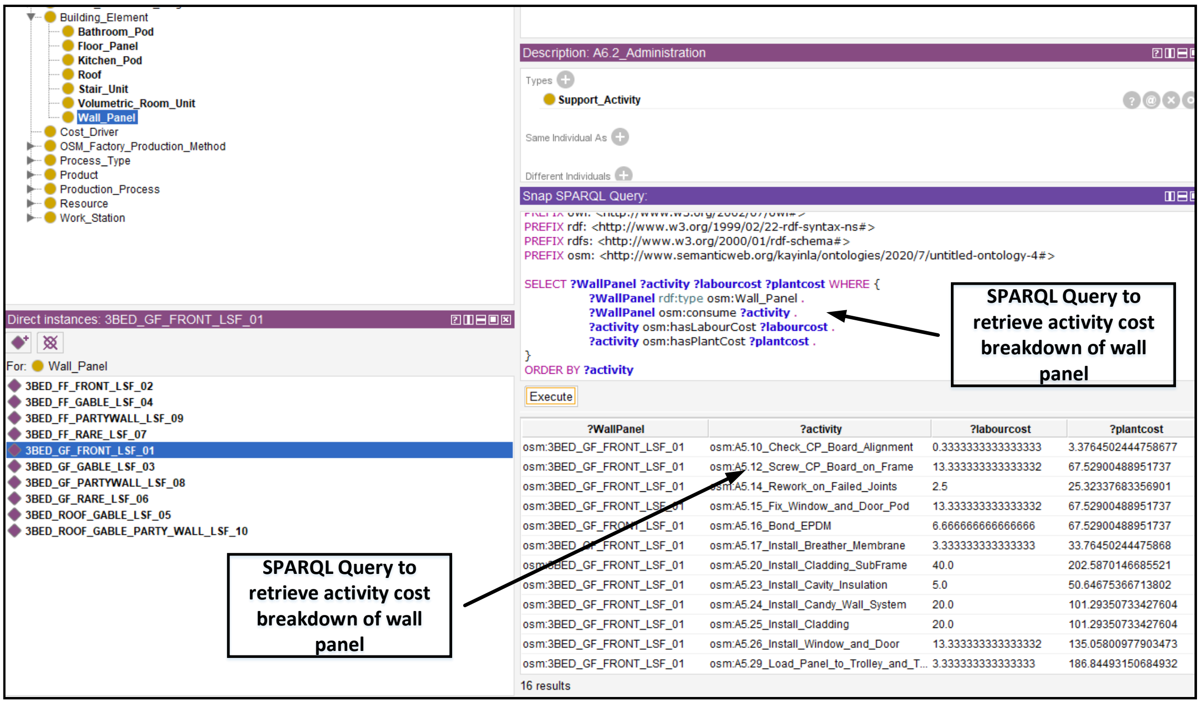


Figure 8.10: SPARQL Query Result - Activities cost breakdown of an instance of wall panel

8.4.3 Experiment 3 – Competency Question 3: retrieving time information for processes

Experiment 3 is based on the third competency question, which relates to retrieving information on time spent on activities, the time spent in each workstation and also the overall time taken to complete production using either the static method or semi-automated method.

> ***Competency Question 3:*** *What is the time spent on each activity and in the associated workstation involved in producing a house in the various OSM method?*

This time information is denoted as the data type property '*hasCycleTime*' in the OPW ontology. The object property '*belongsTo*' which is a transitive property allows the time information to be passed down from the activities to the work station housing the activities, and up to the final production method where these activities are performed. Such that, an 'Activity *belongsTo* 'WorkStation' and 'WorkStation' *belongsTo* a 'ProductionProcess' and the 'ProductionProcess' *belongsTo* an 'OSMFactoryProductionMethod'. The cycle time of these activities will thus be used to infer the cycle time for the workstation by the reasoner. For instance, the activity 'Nut and Bolt frame' is performed on the 'Manual Frame Assembly station' which is part of the 'Frame Assembly' production process and is applicable to the

'Static method' of OSM production. Some SWRL rules have been developed in the ontology to allow for computation of cycleTime (refer to section 7.7.1 for rules).

For a demonstration of the implementation of the rules in the ontology, a SPARQL query was written to retrieve information on the time taken to complete each activity in the frame assembly process when using the static production method (Figure 8.11). Another query relates to generating the overall cycle time in various workstations in an OSM production process (Figure 8.12). These queries imply that it is possible to analyse the time taken in producing various OSM products when using the static method, or the semi-automated linear method of production. Also, the data properties *'hasDurationFromStart'* and *'hasDurationAtFinish'* are inferred by the reasoner and indicate the time at the start and end of an activity in a chain of processes, either parallel or sequential.

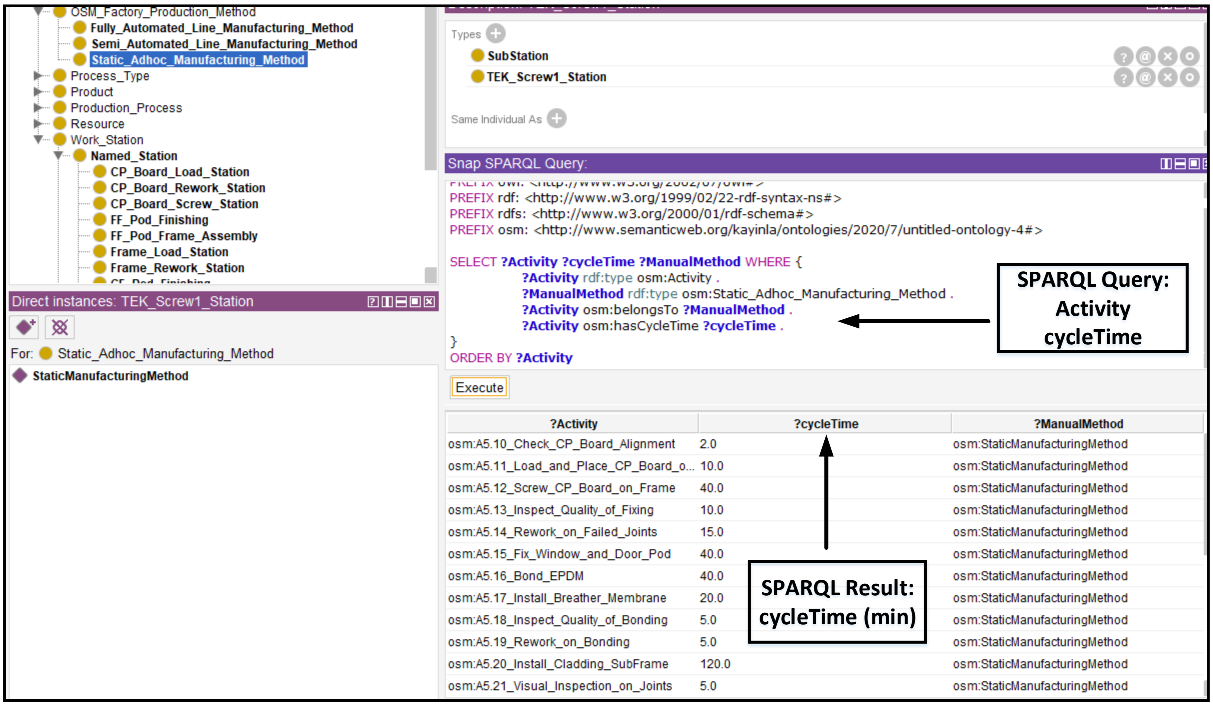


Figure 8.11: SPARQL Query Result – cycle time for activities in the static production method.

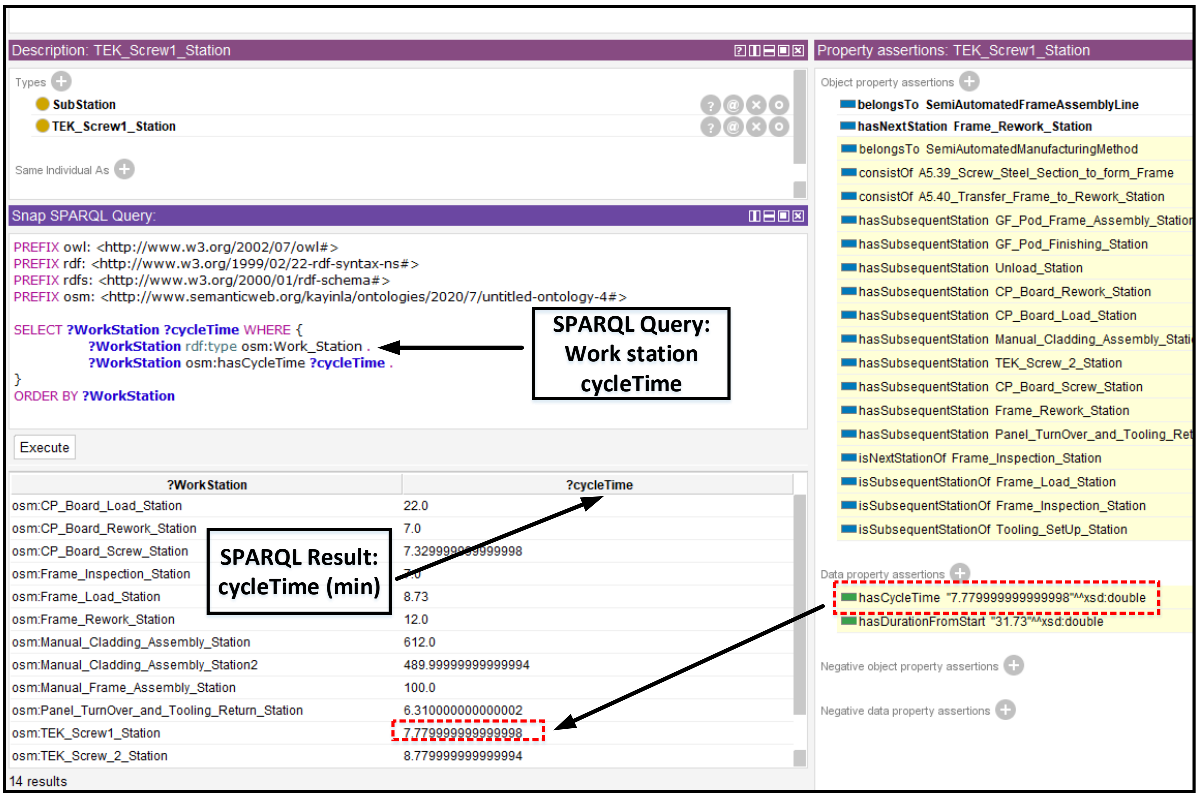


Figure 8.12: SPARQL Query Result – cycle time for workstations in an OSM process

8.4.4 Experiment 4 – Competency Question 4: Analysing process waste

The next experiment based on the fourth competency question is to analyse the process waste in various OSM production methods. There are various types of activities involved in the production of OSM houses in the factory environment and these are classified as either 'ProductionActivity' or 'SupportActivity'. However, not all of the time spent or cost accrued in performing these activities is considered value-adding. These are known as the process waste in the production process.

> ***Competency Question 4:*** *What proportions of the activities involved in the production process of different OSM methods fall in the categories value-adding, non-value-adding and/or necessary non-value-adding?*

It is thus essential for the OPW ontology to be able to retrieve this information as doing this task manually would have proven too challenging given the amount of information required to be processed. The lean manufacturing theory relating to the 8 categories of process waste has been used to determine the waste in the production processes by classifying activities as either

VA, NVA or NNVA. For a demonstration on implementation of the rules in the ontology, a SPARQL query was written to retrieve information on the types of activities involved in the production of a wall panel using the instance of ‘3BED_GF_Front_LSF_01’ when using the static production method or the semi-automated production method. Figure 8.13 illustrates the query result listing the value-added activities and their corresponding cycle times in the production of an instance of a wall panel. Similarly, Figure 8.14 and Figure 8.15 contain the list of activities that are classified as both NNVA and NVA in a wall panel production process respectively.

For the instance of the wall panel ‘3BED_GF_Front_LSF_01’, the result shows that there 26 activities in total involved in the production of that instance while 11 of these activities are classified as VA, 5 of the activities are classified as NNVA while 10 of the activities are classified as NVA i.e. a process waste that could be improved on. The results allow the analysis of the time spent on each category of activities and the breakdown of the resources consumed/cost incurred in the production process.

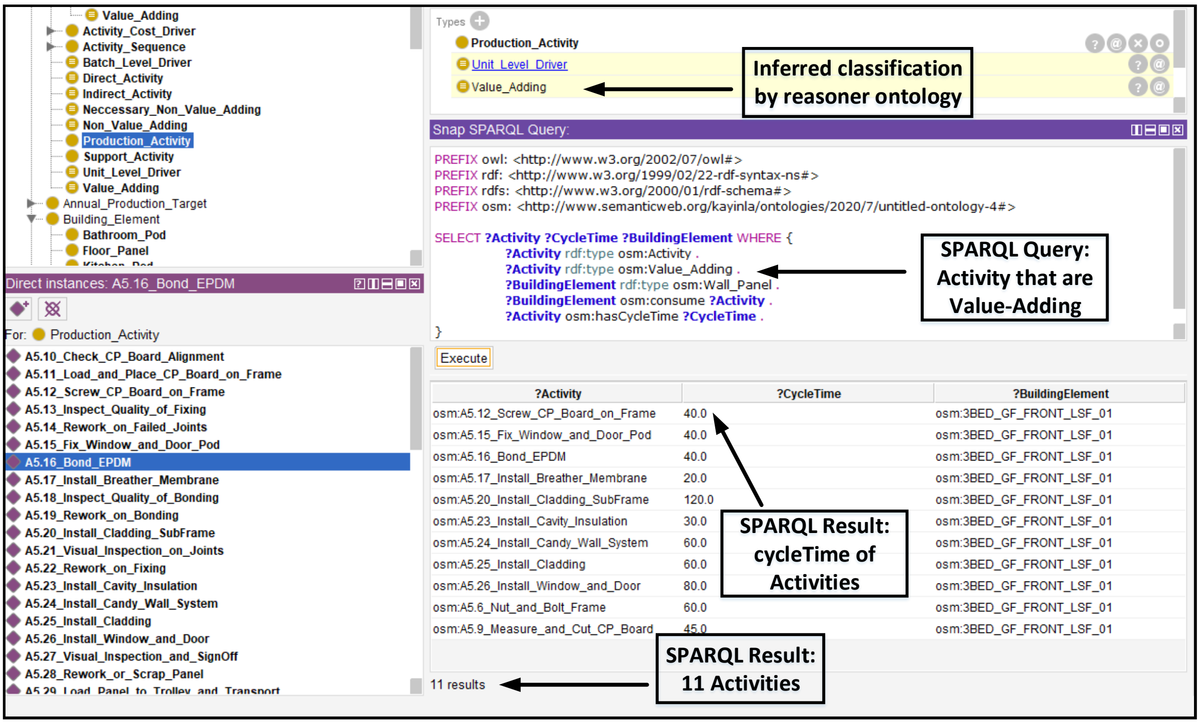


Figure 8.13: SPARQL Query Result – cycle time for value-adding activities in a wall panel production

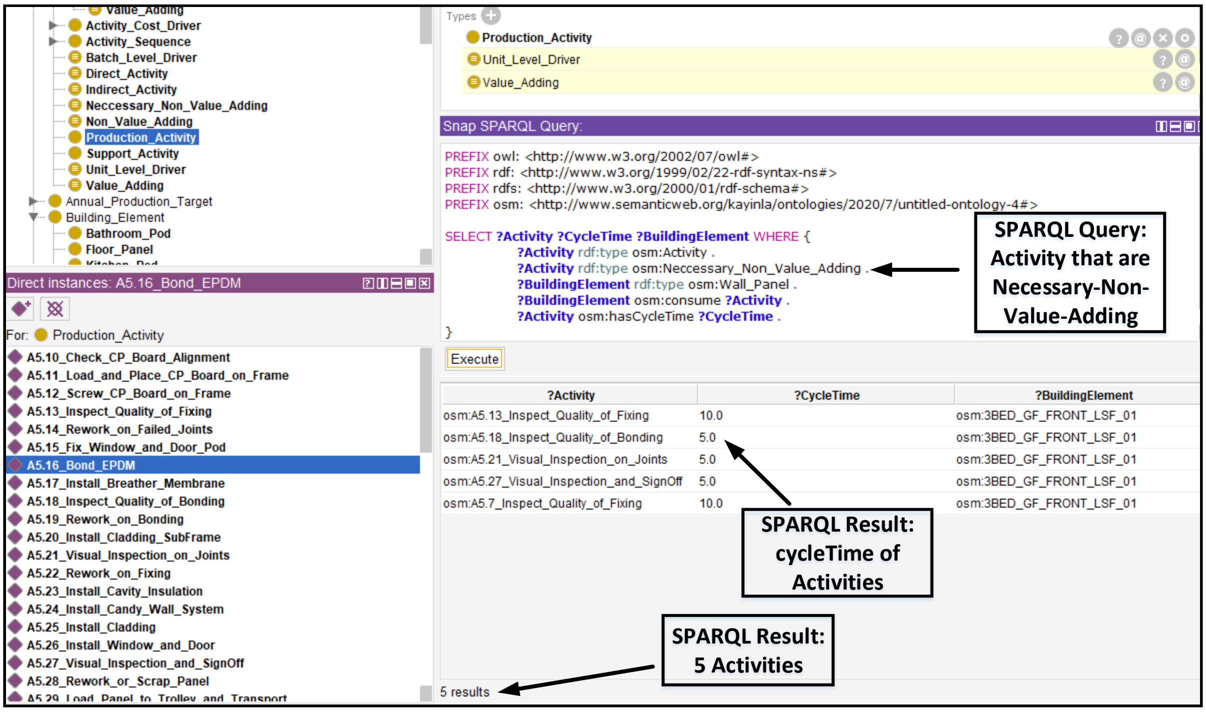


Figure 8.14: SPARQL Query Result – cycle time for necessary-non value-adding activities in a wall panel production

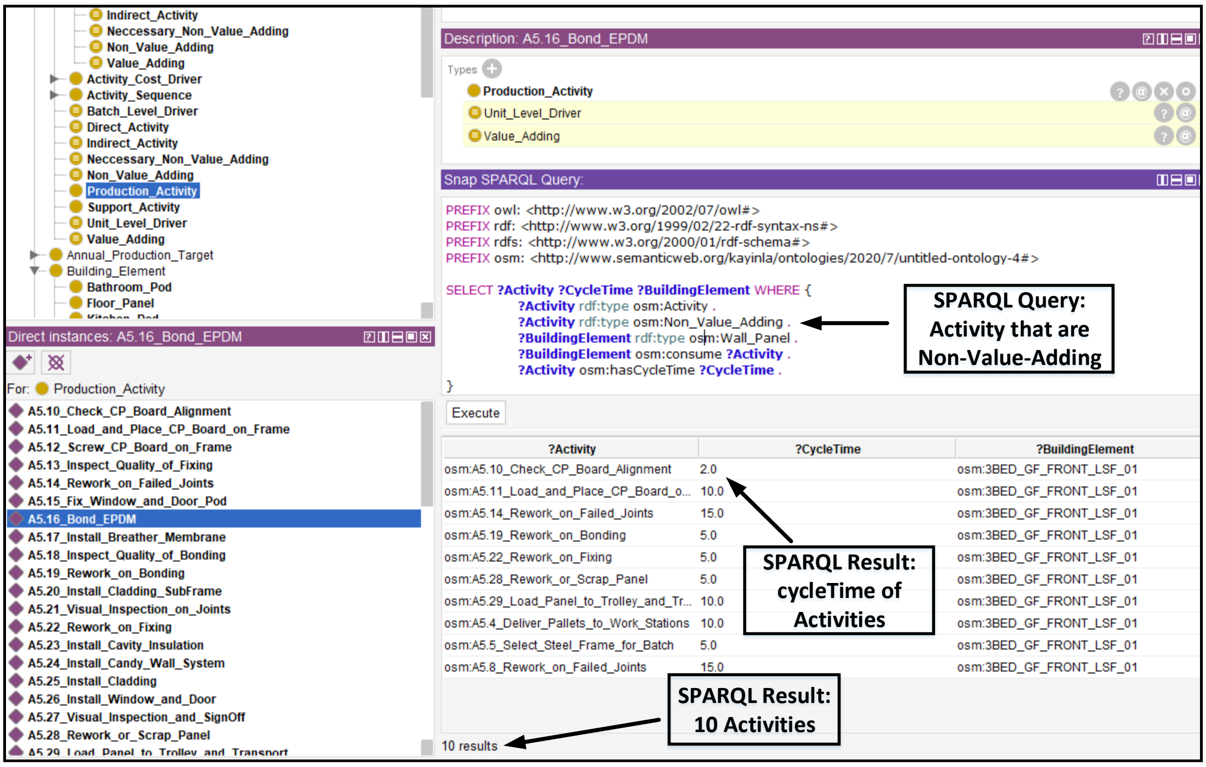


Figure 8.15: SPARQL Query Result – cycle time for non-value-adding activities in a wall panel production

8.4.5 Experiment 5 - Competency Question 5: Analysing time spent on processes

The last experiment is based on the fifth competency question which is also identified as a potential output from the OPW ontology. This is to allow analysis of various methods of OSM production and in this study, the static and semi-automated methods are used as the two units of analysis.

> ***Competency Question 5:*** *What is the percentages/value of the cost and time spent on the various categories of activities in the competing OSM production methods?*

As the ontology already contains knowledge on the two methods and the sort of activities involved. This enables the offsite manufacturer or organisation to analyse both options in aspects such as the time spent on various activities in a product development process and the cost incurred. Potentially also, to determine where intervention is needed for continuous improvement. A SPARQL query has been implemented to retrieve information on the cost and time spent in the production of the wall panel instance '3BED_GF_Front_LSF_01' for both methods of OSM production. Figure 8.16 shows the result for the static method while Figure 8.17 shows the results for the semi-automated linear method of OSM production. These results will be further discussed in the next section.

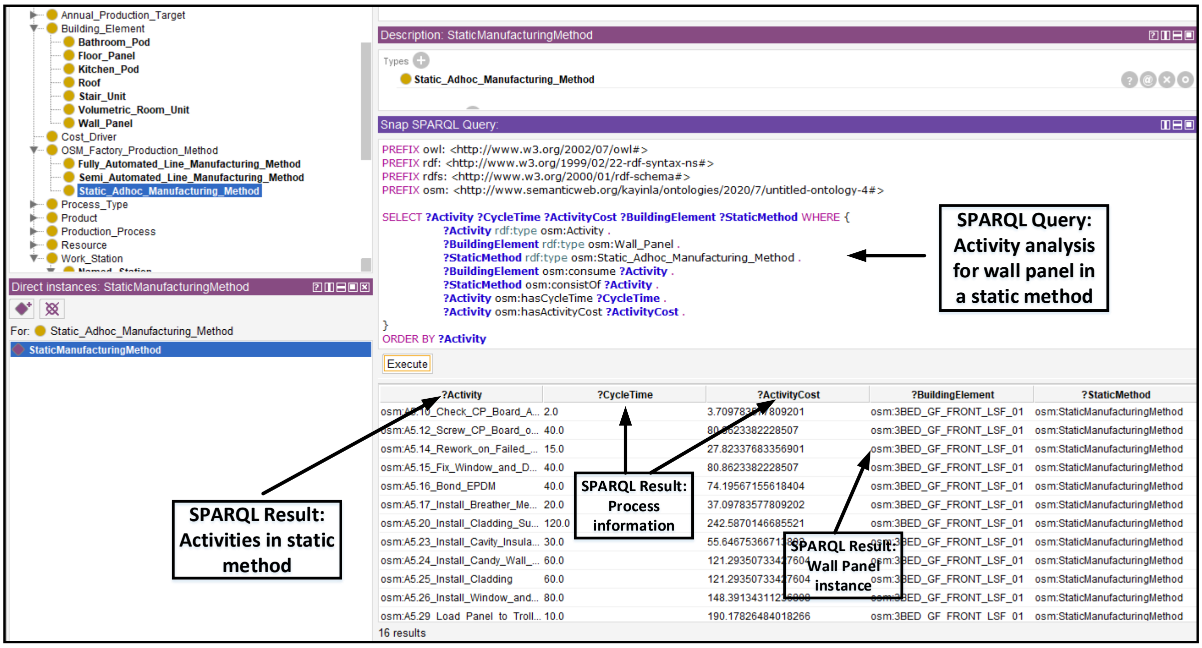


Figure 8.16: SPARQL Query Result – Process Information for the static method of wall panel production

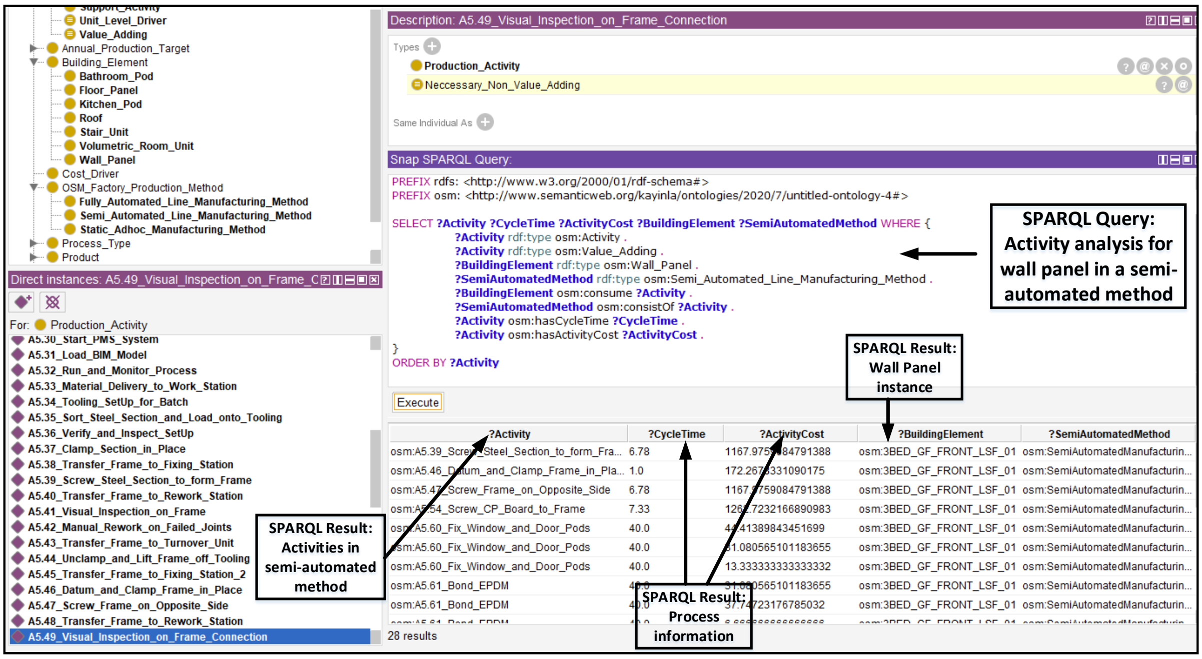


Figure 8.17: SPARQL Query Result – Process Information for the semi-automated method of wall panel production

8.5 Descriptive statistical analysis of experimental results

To enable the second stage of the validation involving domain expert analysis of the results from the OPW ontology, there is a need for further analysis of the results in a plain language separate from the query results from the ontology to enable communication with non-ontology experts. This is achieved with the use of descriptive statistics through charts and graphs displaying results from the ontology. The analysis in this section is an example of the result generated from the OPW ontology from the units of analysis considered for this study. The panelised system of OSM used in this case study is developed based on an actual case of the static method of production, while the data for the semi-automated method is based on a detailed scheme containing the simulations of actual production information and detailed workflow incorporating automated stages of sub-assemblies. For the purpose of this analysis, and for like-to-like comparison between the two methods, the workflows for wall panel production comprising panel frame and panel cladding were used. To complete the analysis and support reasoning in the knowledge semantic model, the economic life of major static equipment/plant used in the production process is assumed to be 10 years (as specified by the design team of the production line) while that of small movable tools is assumed to be 5 years.

Table 8.3 summarises the resource type to be included and excluded for the analysis of the process cost. The boundary of the analysis for the cost comparison is the production stage of the product development starting from 1) the point of material delivery to work stations, to 2) the point of loading the finished products in the transport trolley to the site. In terms of cost analysis, some cost aspects have been excluded from the comparison in order to avoid duplication since the values do not change for both units of analysis (static and semi-automated methods). For instance, the material cost will stay the same for products in both the static and semi-automated methods. Also, the factory space used for the analysis is the same hence aspects like rent, building maintenance, etc. will remain the same. However, the electricity consumption in the semi-automated method will be considerably more than in the static method hence included in the scope of the analysis.

Table 8.3: Resource type for analysis

Scope	Resource Type
Inclusion	Direct Plant/Equipment
	Direct Labour
	Support Labour
	Electricity
Exclusion	Material
	Rent
	Gas and Water
	Building Maintenance and repair
	Factory management charges
	Business Rates

The following sections will analyse the results from the OPW ontology based on the time and cost consumed in the product development process. Additionally, analysis of the process waste generated in both units of analysis is carried out. The process wastes are analysed using the lean manufacturing theory relating to 8 categories of process waste (see Chapter 3) to analyse the activities in the process for the two methods and the waste involved in order to quantify the improvement where applicable and to provide recommendations for CI. The activities as identified in the process map (see Appendix D) were classified into three types, VA, NVA and NNVA.

8.5.1 Process Analysis - Static method OSM production

To facilitate comparison of the cost of a panel using the static method with the semi-automated linear method, assumptions were made regarding the production schedule (Table 8.4). Also, the demand for factory-manufactured houses may vary within the time frame considered. Thus, assumptions based on the 10-year business plan for production provided by the case provider are made regarding the annual production target throughout the assumed economic life (10 years) of the equipment used for production (Table 8.5) to facilitate activity cost estimation using the ABC method. For the static method, the factory in the case study allows 2 shifts per day. Each shift comprises three gangs of workers and each gang includes 3 team members, an additional quality inspector and a supervisor. The total labour input is calculated to be 3174 work hours per year (Table 8.4). Based on this assumption and the time taken to complete a cycle in the production process, it is anticipated that the equivalent output from the factory is 4498 panels per annum. Since there are 32 panels required to build the prototype house, the factory has the maximum capacity to produce 140 houses per annum based on this arrangement (Table 8.5).

The calculations above are based on the full production capacity of the factory arrangement without any disruption. According to the business plan, the production capacity is developing from 50% for the first year to 100% for the last year as shown in Table 8.5.

Table 8.4: Production volume/schedule for static production

Weeks Per Year	**46**
Hours Per week	34.5
Hrs per year	3174
Number of shifts	2
Team/Gang	3 gangs of 3 workers per shift (i.e. 2 fixers, 1 casual worker), Additional 1 Quality Inspector and 1 supervisor per shift.
Annual Volume (in full capacity)	4,498 panels

Table 8.5: Anticipated annual production target for factory manufactured houses using static method of production

Year/Period	Equivalent no. of wall Panels per year	Production Capacity (Units of houses)	Equivalent Capacity Usage (%)
1	2245	70	50
2	2699	84	60
3	3374	105	75
4	3374	105	75
5	3374	105	75
6	3374	105	75
7	3823	120	85
8	3823	120	85
9	4273	134	95
10	4498	140	100

Figure 8.18 shows the process cost analysis of a wall panel production (i.e. instance 3BED_GF_Front_LSF_01) using a static method based on the estimates from the reasoner of the OPW ontology tool. A detailed breakdown of the result is attached in Appendix C (Table 11.1 – Table 11.6).

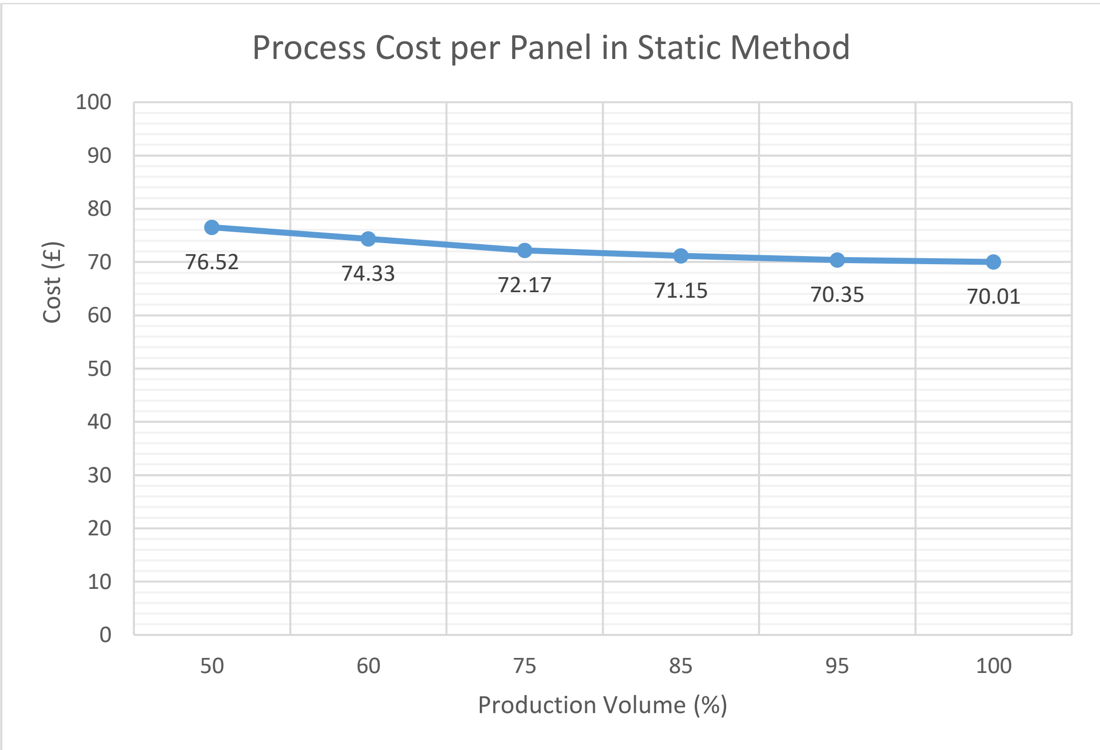


Figure 8.18: Process cost per wall panel vs annual production volume in Static Method

The process cost in Figure 8.18 illustrates the result from the analysis of the process cost of a product (wall panel) depending on the annual volume of production. Some considerations have been put in place in generating this cost such as the cost of rework embedded in the static method. Based on observation and consultation with production experts, the static method has a higher rework rate with a 15 – 20% chance of rework on major activities due to minor errors or deviations from drawings and specifications requirements. Therefore this is considered when recording cycle time for rework activities. Another challenge with static/manual production is that the identified VA activities done by operatives may also include some idle time. However, it is challenging to identify or quantify waste embedded in such activities. Therefore, an allowance has been recorded for some of these activities to denote the wasted time in the processes due to human working habits (see Appendix C).

Similarly, Figure 8.19 illustrates the breakdown of the process cost in order to determine the proportions of waste in the process by separating the process cost into VA, NVA and NNVA proportions.

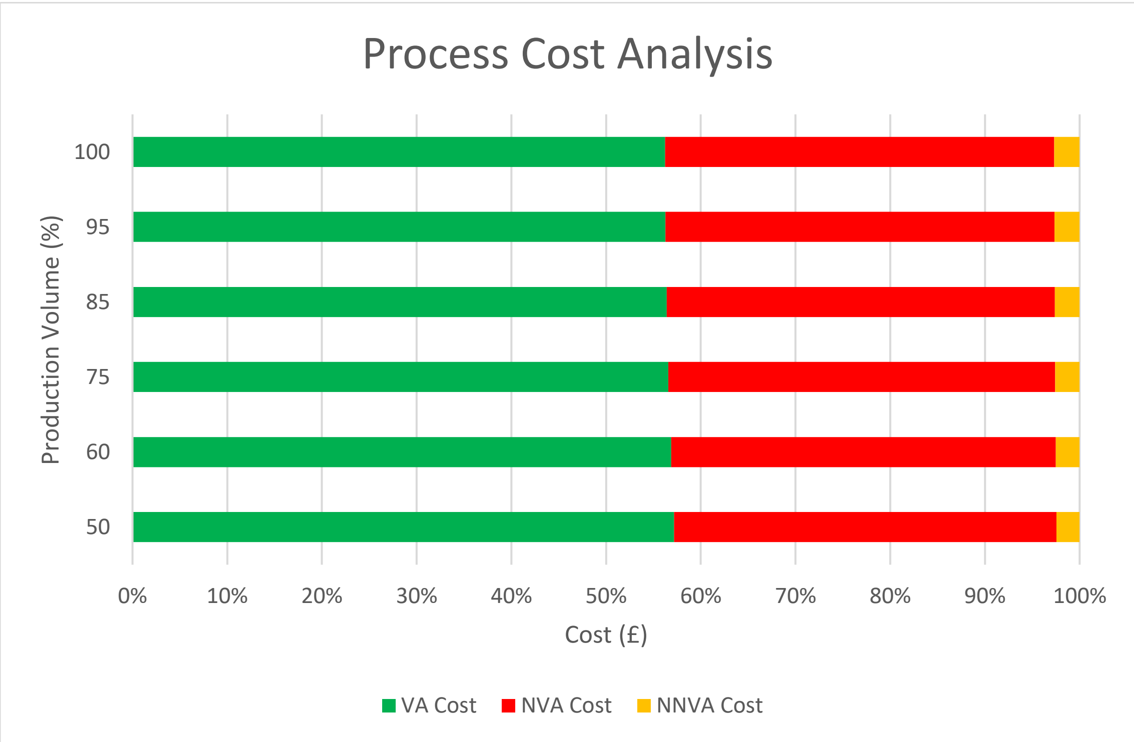


Figure 8.19: Process cost analysis for static method of production

8.5.2 Process Analysis - Semi-automated linear method OSM production

In the semi-automated linear method, similar to the method used in analysing the static method, the cycle time for each activity in the batch manufacturing line has been modelled for the new production line. The cycle time recorded and used for the analysis is the estimated maximum process time for each activity in every station. In this method, the time recorded is based on simulations from the production engineers according to the workflow arrangement and estimated time of product movement through different stages using the simulated model.

Similarly, to facilitate comparison of the process cost of a panel using the automated method when compared to the static process, the same assumptions have been made regarding the production schedule (Table 8.6). According to the data obtained from the production engineering company that designed the production line, overall efficiency of 85% was assumed across the equipment/plant on the production line. With the cycle time per panel (Appendix C, Table 11.7 – Table 11.14), this gives an estimate of the annual production target quantity for the products as 19,200 panels. Since there are 32 units of the product required to build the shell of the prototype house type, the factory has the capacity to produce 600 houses annually based on this arrangement. However, given that this is a fairly new investment and for the sake of future projection, the planned production schedule is varied through the economic life of the equipment to reflect possible demand and supply variants (Table 8.7).

Table 8.6: Production volume/schedule for automated line

Weeks Per Year	46
Hours Per week	34.5
Hrs per year	3174
Number of shifts	2
Team/Gang	1gang comprising of – 2 workers stationed on the production line, and 1 programmer/supervisor.
Projected Annual Volume (in full capacity)	19,200 panels

Table 8.7: Anticipated annual production target for factory manufactured houses using the semi-automated method

Year/Period	Production Target (No. of wall Panels per year)	Production Target (No. Units of houses per year)	Equivalent Capacity Usage (%)
1	1,920	60	10%
2	3,840	120	20%

3	5,760	180	30%
4	7,680	240	40%
5	9,600	300	50%
6	14,400	450	75%
7	16,320	510	85%
8	19,200	600	100%
9	19,200	600	100%
10	19,200	600	100%

Appendix C (Table 11.7 – Table 11.14) contains a breakdown of the data on process cost and time of a panel generated from year 1 to year 10 (i.e. from producing at the minimum and maximum capacity). The values are plotted in a graph (Figure 8.20) illustrating the process cost of a panel based on different volumes of production annually, while Figure 8.21 illustrates the breakdown of the proportions of the process cost to analyse the process waste in this method of production.

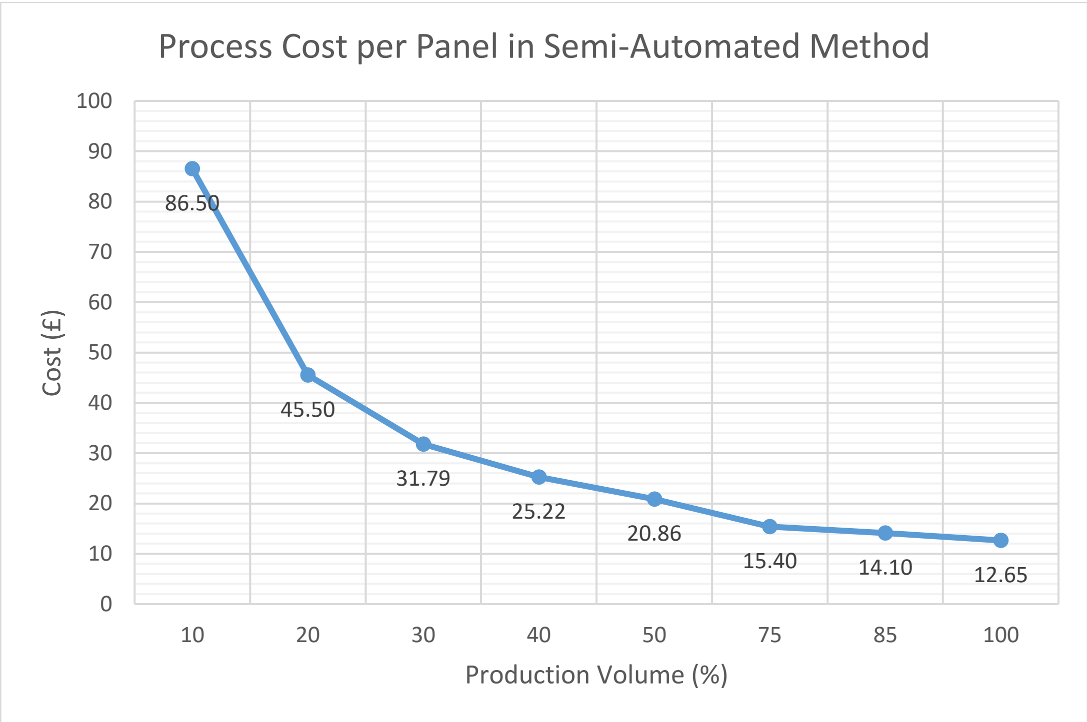


Figure 8.20: Process cost per wall panel based on annual production volume

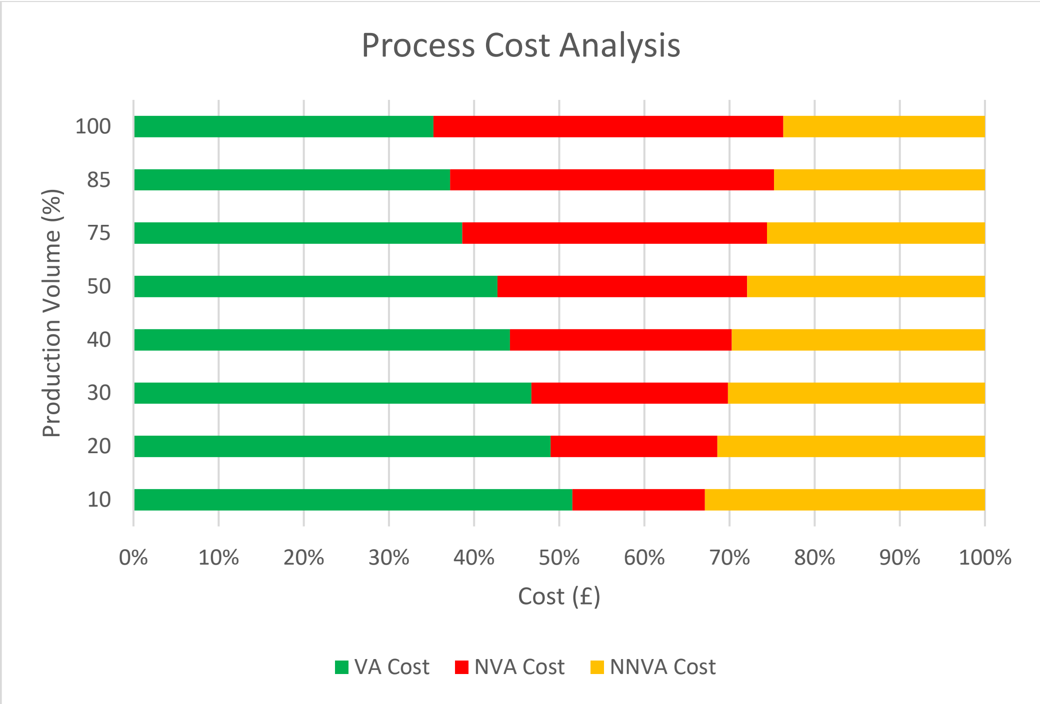


Figure 8.21: Process cost analysis for the semi-automated method of production

8.5.3 Process cost comparison of the two units of analysis – Static vs Semi-automated production methods

Further analysis is carried out to compare the process cost of a product in both units of analysis i.e. cost per panel. The cost per panel for the static method is compared with that of the semi-automated method according to the various volume of production (Figure 8.22). Since the process cost in the static method is close and does not change significantly based on the volume of production. The cost at the maximum capacity has been used in the comparison while varying the volume of production in the semi-automated method of production.

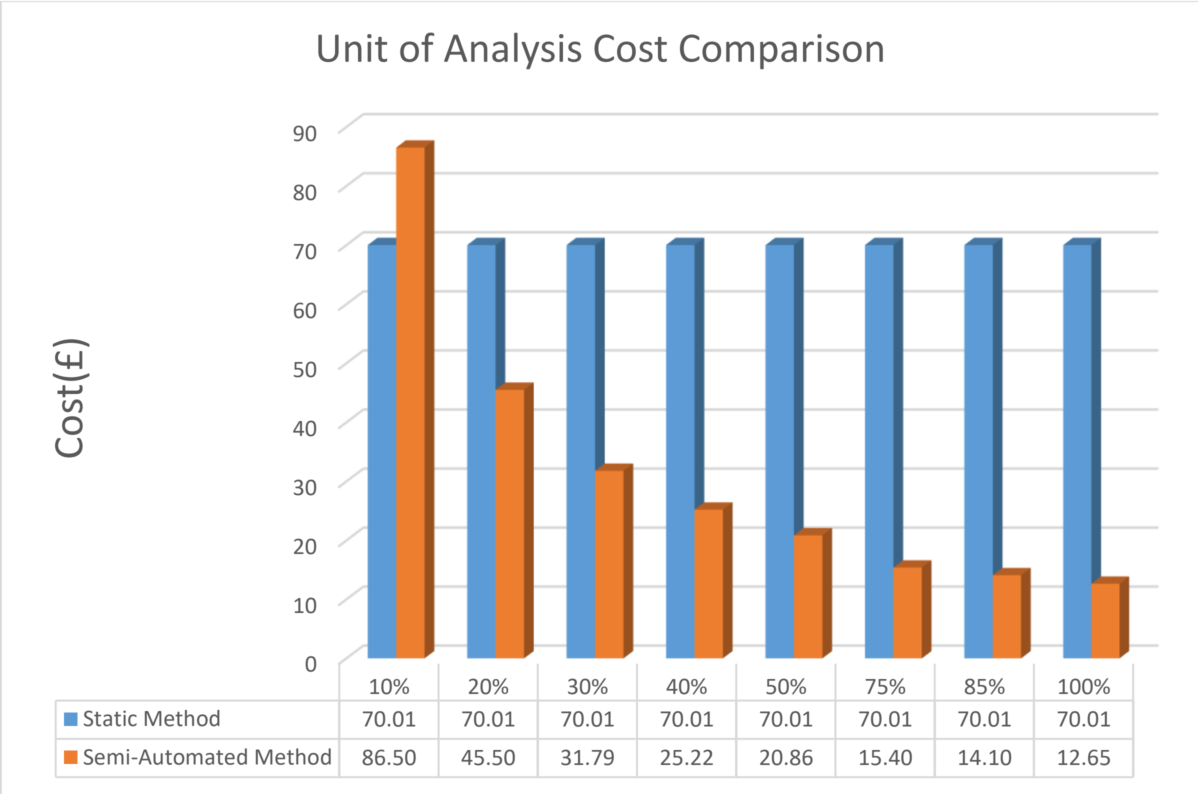


Figure 8.22: Comparison of process cost per panel for wall panel production.

In addition, Figure 8.23 illustrates the breakdown proportion of the process cost in both units of analysis based on process waste categorisation in the process.

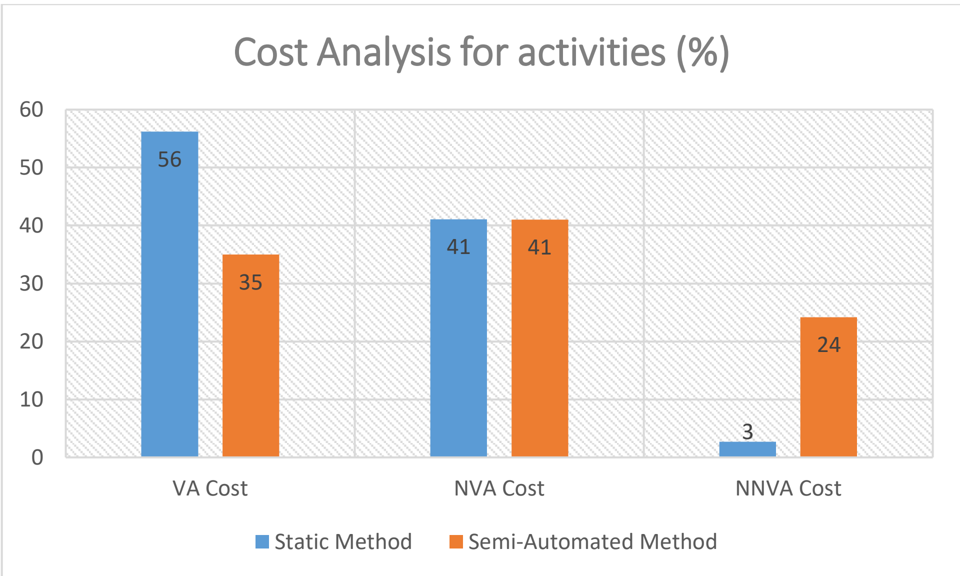


Figure 8.23: Breakdown analysis of cost of activities performed for wall panel production.

8.5.4 Assessing the process cost based on the choice of OSM method

In terms of the process cost associated with the production stage of the two units of analysis, for the static method and based on the result use-case demonstrated, it cost £76.52 to produce a wall panel at 50% capacity of the factory. When the output from the factory is increased to the maximum capacity of 100%, the cost per panel drops to £70.01 (Figure 8.18). This is not a significant difference, and this revelation can be explained in two aspects. The static method of OSM, similar to onsite conventional method of construction is a labour-intensive process and majority of the activities performed are manual in nature, therefore, the output of the production line is driven by the productivity of the workers. The minor difference in process cost when the volume of production is increased is a result of the reduced depreciation expense of some of the small flexible tools used in the production process such as fixing tools. Therefore, the volume of output from the production line can only be increased by increasing the manpower (such as adding another gang) and this has no major impact on the cost of the product.

In contrast, the semi-automated method has a process cost of £20.68 per panel when performing at 50% of its capacity and the cost drops to £12.65 when the factory is running at a maximum capacity of 100% (Figure 8.20). This is different from the trend observed in the static method. The cost saving in this method of production can be linked to the result of the process being driven by large static plant/equipment on the production line with minimal human intervention. The equipment has a depreciation expense spread over its economic life therefore, the more products being produced, the lesser the production process cost.

Ultimately, at maximum output, the cost of the product in a semi-automated method is approximately 82% cheaper than in the static method of production. However, this cost-saving is dependent on the volume of production and one of the challenges with the OSM market is being able to project the market in terms of demand as identified by (Lang *et al.* 2016). As the semi-automated method is capital intensive to set up, this makes it a risk for housebuilders, if demands of factory manufactured houses is considerably lower than the capacity of the production line thus, may partly explain the reason why housebuilders continue to implement non-standardised practices as discussed in Zhang *et al.* (2020) and Pasquire and Connolly (2002). In order to encourage the use of automation and advanced manufacturing practices in construction, it is important to determine the break-even point to support informed decisions by intended OSM users. Upon further analysis of the process cost with both methods of production (Figure 8.22), results show that the semi-automated method breaks even with the ad-hoc static method when the volume of production is around 12% of its capacity.

Also with the semi-automated method, at 20% volume, around 120 units of houses production annually, the process cost per panel is 35% lower than the maximum capacity in the static method which equates to 140 houses annually in the current setting (except if the production space and manpower is increased). This implies that the implementation of advanced manufacturing systems and automation in construction processes although requires a significant initial capital investment, the semi-automated method can attain a competitive price if demand is similar to the current market. Also, as previous studies by Shostak and Houghton (2008) and Griffith and Jefferys (2013) has reported the pressure on the UK housing sector to increase low-cost housing delivery to combat the housing shortage experienced, it is clear that the government have to start considering the use of the semi-automated method as a means to meet the demands of affordable homes since this method of production produces more for less price.

8.5.5 Time comparison of two units of analysis – Static vs Semi-automated production methods

Similarly, analyses have been carried out to compare the total time spent per panel in the production process and also the cycle time taken to complete the production of a unit of wall panel in both units of analysis. As the production time per panel does not depend on the volume of production, the values obtained from the previous analysis stay the same regardless of the volume of production and are plotted in Figure 8.24. It takes a total of 127 minutes to produce a unit of wall panel in the static method. The aggregated total process time in the semi-automated method is 58 minutes, i.e. a linear production without any overlapping of sub-processes (i.e. processes for each station). As stations are grouped to produce concurrently for the semi-automated method, the processing time per panel is the maximum time taken for a sub-process, which is 6.78 minutes per panel (Figure 8.24) relating to activities 5.39 and 5.47 (see Appendix C for details).

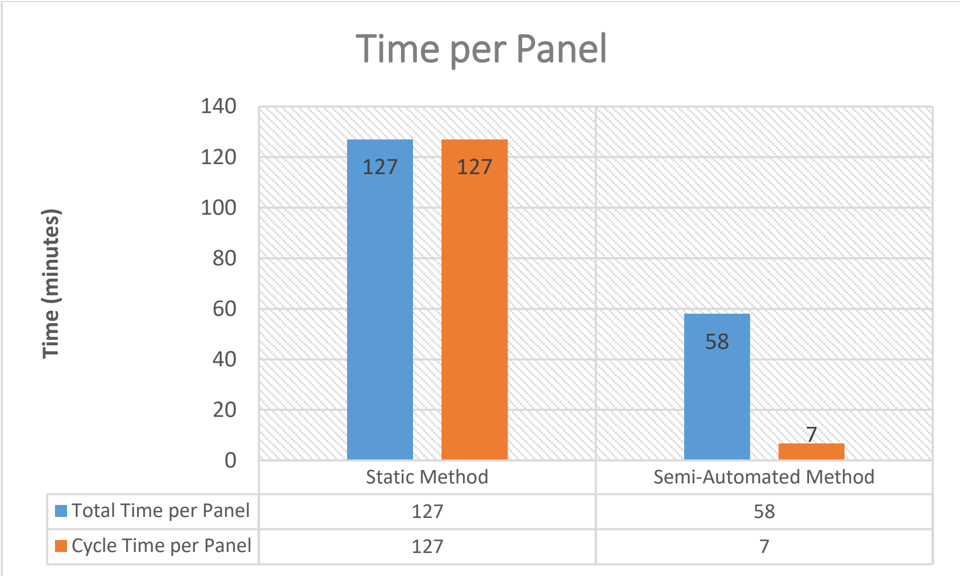


Figure 8.24: Comparison of time taken on activities performed for wall panel production.

In addition, Figure 8.25 illustrates the breakdown proportion of the time spent on various categories of activities in both units of analysis based on the value-added time and the NVA waste categorisation.

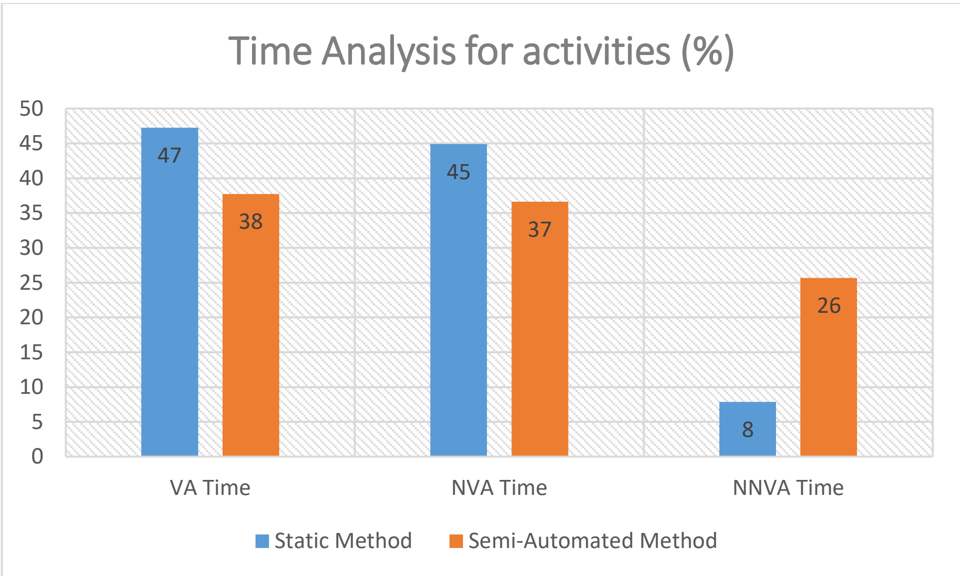


Figure 8.25: Breakdown of time taken on activities performed for wall panel production.

8.5.6 Assessing the process time based on the choice of OSM method

The results from the analysis also quantify the time taken to produce a unit of the product and the output from the units of analysis. It takes 127 minutes for a product to move through the production line in the static method while it takes 58 minutes in the semi-automated method i.e. total time per panel (Figure 8.24). However, since the workflow of the semi-automated method is structured with pre-determined stages, the process is not a finish-to-start process therefore as one the product leaves a workstation, the next product follows. This brings the cycle time per panel in the semi-automated method to 7 minutes per panel while the static method remains at 127 since the production is done in silos. Consequently, the use of automated and structured stages presents a time saving of up to 94% less than the use of the static method of production. This explains why the annual production capacity of the semi-automated method is 600 houses while the static method can only produce 140 houses in a similar arrangement (i.e. up to 77% less output in the static method). Also, as the semi-automated method automates some key activities with the use of robotic arms for the fabrication of the steel frame for wall panels, this reduces the time required significantly compared to the manual assembly method. Also, the precision is improved and less prone to error therefore rework time is mostly eliminated.

As reviewed in the previous literature chapters, although OSM has been gaining interest and increased adoption due to government intervention, the UK housing industry is still not able to meet the demands of affordable house needs and the growing population (GOV.UK 2020). Perhaps this could be linked to the persistent use of the static method of production and non-standardised practices similar to the traditional onsite method. The results have shown that the annual volume of houses produced could be increased significantly with the implementation of automation in the factory workflow. It is apparent that this is where the industry should be gearing towards, however, the demands of factory manufactured houses is a key determinant.

8.5.7 Assessing the process waste generated depending on the choice of method

In regards to the waste generated in the production process of both units of analysis. The semantic ability of the ontology helped to automatically classify the activities in the production process based on the lean principle of assessing waste in a process. Activities are classified as

VA, NVA or NNVA to meet the objective of analysing the improvements realised by moving construction activities into a controlled factory environment.

Firstly, the process waste has been broken down in terms of the cost consumed on these categories of activities. In the static method, the proportion of the process cost consumed on NVA activities remains the same regardless of the volume of production (Figure 8.19) while for the semi-automated method, the proportion of process cost for NVA activity increases with an increase in volume/output from the production line (Figure 8.21). The trend in the static method is expected since the process is labour intensive and the activities that add no value to the product development will be repeated for each product. However, the trend observed in the semi-automated method is surprising since one would expect the cost of NVA activities to reduce as the number of output increases. Upon further assessment, the increase in the proportions of the NVA activities in this method is linked to the manually performed tasks where the labour hour spent on those tasks remains the same irrespective of the volume of production. Thus, while the cost of automated activities decreases with the volume of production, the cost of the manual activities remains the same and these are the majority of the NVA tasks performed of the production line, e.g. material delivery and rework.

Comparing both units of analysis in terms of cost of waste in the process, results show that both methods have a similar percentage of NVA cost which makes up 41% of the product cost (Figure 8.23). However, the time spent on NVA activities per product is estimated as 37% for the semi-automated method and 45% for the static method (Figure 8.25). The results estimated are similar to values obtained for the traditional onsite methods reported in previous research, i.e. up to 50% non-value added activities (Liu *et al.* 2011, Nikakhtar *et al.* 2015). The result implies that not much improvement has been realised from the static method of production in terms of process waste, which is coherent with what has been suggested previously. However, even the semi-automated method contains 37% of the time spent on NVA activities which is still a considerable amount of time. As a majority of these activities are manually performed tasks, this is a good insight for offsite manufacturers in terms of analysing their processes and trying to implement better ways of performing the tasks.

8.6 Results from root cause (RC) analysis of process waste

Finally, the last stage of the data collection process was done through the focus group discussion with experts to help identify some of the root causes (RC) of the process waste generated in the production process. This is specifically relating to the NVA activities which are the main waste in the process. The activities categorised as NVA were therefore identified and the process wastes relating to these activities have been assessed. The RC analysis of the sources of the process waste is presented in Table 8.8.

Table 8.8: RC analysis for static production method NVA activities

Production Line		Waste	Issue/ Symptom	5Whys of lean				
Activity Code	Activity			Why 1	Why 2	Why 3	Why 4	Why 5 (RC)
1.4	Material delivery	Waiting	Operatives waiting for stock on the production line	Needs to be moved from store to production area	Inventory checks need to be carried out	Process too slow, causing an impact on production flow	Variable task duration	Inefficient process flow design
		Movement and Transportation	Moving and transporting materials from store to production area	Moving materials from storage	Storage not close to production line	Space management	Factory arrangement	Inefficient factory arrangement
1.5	Sorting steel sections	Waiting	Operatives sorting appropriate frames from material batch	Variable task duration	Non-balanced line	Non-balanced flow	Ill designed space to pick and store frames	Inefficient work station
		Inventory	Batches of materials waiting to be processed	Inventory needs to be completed	To ensure correct materials are being chosen	Ensure specifications are being followed	Correct drawings in place	Problem from push production method
1.8	Rework on frames	Waiting	Waiting for quality inspection to be completed slows down the following process	Not enough QI inspectors to meet production flow	Bottleneck in production flow	Bottleneck in production flow	Trades not being used to full capacity during shifts	Lack of investment in automated inspection systems
		Defect	Frame joints not properly connected	Human error from operatives such as omission	Delay in target which causes work to be rushed	Time constraints to meet customer demands	Delay and waiting in the process such as stage sign off by Q1	Inefficient flow of production with many delays
1.9	Measuring and cutting CP Board	Over-processing	Extra processing on cement board before being used	Cement Board not pre-cut from supplier	Process is slow due to dust generation	Process not automated for machine cut	Process not automated for machine cut	Process not automated for machine cut
1.10	Check alignment	Over-processing	Too many quality checks that could be avoided	Human error from operatives	Inexperienced trades carrying out the works	Re-skilling of workforce not adequately invested in	Lack of investment in people and skills training	Lack of investment in people and skills training
		Waiting	Operatives having to wait for checks to be completed to execute next process	QI inspection process too slow	Quality inspector working on other jobs	Operatives not skilled to self-check	Lack of investment in automated inspection systems	Lack of investment in automated inspection systems
1.11	Load cement board on frame	Movement	Operatives moving from material storage to line	Fork lift truck not available	Not enough CAPEX invested for more than one fork lift truck	Not forecasted correctly with new orders	Lack of understanding of Supply & Demand	Lack of understanding of Supply & Demand
1.14	Rework on joints	Defect	Wall joints not properly connected	Rushed work and quality of install not adequate	Too much of a backlog	Work shifts not planned correctly	Work not planned correctly	Inefficient process flow design

1.18	Visual inspection on bonding	Over-processing	Too many quality checks that could be avoided	Too many mistakes made previously	Ill planning of work and orders	Not enough skilled workforce	Lack of investment in people and skills training	Lack of investment in people and skills training
		Waiting	Operatives having to wait for QI to be completed	QI inspection process too slow	Quality inspector working on other jobs	Operatives not trained to self QI	Lack of investment in automated inspection systems	Lack of investment in automated inspection systems
1.19	Rework on joints	Defect	EPDM and window joints not properly fixed	Rushed and quality of install not adequate	Too much of a backlog with too many defects	Not enough skilled workforce	Lack of investment in people and skills training	Lack of investment in people and skills training
1.21	Visual Inspection on sub-frame fixing	Over-processing	Too many quality checks that could be avoided	Too many mistakes on joint fixings	Rushed work and quality of install not adequate	Too much of a backlog	Work shifts not planned correctly	Inefficient process flow design
1.22	Rework on sub frame	Defect	Sub-frame not properly fixed	Too many mistakes on joint fixings	Rushed work and quality of install not adequate	Too much of a backlog	Work shifts not planned correctly	Inefficient process flow design
1.28	Final rework on defect wall	Defect	Panel did not pass quality checklist	Rushed and quality of install not adequate	Sequencing broken down due to too many defects in previous panels	Too much of a backlog with too many defects	Not enough skilled workforce	Lack of investment in people and skills training
1.29	Load finished panels to transport trolley	Movement	The need to move completed batch from work area	Movement of workers in the factory	Large amount of work in progress (WIP)	Overproduction	Overproduction	Overproduction
1.30	Transport and load finished panels to storage	Transportation	Movement of finished panels to storage area because not ready to deliver to site	Not due to arrive onsite	Overproduction	Push manufacturing system	Push manufacturing system	Push manufacturing system

8.6.1 Assessing the RC of waste in the production process

Upon further assessment of the root cause (RC) of the process waste generated relating to the proportion of NVA activities in the manufacturing process, some constraints in the processes were revealed (Table 8.8). In regards to the static method, a large proportion of the process wastes are from activities involving waiting (W) and movement (M). For these types of waste, factory/workstation arrangements and inefficient process flow were reported as the RC of the issues. The ad-hoc nature of activities led to a non-guaranteed cycle time for each activity as no standardised sequence was adopted. Activities like Quality Inspection (QI) is a major source of delay in the static method due to operatives waiting for inspection to be completed in order to move on to the next step. Although QI is highly important to avoid scraping finished panels due to defects, it also causes waste of over-processing (P) because of the number of intermediate inspections incorporated in the process, which are too many and could perhaps be streamlined.

The workflow design of the semi-automated method addressed some of the issues of the static method. For instance, the use of a manufacturing line with dedicated stages improves the workstation arrangement and the process flow as a result. A visual inspection system displaying the position of fault screws was included in the semi-automated method manufacturing line, which enables the operators stationed in the rework to fix the fault in a speedy manner and as the accuracy of the robotic arms is around 95%, the chances of these rework being carried out is reduced. This eliminates some of the waste relating to waiting and movement in the static method.

Another major waste in the static method is due to the frequent rework required in the process and the time spent on completing these activities. In the static method, the chances of process waste due to defects, thus resulting to rework, is around 20% upon assessment. In contrast, the need for rework is projected to be below 5% in the semi-automated method according to the simulated data since key activities related to fixing the panels are automated. The efficiency of the robotic arms is estimated at 95% by the manufacturer.

However, although the semi-automated method helped in eliminating some of the process waste in the static method, both methods have some similar waste due to the push manufacturing method (batch system production) adopted. This causes inventory to be built up in the process. As the batch manufacturing method is adopted, there is a need to have a storage area in the factory to stack the work-in-progress (WIP) panels until they are ready to be moved to the construction site and the estimated waiting time is between 4-5 days in the static method. The identified process waste results in an added cost for a single unit of the product and could perhaps increase the cost of offsite production and reduce the competitiveness of OSM houses as compared with houses built on-site.

8.7 Validation of results – External validation with expert evaluation

The second stage of the validation process for the OPW ontology involved seeking domain expert evaluation of the results from the ontology. The use case project used in testing the OPW ontology is based on a case study involving the production process information of a specific company (i.e. house design and production activities used in instantiating the OPW ontology). A non-disclosure agreement has been put in place thereby necessitating some restrictions in relation to the validation process. Therefore, the experts chosen for the validation process are construction practitioners from the case study directly involved in the use case project. This consists of representatives from three different participating companies involved in the project. A total of five experts participated in the validation process, including four industry personnel working on the case project and one academic (domain expert in ontology development) to validate the semantic model structure and composition. These experts have a minimum of one year of experience working on OSM and are capable of evaluating the results from the OPW ontology (Figure 8.26).

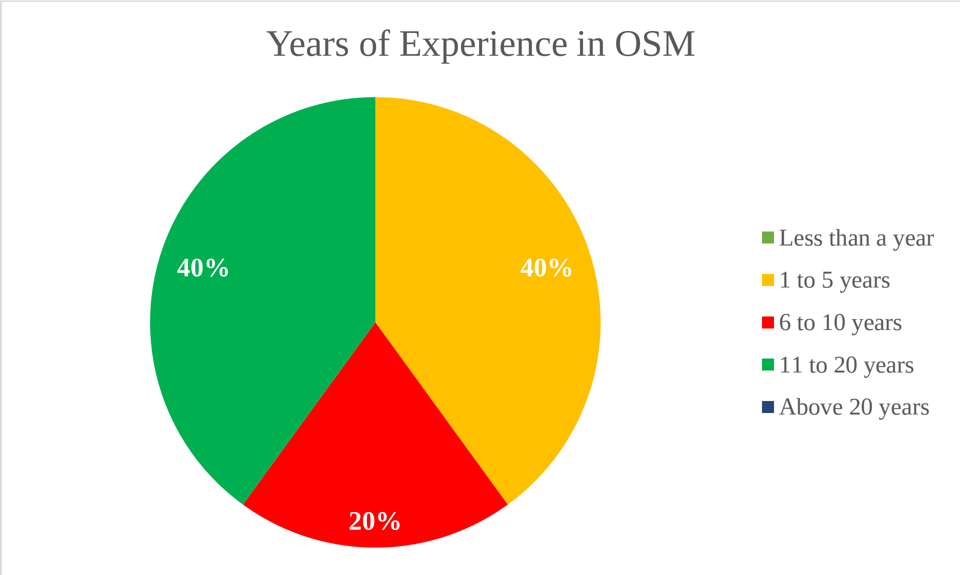


Figure 8.26: Participants years of experience with OSM

The validation process took place in form of a group discussion. The researcher first presented the findings of the research and a demo of the OPW ontology which was then followed by a question and answer session. Then the experts were given time to analyse the results from the semantic model before filling out the expert validation questionnaire based on the three assessment criteria considered relevant to the objective of the study (Appendix B). The following sections present the results from the validation process.

8.7.1 Assessment Criteria 1: Accuracy and clarity

The first criteria used in validating the OPW ontology assess how accurate the results from the ontology are and the clarity of the information retrieved from the ontology. Three questions based on a 5-point Likert scale ranging from 0 to 5 (denoting strongly disagree to strongly agree) have been used to assess the opinion of experts on the OPW ontology developed. Responses are mostly positive with a mean value of 4.4/5 regarding the reliability of the results (Figure 8.27), and a mean value of 4.6/5 in the opinion of experts on the practicality of the terminologies used (Figure 8.28) and the methodology used (Figure 8.29) in the tool.

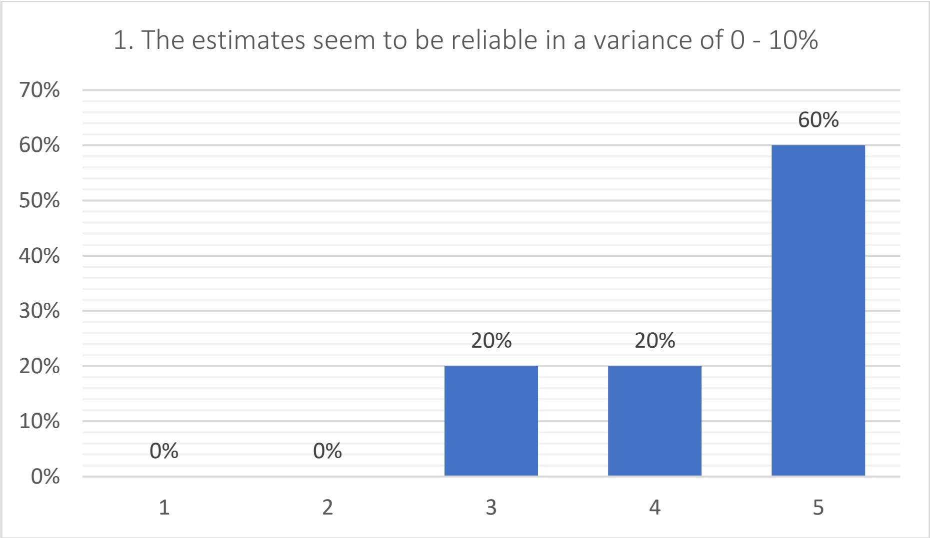


Figure 8.27: Participant responses on the reliability of results from OPW ontology

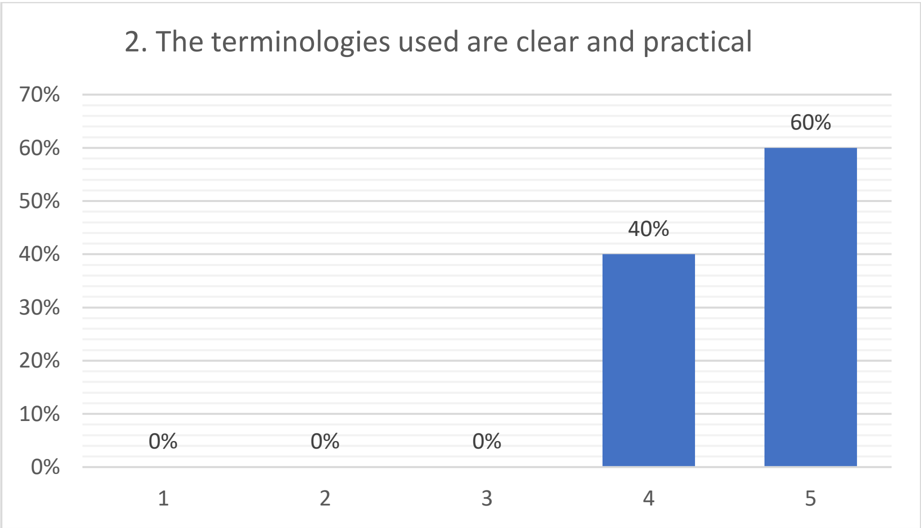


Figure 8.28: Participant responses on the practicality of terminologies used in OPW ontology

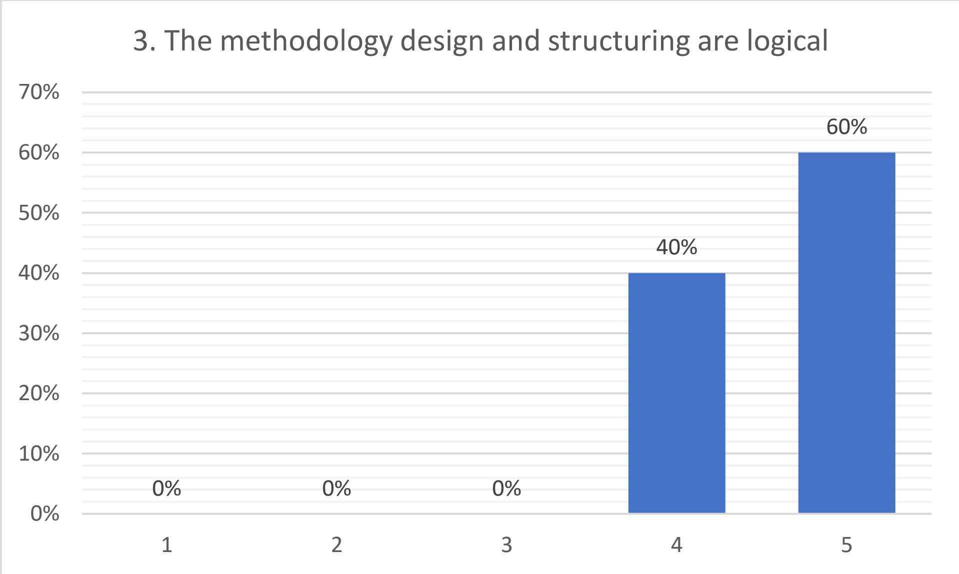


Figure 8.29: Participant responses on the methodology used in OPW ontology

8.7.2 Assessment Criteria 2: Usefulness & Adaptability

The second criteria used in validating the OPW ontology assesses the applicability of the results retrieved in addressing process design issues for OSM methods in real life and how well the results from the tool can be applied to another context. Four questions based on a 5-point Likert scale ranging from 0 to 5 (denoting strongly disagree to strongly agree) have been used to assess the opinion of experts on the OPW ontology developed. The responses to the questions asked are mostly positive with a mean value score of 4.4/5 regarding if the tool is beneficial to users (Figure 8.30) and if the scope of the tool is wide enough to suit the needs of users (Figure 8.32). Similarly, a mean value score of 4.8/5 was recorded on the opinion of experts on the applicability of the knowledge in real-life scenarios (Figure 8.31), while a mean score of 4.2 was recorded regarding the flexibility of the tool and how transferable the knowledge is to other OSM scenarios (Figure 8.33).

This indicates that overall, the experts agree on the results from the ontology and have testified that it applies to the real world and useful for assessing the performance of OSM methods.

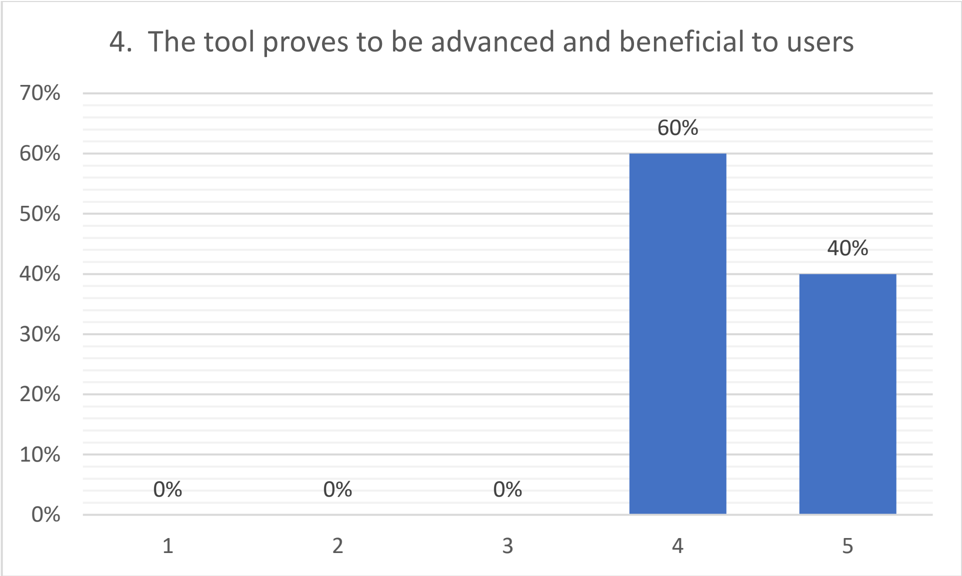


Figure 8.30: Participant responses on the usefulness of the OPW ontology

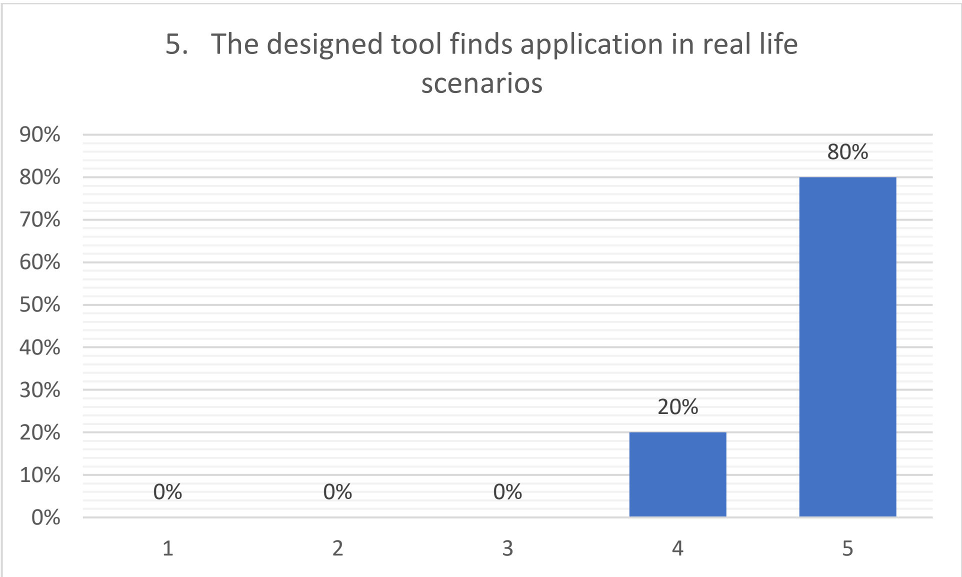


Figure 8.31: Participant responses on the applicability of the OPW ontology in real-life

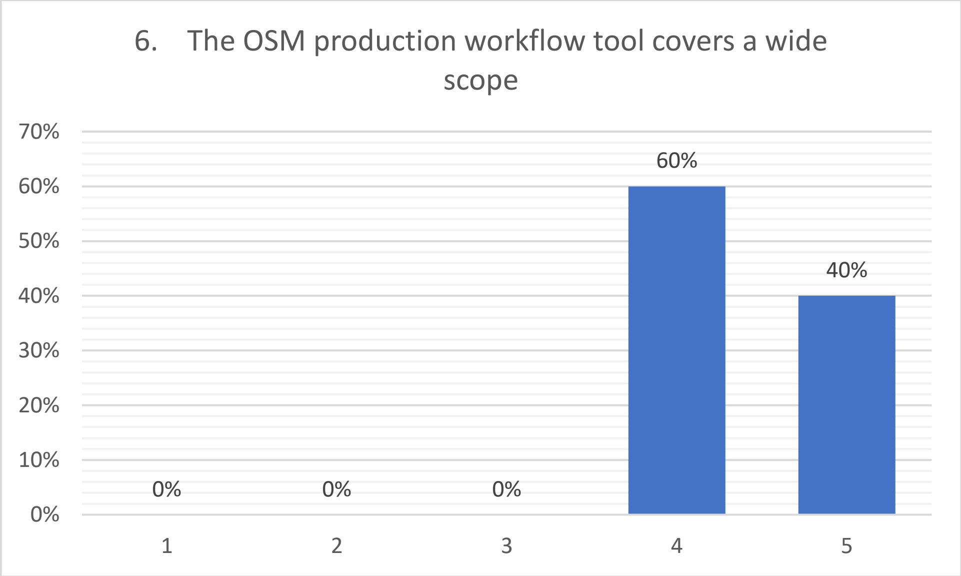


Figure 8.32: Participant responses on the scope of the OPW ontology

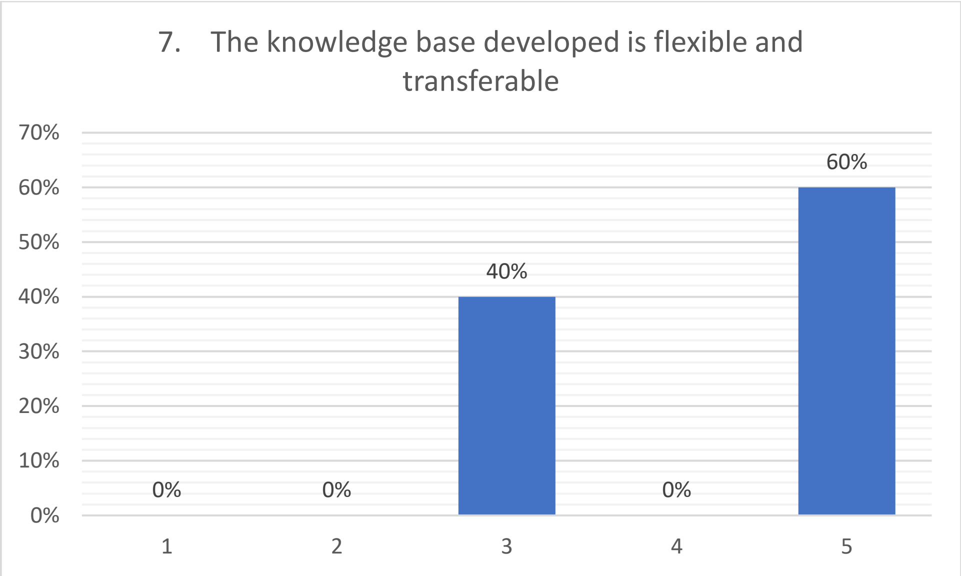


Figure 8.33: Participant responses on the flexibility of the OPW ontology

8.7.3 Assessment Criteria 3: Completeness

The third criteria used in validating the OPW ontology assesses how capable the results from the ontology are in terms of providing answers to the competency questions intended to be addressed. Two multiple-choice questions have been used to assess the opinion of experts for rating the developed tool. 80% of the experts that participated in the validation of the OPW ontology rated the results as an advanced level while the remaining 20% rated at the intermediate level (Figure 8.34). Also, there is a mixed opinion regarding the completeness of the tool in responding to the competency questions (Figure 8.35) however, non of the participant is of the opinion that the ontology requires more work in addressing the objectives stated at the specification stage of the development of the model.

However, additional feedback was given by the experts in terms of extending the OPW ontology to capture more production lines and if a user interface can be developed to allow end-users without knowledge of ontologies to query the ontology for results. This aspect will be addressed in the next chapter.

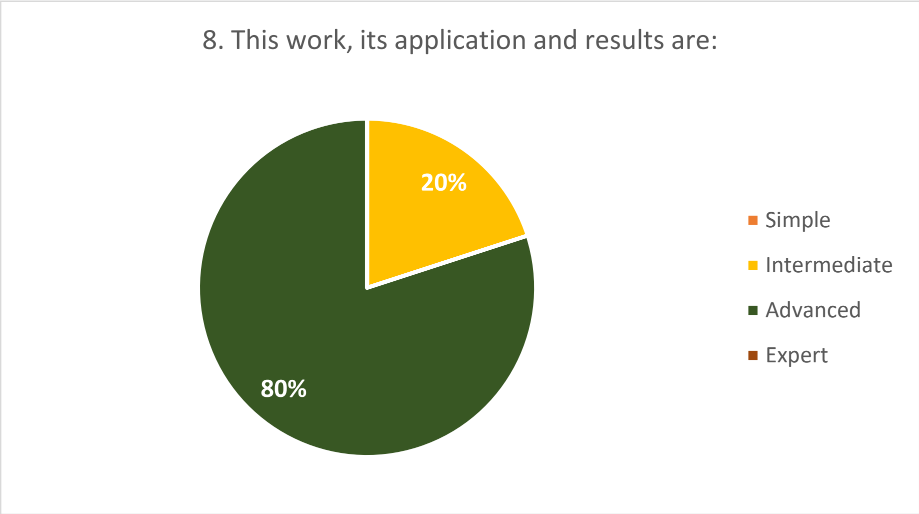


Figure 8.34: Participant opinion in rating the research work done

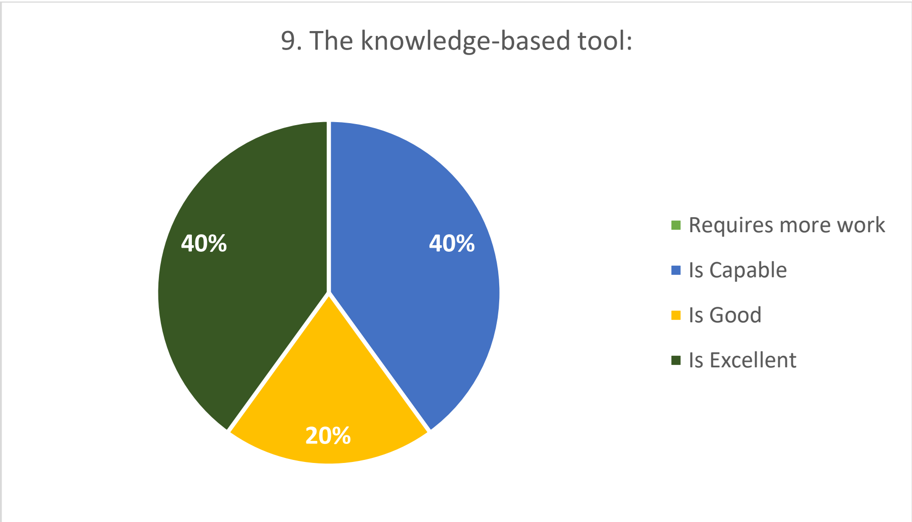


Figure 8.35: Participant opinion in rating the tool developed

8.8 Chapter Summary

This chapter described the methodology for evaluating and testing the OPW ontology developed by analysing the two units of analysis using a use-case of a 3Bbed semi-detached house type with a panelised system of OSM. The first stage presents the findings of the experimental process in OWL/SWRL following the 5 sets of competency questions expected for the OPW ontology to answer. This aspect covered the initial stage validation exercise within the context of an internal approach using the reasoning in the ontology. Pallet reasoner was used in the ontology to generate inferred results while SPARQL and SQWRL query languages were used in querying the ontology. The query results returned shows a consistent logic in the ontology as the rules run without inconsistency being discovered by the reasoner.

The results from the OPW ontology have also been further analysed to enable comparison of the values obtained for both units of analysis by comparing the cost, time and waste generated from the production process. This was followed on by an expert validation exercise, by comparing the values from the sematic model to those obtained from the judgement of an expert. Finally, a root cause analysis was implemented for determining the sources of the process waste by analysing the NVA activities in the production process.

In the next chapter, the results from the experiment and analysis will be discussed in the context of the objectives of the research, thus leading to a conclusion being reached based on the research objectives set out initially for the research. This will also be supported with some relevant recommendations.

CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

The purpose of this research work is to develop a proof-of-concept knowledge-based process analysis tool to enable the analysis and evaluation of alternative OSM production methods. The intelligent knowledge-based tool was developed using a newly constructed OSM production workflow (OPW) ontology that maps the production processes of alternative OSM methods using a bottom-up approach. To demonstrate its use, the ontology was tested using a case study comprising two units of analysis: (i) the static OSM production method and (ii) the semi-automated linear OSM production method. The research problem for this study is addressed by 5 different objectives to enable the fulfilment of the research aim. In this chapter, the main findings of the study will be discussed and conclusions will be reached on the objectives of the research work based on the results obtained from the previous chapters.

The chapter is laid out into different subsections providing discussions on how the findings from the research have addressed the objectives of the study. Also, some recommendations are provided for future work and the main contributions to knowledge are discussed along with some practical implications identified.

9.2 Main findings

This study presents a novel approach to analysing production processes for the OSM methods of construction by integrating the concept of artificial intelligence through the use of semantic knowledge-based modelling methods. The work done has been demonstrated through the newly developed OSM Production Workflow (OPW) ontology and how it can be applied for obtaining process data for assessing and evaluating alternative OSM methods and production processes. The research work also demonstrates how semantic technologies can be applied to link production data to offsite manufactured products. The OPW ontology can complement widely adopted data exchange schema used in the construction industry such as IFC. The latter focuses on geometric data exchange. Thus, the use of OPW ontology adds another dimension of knowledge relating to production workflow. The linkage between production data and building design data is a novel development as the use of ontology for modelling knowledge of the OSM domain enables integration of multiple sources of knowledge into a single data source while simultaneously capturing the reasoning of experts through the use of semantic models built in the system. The OPW ontology can be queried, monitored and improved continuously over time to capture changes due to changes in business processes, operation processes, resource redeployment and the introduction of new products. While the case in this study is based on two methods of OSM production, it is expected that house building processes will contain a level of similarities in relation to the concepts/classes, subclasses and relationships in the processes. The approach used in this study can thus be expanded to analyse other production methods, OSM systems, and processes. This will support a more informed choice of OSM methods with more quantifiable data recorded in the system in the long run.

The findings are presented in three key parts: (i) assessment of the impact of platform-independent knowledge-based systems in formalising and sharing knowledge (ii) assessments of the process benefits with various OSM method choices and (iii) assessments of the process waste in the various OSM method choices and the constraints resulting to the waste.

9.2.1 Conclusion for Objective 1

1. To examine the contemporary issues with existing knowledge of OSM and where necessary to develop theoretical definitions and classifications to support better understanding and communication in the OSM domain.

OSM as a domain has been reviewed in this study to identify issues with the knowledge in the domain to enable systematisation of such knowledge to support various tasks. Finding from the review suggests that there is a great level of misconceptions about the definition and taxonomies used in the domain. This study, therefore, proposed a definition and classification approach which combines the essential elements of existing classifications with the aim of supporting formalisation of the domain knowledge and for easy communication. The following conclusions have been drawn on this objective.

- Although OSM is defined differently by most researchers in the field, most existing definitions mostly cover the essential aspect that distinguishes OSM concept from the conventional approach. However, elements of the benefits of modularisation and standardisation are largely missing from most of the definitions.

- There is a significant lack of consensus on OSM classification approach thus leading to misunderstanding on what should be regarded as part of OSM and what is not.

Researchers tend to classify OSM based on the particular theme of their study or the purpose for which the classification is needed.

- Existing classification systems in the UK such as Uniclass and IFC are limited in terms of providing a detailed level classification for OSM required to distinguish it from construction using the traditional approach. These classification systems require further support to give coherent OSM classes and sub-classes, and also should be extended to cover missing elements and serve as a basis for a unified approach for classifying OSM.

Although an attempt has been made in this study to develop a generic definition and classification system for OSM. This is only based on high-level concepts and essentially identifies common traits and includes most distinguishable aspects from previous classification systems. The generic classification for OSM will need to be extended in order to provide a more robust system that fits for different purposes such as cost, time and risk analysis in relation to the method. The researcher believes that to fully benefit from the classification system, there is a need to adopt both top-down and bottom-up approaches. The attempt to review previous works on classifications in this study to develop the high-level OSM classification is an example of a top-down approach to integrate the existing ideas and concepts. Efforts will need to be spent on developing the classification further using a bottom-up approach as well, i.e. through capturing knowledge from individual cases of offsite (e.g. steel, timber or concrete offsite systems), as OSM knowledge is likely highly specialised and can involve a lot of localised properties that is not necessarily possible to be generalised without learning from actual cases. This approach has been adopted in this study to develop the OPW ontology by following the bottom-up approach for populating the classification system with low-level concepts using a case study.

9.2.2 Conclusion for Objective 2

2. To apply industry-based approaches for analysing manufacturing processes and determine a suitable approach for evaluating the performance of competing OSM processes.

The study looked into assessing suitable methods for analysing processes and the available tools and techniques used in the manufacturing sector with the aim of learning from this sector on how OSM methods shall be analysed to meet the manufacturing requirements. In response, this study has identified lean-based techniques such as ABC, VSA and 5Whys as suitable methods for assessing manufacturing processes of OSM. In addition, the techniques have been applied in analysing the production process of two OSM methods using a case study. The following conclusions have been drawn from the analysis.

- It has been determined in this study that the value system analysis (VSA) and 5Whys methods are the best suited in analysing the activities of the various OSM methods for the developed tool given the ease at which these methods can be implemented by non-lean experts in analysing the manufacturing processes. Also, the expertise and amount of data required in implementing these methods are fairly accessible thus making the results of the analysis traceable. Industry practitioners will welcome those intuitive tools when a user interface is further developed where non-expert interaction with the tool can be done.

- The study concludes that the activity-based costing (ABC) method is better suited for analysis manufacturing-based processes involving the use of large static tools and automation such as the OSM method, compared to the resources-based method widely adopted in the construction industry. This is because ABC allows businesses to take a process view of their processes by enabling the breakdown of cost and time into categories based on the value-added to the process. However, as identified in previous studies, one of the criticism is that this method is data reliant and tedious to undertake due to the high volume of data for processing, the use of artificial intelligence (AI) such as expert systems for automating the reasoning process of an expert offers a means of benefiting from the accuracy of this method.

9.2.3 Conclusion for Objective 3

3. To investigate the use of knowledge acquisition and modelling methods and languages and determine the best-suited approach to support formalisation and systematisation of OSM knowledge in a tool to support objective (2).

In response to this research objective, a critical review of knowledge-based modelling methods and languages has been completed in this study and the use of OWL and SWRL has been selected for the development of the OPW ontology. The conclusions are drawn from the implementation of the knowledge using these methods are outlined as follows.

- It has been demonstrated in this study that knowledge-based engineering through ontology knowledge modelling is capable of handling data of multiple forms. Also, OSM knowledge has been systemised in the development of a production workflow analysis tool. This method is efficient and fast in enabling the retrieval of quantitative data of OSM processes required for decision support. One of the benefits of the semantic model is the speed at which the reasoning takes place. For instance, ABC, as a costing method used in this study, has been criticised as being time-consuming and tedious due to the amount of data needed for generating cost information. The use of the tool automates the estimation through the use of a reasoning facility in the ontology, which has the capability in handling both production and design-related data. It is done through formalising the knowledge of ABC for automated reasoning. In addition, the classification function in the ontology allows new knowledge to be generated such as classifying activities into VA, NVA and NNVA categories to identify non-value added activities. The reasoning process in the OPW ontology using OWL and SWRL takes an average of 60 seconds when the reasoner is invoked and around 10 seconds to return results when queried. This is very efficient when compared to manual methods to estimate costs.

- The use of ontology for knowledge modelling has been demonstrated to be efficient in knowledge capture and sharing, and is capable of giving intelligent context-specific data, which would be useful for process design analysis in the OSM domain. The OPW ontology developed in this study has been able to link meta-data in relation to time, cost, resources, and sequences to model the production workflow of two different OSM methods. The experimental results from the use case of a typical factory-manufactured house have been used in obtaining insight on the sources of process waste by breaking down the process data into categories of value-adding in the process. As identified in the previous literature studies, this type of knowledge is not readily available in a BIM model and the data needed to support this analysis can prove tedious to gather as it involves data from different sources. The result from the study thus proves the capability of knowledge engineering systems in handling a high volume of data needed. This builds further on previous attempts by researchers (Staub-french *et al.* 2002, Abanda *et al.* 2011, 2017, Nepal *et al.* 2013, Lee *et al.* 2014) in the construction domain to develop platform-independent knowledge that can be easily integrated to obtain rich data that are not restricted for use by particular software as the knowledge in the ontology can be converted into RDF and XML data suitable for use in many platforms.

The OPW ontology has demonstrated that it is flexible and adaptable as the knowledge modelled in the ontology has been applied to evaluate alternative production methods using cases of OSM projects. The results returned demonstrate the capability of the ontology in facilitating the comparison of processes. The knowledge can be extended to capture other methods of production, types of products and other assessment matrices since ontology can be reused and recycled, which will also contribute to structured knowledge sharing in the construction domain.

9.2.4 Conclusion for Objective 4

4. To assess the performance of competing OSM production methods using the tool developed based on the outcome of objective (2) using an example of methods involving non-standardised and standardised processes.

Research objective 4 relates to assessing the performance of two alternative OSM methods by examining the data generated from the developed tool. The following conclusions have been drawn based on two units of analysis in this study:

- The study concludes that moving the production of houses offsite using the static method does not provide a significant improvement of the process in terms of waste. 45% of the production time in the static method is spent on NVA activities which are close to the 50% NVA time reported for the traditional onsite method. This is as a result of the static method of OSM being a labour-intensive process and the majority of the activities performed are manual in nature therefore the output of the production line is driven by the productivity of the workers.

- The automation of key activities in the production process and structured workflow (through the semi-automated method) offers a time saving of up to 94% more than if the same task is done manually in the same environment (the use of the static method of production). Consequently, the introduction of automation of key activities in the production process allows up to 77% more output (productivity) from the factory while also reducing rework on products as the precision is improved by using machines that are less prone to error.

- Based on similar factory conditions, the process cost of an OSM product is 82% less via the semi-automated method than the static method of production, at maximum production capacity. The semi-automated method breaks even with the ad-hoc static method at around 12% production capacity.

- The process cost of the semi-automated method alone (excluding fixed cost) per product is about 35% lower than that of the static production method on average. Thus, the implementation of advanced manufacturing systems and automation (e.g. semi-automated method) in OSM processes can create saving if the initial fixed cost investment, e.g. on plant and facilities can be offset by the saving in process cost depending on the volume of works.

9.2.5 Conclusion for Objective 5

5. To investigate the constraints in the performance of the OSM methods from objective (4) and determine the causes of these constraints so as to support informed decision-making and continuous improvements.

Another objective of the research relates to evaluating some of the constraints in the factory housebuilding process and how these can be improved. The breakdown of the time spent on production revealed that there is still a considerable amount of NVA activities embedded in the factory production process despite the industry claims on OSM being a leaner approach than the onsite method. The results generated from the OPW ontology have been further analysed using the lean 5Whys method to reveal some of the issues and constraints in the current practice with the OSM methods and the conclusions drawn are as follows.

- It is discovered in this study that a large proportion of the process waste in the static method of OSM is a result of waiting and non-productive movement of resources within the factory environment. The major constraints leading to this process waste is the factory workstation arrangement and inefficient process flow resulting from the ad-hoc nature of activities. There is no guaranteed cycle time for each activity and no standardised sequence. Therefore, the nature of the production method leads to the process waste.

- Quality Inspection (QI) although is encouraged as a good practice to be embedded in manufacturing and construction processes, this activity contributes to process waste from over-processing and is a major source of delay in the process, especially in the static method of production. In the static production method, the number of intermediate inspections to mitigate the risk of scrapping defective products is higher and this contributes to the proportion of NVA cost and time spent on these activities. Having better precision and increasing the quality of the work at the first attempt can be used to mitigate this constraint. Therefore, offsite manufacturers should look into automating the key tasks that are prone to rework as this leads to a 15% less chance of rework in the process thus saving time and cost of processing.

- The use of batch production systems in OSM methods is a major source of process waste due to inventory built up in the process. It is discovered that finished products (i.e. completed modules) can be stored up to 4-5 days in the factory before being transported to construction sites. Thus, a lot of waiting and storage are incurred in OSM processes in both structured and non-structured workflow processes leading to wasted cost. This could consequently increase the cost of offsite production and reduce the competitiveness of OSM methods as compared with traditional methods built on-site. Considerations need to be made in the OSM domain for integrating manufacturing concepts such as 'one-piece flow' and 'just-in-time' (JIT) delivery to reduce NVA cost further.

9.3 Research contribution and practical implication

The main contributions of the research output are summarised according to the contributions to existing knowledge and practice in the following sections.

9.3.1 Contribution of research to knowledge

1. The output of this research contributes to the body of literature on offsite concepts, definition and classification, through the generic classification framework developed for the OSM domain knowledge and provides a means of supporting clear

communication and knowledge sharing in the domain. The developed generic classification system method helps to minimise identified issues relating to fragmentation of OSM knowledge due to the various conflicting understanding and duplications of concepts in the domain. The generic classification system thus facilitates communication in the domain. The classification system can be adapted by expanding the high-level categories and populating these with related subclasses to suit other purposes such as populating product and process concepts to suit cost and time estimation, development of knowledge systems through the re-use of shared conceptualisation, etc.

2. The methodology and approach used in this research by integrating the value system analysis (VSA) and activity-based costing (ABC) methods for analysing a process is a novel approach for evaluating and optimising the performance of a manufacturing process. This approach is useful in generating detailed process-related data to support cost/time-based analysis of OSM processes and opens a new vista for accurately generating detailed level process data that allows a process view of various processes thus can be adopted in evaluating future case studies on OSM methods.

3. The results from the analysis have also contributed to existing knowledge on the root causes of process waste in competing methods of OSM by revealing some key aspects that need to be considered in order to obtain a good performance of OSM processes. Also, the result from the study provides quantitative evidence of the performance of competing structured and non-structured OSM methods thus contributing to knowledge on the comparison of the output of these methods.

4. The knowledge structure and rules integrated into the OPW ontology have been published on the web for knowledge sharing and re-use in the domain. This is a major contribution that enables researchers in the domain to reuse existing classification and terminology while expanding further on some concepts where necessary. This contributes to the ultimate goal of formalising knowledge to enable the realisation of the next-generation web – the semantic web with linked data.

9.3.2 Contribution of research to practice

1. In this study, a platform-independent semantically rich and formal representation of OSM knowledge (including its systems, methods, processes, and products) was developed. The approach used in this tool and detailed breakdown of data generated is novel in that it allows easy application of the ABC methodology in the construction sector different from the RBC method commonly used. Therefore, the OPW ontology enables construction professionals to take a process view of their approaches by benefiting from the rich and more comprehensive data involved with the use of ABC that would have otherwise been challenging or difficult to model.

2. The methodology used in this research by integrating the value system analysis (VSA) and activity-based costing (ABC) methods can be adapted by existing and prospective OSM organisations as an optimisation approach in assessing their processes and determining areas of possible improvements. This is particularly useful at the product development (production and manufacturing stage) phase to gather detailed information on the performance and lessons learnt for continuous improvement (CI).

3. This tool developed is flexible and can be adapted by OSM housebuilders for developing a company-specific tool that captures their specific business processes to support the evaluation of their processes and to promote continuous improvement. Achieving these could therefore increase the uptake of OSM in the construction industry and collectively, thus taking full advantage of its benefits.

4. The use of a platform-independent system and the inclusion of semantic web technologies such as Linked Data (LD) and Web Ontology Language (OWL) models has proven to better address the challenges of interoperability and unambiguous knowledge systematisation. Therefore, existing processes used in the construction industry such as Building Information Modelling (BIM) can benefit from real-life data input of manufacturing processes of building elements through the knowledge integration using the OPW ontology. This will be a major advantage in helping offsite housebuilders to design out waste from their processes.

9.4 Research challenges and limitations

In this study, a bottom-up approach to data collection was adopted due to the need for capturing context-specific data on OSM processes. Despite the strength of the case study method in the exploration of complex issues in their real-life context, some weaknesses have been associated with this method. Case studies are traditionally perceived as a less desirable method compared to surveys or experimental methods (Schell 1992, Yin 2009) due to insufficient rigour and non-systematic procedural approach making them more prone to bias and subjectivity. Another major barrier and criticism of using the case study method is in the sense of its validity when it comes to generalising results which is particularly common in the case of a single case (Schell 1992, Yin 2009). Therefore, the limitations of the methods and techniques used in relation to the research questions are identified. The research is limited by the following factors:

- **Sample size – single case study design:** only one case study was used in developing the ontology and this also only applies to the steel frame offsite solution. Therefore, the developed knowledge model may not fit well for other solutions such as timber frame or concrete buildings as the methods and techniques involved may vary. However, this can be resolved by expanding the ontology to capture new classes, subclasses, instances and relationships that will allow for a different product design or scenario to be computed.

- **Generalisation:** since the case study is based on the steel frame offsite solution, the knowledge modelled in the OPW ontology only covers products and processes involving light steel frame (LSF) OSM. This means that the results from the ontology may only be generalizable to similar cases of steel OSM. However, as the essence of the study is to establish a proof-of-concept, this is not considered a significant limitation because the essence of designing case studies is to optimise understanding of a phenomenon rather than the focus on generalising beyond (Denzin and Lincoln 2000). Also, since analytical generalisation is what is intended for in the research design, generalising the unique set of results from this study to a broader theory is possible thus defining other aspects/domains in which the result can be generalised is possible (Yin 2009). It is believed that OSM products and processes for house building may be similar in some ways such that it is possible to transfer the knowledge to other OSM types such as those using different materials such as timber or concrete.

- **Computational method:** The ontology development language used also has its limitations. The expressivity of OWL-DL is limited and may not be able to cover the level of reasoning required for some tasks, such as expressing advanced mathematical concepts in cost and time estimation. However, this drawback has been addressed by extending the ontology to include some SWRL rules.

9.5 Recommendations and Future work

9.5.1 Research Objective 6 (Recommendation)

6. To validate the developed tool and provide guidance/recommendations on the use and application

As part of this research objective, some recommendations have been proposed for future work by domain experts. The OPW has been validated using a two-staged validation method involving an internal/logic validation and an external/expert validation approach. the ontology has been tested based on the set of competency questions laid out for the ontology to answer and the model has been successful in retrieving data in response to the questions. Also, the OPW ontology has been validated based on 3 major sets of criteria set by experts. The opinions of experts have been consistent and positive about the outputs generated from the developed tool. The following recommendations have been provided on the tool developed by the experts that participated in the validation process.

- Although the OPW ontology captures the required knowledge for performing different analyses and estimations on OSM processes, the current limitation of the ontology is the fact that the knowledge is collected from a limited number of production lines. Therefore, it is recommended for future work that the knowledge base shall be expanded to incorporate other production workflow designs to enable more choices in production workflow designs.

- For future work, considerations should be given to the expansion of OPW ontology to cover both the design and assembly stages and processes of a product. This will enable a more robust scenario-based assessment by alternating variables in the various stages to determine the impact of changes on various methods.

- It is recommended that the work is taken further to develop a user interface where the OPW ontology can be queried by non-ontology experts in order to support wider use of OPW by industry participants. Making a user-friendly interface would require the additional need for both an API to input parameters in the ontology to enable evaluation, as well as retrieving useful information out. It can also enable users to generate reports from the system such as how the costs are made up, the makeup of the VA, NVA and NNVA for the various rates of production, number of personnel at each production %, etc.

- Lastly, for future work, the OPW ontology could be expanded to include the knowledge required for the assessment of other process assessment metrics such as life-cycle cost and carbon footprint. This is particularly important to allow a more holistic judgment of the performance of alternative OSM methods.

REFERENCES

AAQS, 2016. *Guide to Elemental Cost Estimating & Analysis for Building Works 2016*. Second.

Abanda, F.H., Tah, J.H.M., and Cheung, F.K.T., 2017. BIM in off-site manufacturing for buildings. *Journal of Building Engineering*, 14 (September), 89–102.

Abanda, F.H., Taj, J.H.M., Pettang, C., and Manjia, M.B., 2011. An ontology-driven building construction labour cost estimation in Cameroon. *Journal of Information Technology in Construction (ITcon)*, 16, 617–634.

Abdullah, M.. and Egbu, C.., 2010. Selection criteria frameword for choosing industrialized building systems for housing projects. *In*: C. Egbu, ed. *Procs 26th Annual ARCOM Conference, 6-8 September 2010*. Leeds: Association of Researchers in Construction Management.

Abdullah, M.R. and Egbu, C.O., 2009. *Industrialised building system in Malaysia: Issues for research in a changing financial and property market*. Proceedings of the BUHU 9th International Post Graduate Research Conference.

Abdulmalek, F.A. and Rajgopal, J., 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of Production Economics*, 107 (1), 223–236.

Abosoad, H., Underwood, J., and Boreny, S., 2009. Towards an Information System Representation of off Site Manufacturing (OSM) in Facilitating the Virtual Prototyping of Housing Design. *In*: *9th International Postgraduate Research Conference (IPGRC)', University of Salford, Salford, UK*. 509–520.

Adamides, E.D. and Karacapilidis, N., 2006. A knowledge centred framework for collaborative business process modelling. *Business Process Management Journal*, 12 (5), 557–575.

Adeli, H. and Wu, M., 1998. Regularization neural network for construction cost estimation. *Journal of Construction Engineering and Management*, 124 (1), 18–23.

Afsari, K. and Eastman, C.M., 2016. A Comparison of Construction Classification Systems Used for Classifying Building Product Models. *In*: *52nd ASC Annual International Conference Proceedings*. Associated Schools of Construction.

Aguilar-Savén, R.S., 2004. Business process modelling: Review and framework. *International Journal of Production Economics*, 90 (2), 129–149.

Ahmed, V., Opoku, A., and Aziz, Z., 2016. *Research Methodology in the Built Environment: A selection of case studies*. New York: Routledge.

Akasah, Z.A., Amirudin, R., and Alias, M., 2010. Maintenance management process model for school buildings: An application of IDEF 0 modelling methodology . *Australian Journal of Civil Engineering*, 8 (1), 1–12.

Akintoye, A. and Fitzgerald, E., 2000. A survey of current cost estimating practices in the UK A. *Construction Management & Economics*, 18, 161–172.

Akyol, D.E., Tuncel, G., and Bayhan, G.M., 2007. An Analysis of Activity-Based Costing in a Manufacturing System. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, 1 (11), 1040–1043.

Aldridge, G., Pasquire, C., Gibb, A., and Blismas, N., 2001. Methods for Measuring the "Unmeasurable": Evaluating the Benefits of Pre-Assembly and Standardization in Construction. *In*: *17th Annual ARCOM Conference, 5-7 September 2001, University of Salford. Association of Researchers in Construction Management*. 311–9.

Almeida, A. and Cunha, J., 2017. The implementation of an Activity-Based Costing (ABC) system in a manufacturing company. *Procedia Manufacturing*, 13, 932–939.

Alonso, R., Borras, M., Koppelaar, R.H.E.M., Lodigiani, A., Loscos, E., and Yöntem, E., 2019. SPHERE: BIM Digital Twin Platform. *Proceedings*, 20 (1), 9.

Arafa, M. and Alqedra, M., 2011. Early Stage Cost Estimation of Building Construction Projects using Artificial Neural Networks. *Journal of Artificial Intelligence*, 4 (1), 63–75.

Arbizzani, E. and Civiero, P., 2013. Technical solutions and industrialised construction systems for advanced sustainable buildings. *In*: *PORTUGAL SB13 - CONTRIBUTION OF SUSTAINABLE BUILDING TO MEET EU 20-20-20 TARGETS*. 371–378.

Arditi, D. and Mochtar, K., 2000. Trends in productivity improvement in the US construction industry. *Construction Management & Economics*, 18 (1), 15–27.

Arif, M. and Egbu, C., 2010. Making a case for offsite construction in Making a case for offsite construction in China. *Engineering Construction & Architectural Management*, 17 (6), 536–548.

Assaf, S.A. and Al-Hejji, S., 2006. Causes of delay in large construction projects. *International Journal of Project Management*, 24, 349–357.

Awuzie, B. and McDermott, P., 2017. An abductive approach to qualitative built environment research: A viable system methodological exposé. *Qualitative Research Journal*, 17 (4), 356–372.

Ayachit, A.C., Attarde, P.M., and Kulkarni, S., 2014. Activity Based Costing in Construction. *International Journal of Advanced Engineering Research and Studies*, 4 (1), 9–14.

Ayinla, K.O., Cheung, F., and Tawil, A.R., 2019. Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system. *Construction Innovation*, 20 (2), 223–246.

Badir, Y.F., Kadir, M.R.A., and Hashim, A.H., 2002. Industrialized Building Systems Construction in Malaysia. *Journal of Architectural Engineering*, 8 (1).

Baghchesaraei, A., Kaptan, M.V., and Baghchesaraei, O.R., 2015. Using prefabrication systems in building construction. *International Journal of Applied Engineering Research*, 10 (24), 44258–44262.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., and Wong, I., 2006. Designing out waste in high-rise residential buildings : analysis of precasting and methods and traditional construction. *In*: *The International Conference on Asia-European Sustainable Urban Development*. Chongqing, China.

Baloi, D., 2003. Sustainable construction: Challenges And Opportunities. *In*: *19th Annual ARCOM Conference*. 289–97.

Barber, K.D., Dewhurst, F.W., Burns, R.L.D.H., and Rogers, J.B.B., 2003. Business-process modelling and simulation for manufacturing management: A practical way forward. *Business Process Management Journal*, 9 (4), 527–542.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertran, N., and Brown, S.V., 2017. *Reinventing construction through a productivity revolution*.

Bari, N.A.A., Abdullah, N.A., Yusuff, R., Ismail, N., and Jaapar, A., 2012. Environmental Awareness and Benefits of Industrialized Building Systems (IBS). *Procedia - Social and Behavioral Sciences*, 50 (July), 392–404.

Baxter, P. and Jack, S., 1990. Qualitative case study methodology: study design and implementation for novice researchers. *The Qualitative Report*, 13 (4), 544–559.

Baxter, P. and Jack, S., 2008. Qualitative Case Study Methodology : Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13 (4), 544–559.

Ben-Arieh, D. and Qian, L., 2003. Activity-based cost management for design and development stage. *International Journal of Production Economics*, 83 (2), 169–183.

Bertelsen, S., 2005. Modularization – a third approach to making construction lean? *In*: *13th annual conference in the International Group for Lean Construction*. Sydney, Australia, 1–11.

Blismas, N., Pasquire, C., and Gibb, A., 2006a. Bene t evaluation for o ff-site production in construction. *Construction Management & Economics*, 24 (2), 121–130.

Blismas, N., Pasquire, C., and Gibb, A., 2006b. Benefit evaluation for off - site production in construction. *Construction Management and Economics*, 24 (2), 121–130.

Blismas, N. and Wakefield, R., 2007. Drivers constraints and the future of off-site manufacture in Australia. *Construction Innovation Special Edition*.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114 (January), 103179.

Bottom, D., Gann, D., Groak, S., and Meikle, J., 1996. *Innovation in Japanese Prefabricated House-Building Industries: Department of Trade and Industry Overseas Science and Technology Expert Mission Visit Report*. Construction Industry Research and Information Association.

Brockmans, S., Haase, P., Hitzler, P., and Studer, R., 2006. A Metamodel and UML Profile for Rule-extended OWL DL Ontologies. *In*: Y. Sure and J. Domingue, eds. *ESWC 2006*. Berlin Heidelberg: Springer-Verlag, 303–316.

Bryman, A., 2012. *Social Research Methods*. 4th editio. New York: Oxford University Press.

buildingSMART, 2016. IFC4 Add2 - Addendum 2 [online]. *buildingSMART International Ltd.* Available from: http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/ [Accessed 2 Jan 2019].

Cabinet Office, 2011. *Government Construction Strategy*. London.

Caputo, A.C. and Pelagagge, P.M., 2005. Parametric and Neural Methods for Cost Estimation

Of Process Vessels. *In*: *18th International Congress of Mechanical Engineering*.

Carli, G. and Canavari, M., 2013. Introducing Direct Costing and Activity based Costing in a Farm Management System: A Conceptual Model. *Procedia Technology*, 8 (Haicta), 397–405.

Carr, R.I., 1989. Cost - Estimating Principles. *Journal of Construction Engineering and Management*.

Chan, C.W. and Johnstonb, M., 1996. Knowledge modelling for constructing an expert system to support reforestation decisions. *Knowledge-Based Systems*, 9, 41–59.

Chan, E.H.W. and Tse, R.Y.C., 2003. Cultural Considerations in Cultural Considerations in International Construction Contracts. *Journal of Construction Engineering and Management*, 129 (4), 375–381.

Chau, K.W., 1995. The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs : empirical evidence from Hong Kong. *Construction Management and Economics*, 13 (1), 15–21.

Chau, K.W. and Anson, M., 2002. A Knowledge-Based System for Constr uction Site Level Facilities Layout, 2358, 393–402.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010a. Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction*, 19 (2), 235–244.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010b. Automation in Construction Decision support for construction method selection in concrete buildings : Prefabrication adoption and optimization. *Automation in Construction*, 19, 665–667.

Cheng-Leong, A., Pheng, K.L., and Leng, G.R.K., 1999. IDEF: A comprehensive modelling methodology for the development of manufacturing enterprise systems. *International Journal of Production Research*, 37 (17), 3839–3858.

Cheung, F.K.T., Kurul, E., and Oti, A.H., 2016. A case study of hybrid strategies to create value for a contracting business in the education sector in England and Wales. *Construction Management and Economics*, 34 (4–5), 335–352.

Chevallier, Z., Finance, B., and Boulakia, B.C., 2020. A reference architecture for smart building digital twin. *CEUR Workshop Proceedings*, 2615, 1–12.

Chiang, Y.H., Hon-Wan Chan, E., and Ka-Leung Lok, L., 2006. Prefabrication and barriers to entry-a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, 30 (3), 482–499.

Chou, J.-S., Yang, I.-T., and Chong, W.K., 2009. Probabilistic simulation for developing likelihood distribution of engineering project cost. *Automation in Construction*, 18 (August), 570–577.

Chou, J.S., 2011. Cost simulation in an item-based project involving construction engineering and management. *International Journal of Project Management*, 29 (6), 706–717.

Corcho, O., Fernandez-Lopez, M., and Gomez-Perez, A., 2003. Methodologies , tools and languages for building ontologies . Where is their meeting point ? *Data & Knowledge Engineering*, 46, 41–64.

Corcho, O. and Gómez-Pérez, A., 2000a. Evaluating Knowledge Representation and Reasoning Capabilities of Ontology Specification Languages. *In*: *Applications of Ontologies and Problem Solving Methods 14th European Conference on Artificial Intelligence (ECAI'00)*. 3.1 – 3.9.

Corcho, O. and Gómez-Pérez, A., 2000b. A roadmap to ontology specification languages. *In*: R. Dieng and O. Corby, eds. *EKAW*. Berlin Heidelberg: Springer-Verlag Berlin, 80–96.

Cox, R.F., Issa, R.R.A., Asce, M., and Ahrens, D., 2003. Management ' s Perception of Key Performance Indicators for Construction. *Journal of Construction Engineering & Management*, 129 (2), 142–151.

Creswell, J.W., 2009. *Research Design_ Qualitative, Quantitative, and Mixed Methods Approaches*. Third edit. London: SAGE Publications.

Cutting-Decelle, A.-F., Young, B.I., Das, B.P., Case, K., Rahimifard, S., Anumba, C.J., and Bouchlaghem, D.M., 2007. A Review of Approaches to Supply Chain Communications: From Manufacturing to Construction. *ITcon*, 12, 73–102.

Datta, P.P. and Roy, R., 2009. Cost Modelling Techniques for Availability Type Service Support Contracts : a Literature Review and Empirical Study. *In*: *Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2)*. 216.

Dave, B., Koskela, L., and Kiviniemi, A., 2013. *Implementing Lean in construction: Lean construction and BIM*. CIRIA Guide C725 - Construction Industry Research and Information Association. London: CIRIA.

Delany, S., 2015. Classification [online]. *National Building Specification (NBS) BIM Toolkit*. Available from: https://toolkit.thenbs.com/articles/classification#classificationtables [Accessed 4 Feb 2019].

Denzin, N.K. and Lincoln, Y.S., 2000. *Handbook of Qualitative Research*. Second. London: SAGE Publications.

Djurić, D., Gašević, D., and Devedžić, V., 2005. Ontology modeling and MDA. *Journal of Object Technology*, 4 (1), 109–128.

Doomun, R. and Jungum, N.V., 2008. Business process modelling, simulation and reengineering: Call centres. *Business Process Management Journal*, 14 (6), 838–848.

Doran, D. and Giannakis, M., 2011. An examination of a modular supply chain : a construction sector perspective. *An International Journal of Supply Chain Management*, 16 (4), 260–270.

Dubois, A. and Gadde, L.-E., 1999. Case studies in business market research: An abductive approach. *In*: M. Damien and C. Horan, eds. *Proceedings of the 15th Annual IMP Conference*. Dublin, 1–20.

Duncheva, T. and Bradley, F.F., 2016. A comparison between Volumetric Timber Manufacturing Strategies in the UK and mainland Europe. *In*: *2016 Modular and Offsite Construction (MOC) Summit*. Edmonton, Alberta, Canada, 10–17.

Durdyev, S. and Mbachu, J., 2011. On-site Labour Productivity of New Zealand Construction Industry : Key Constraints and Improvement Measures. *Australasian Journal of Construction Economics and Building*, 11 (3), 18–33.

Duverlie, P. and Castelain, J.M., 1999. Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method. *The International Journal of Advanced Manufacturing Technology*, 15, 895–906.

Eastman, C.M. and Sacks, R., 2008. Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134 (7), 517–526.

Egan, J., 1998. *Rethinking Construction*. The Report of the Construction Task Force.

El-Diraby, T.A., Lima, C., and Feis, B., 2005. Domain Taxonomy for Construction Concepts : Toward a Formal Ontology for Construction Knowledge. *JOURNAL OF COMPUTING*

IN CIVIL ENGINEERING, 19 (4), 394–406.

El-Gohary, N.M. and El-Diraby, T.E., 2015. Domain Ontology for Processes in Infrastructure and Construction. *Journal of Construction Engineering and Management ASCE*, (January).

Elhag, T.M.S. and Boussabaine, A.H., 1998. An Artificial Neural System for Cost Estimation Of Construction Projects. *In*: *14th Annual ARCOM Conference*. 219–226.

Elnaas, E., 2014. The Decision To Use Off-Site Manufacturing (OSM) Systems for House Building Projects in the UK. University of Brighton. UK.

Elo, S. and Kyngäs, H., 2008. The qualitative content analysis process. *Journal of Advanced Nursing*, 62 (1), 107–115.

Enshassi, A., Mohamed, S., and Abushaban, S., 2009. Factors affecting the performance of construction projects in the Gaza strip. *Journal of Civil Engineering and Management*, 15 (2), 269–280.

Farmer, M., 2016. *Modernise or die: The Framer Review of the UK construction labour market*. The Farmer Review of the UK Construction Labour Model.

Fellows, R.F. and Liu, A.M.M., 2015. *Research Methods for Construction*. Fourth Edi. West Sussex: John Wiley & Sons Ltd.

Fensel, D., 2000. Relating Ontology Languages and Web Standards Ontology Languages.

Fernández-solís, J.L., 2009. How the Construction Industry does differ from manufacturing ? *In*: *Associated Schools of Construction International Proceedings of the 45th Annual Conference*. Gainesville.

Fernández, L.M., 1999. Overview Of Methodologies For Building Ontologies. *Proceedings of the IJCAI99 Workshop on Ontologies and ProblemSolving Methods Lessons Learned and Future Trends CEUR Publications*, 1999 (2), 1–13.

Fernandez, M., Gomez-Perez, A., and Juristo, N., 1997. *METHONTOLOGY : From Ontological Art Towards Ontological Engineering*.

Finnimore, B., 1989. *Houses from the Factory: System Building and the Welfare State*. California: Rivers Oram Press.

Flick, U., 2007. *Designing Qualitative Research*. London: SAGE Publications.

Flick, U., 2014. *The SAGE Handbook of Qualitative Data Analysis*. London: SAGE Publications.

Formoso, C.T., 1991. A Knowledge-based Framework for Planning House Building Projects. University of Salford.

Forsberg, A. and Saukkoriipi, L., 2007. Measurement of waste and productivity in relation to lean thinking. *In*: *Lean Construction: A New Paradigm for Managing Capital Projects - 15th IGLC Conference*. 67–76.

Fortineau, V., Paviot, T., Louis-Sidney, L., and Lamouri, S., 2012. SWRL as a rule language for ontology-based models in power plant design. *IFIP Advances in Information and Communication Technology*, 388 AICT, 588–597.

Froese, T., 2003. FUTURE DIRECTIONS FOR IFC-BASED INTEROPERABILITY. *ITcon*, 8 (December 2002), 231–246.

Future Focus, 2017. *Offsite and Modular Building Market Research*.

Gann, D.M., 1996. Construction as a manufacturing process ? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics*, 14 (5), 437–450.

Gbadamosi, A.Q., Mahamadu, A.M., Oyedele, L.O., Akinade, O.O., Manu, P., Mahdjoubi, L., and Aigbavboa, C., 2019. Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, 215, 1180–1190.

Giacobbi, P.R., Poczwardowski, A., and Hager, P., 2005. A pragmatic research philosophy for applied sport psychology. *Sport Psychologist*, 19 (1), 18–31.

Gibb, A.G.F., 1999. *Off-site fabrication: Prefabrication, Pre-assembly and Modularisation*. New York: John Wiley & Sons.

Gibb, A.G.F., 2001. Standardization and pre-assembly – distinguishing myth from reality using case study research. *Construction Management and Economics*, 19, 307–315.

Gibb, A.G.F. and Isack, F., 2003. Re-engineering through pre-assembly : client expectations and drivers. *Building Research & Information*, 31 (2), 146–160.

Girmscheid, G. and Scheublin, F., 2010. New perspective in industrialisation in construction - a state of the art report. *International Council For Research And Innovation In Building And Construction (CIB)*, (May).

Golbreich, C., 2004. Combining Rule and Ontology Reasoner for the Semantic Web. *In*: Grigoris Antoniou and H. Boley, eds. *Third International Workshop, RuleML 2004*. Berlin: Springer, ??? ????

Gómez-Pérez, A. and Corcho, O., 2002. Ontology languages for the semantic web. *IEEE Intelligent Systems and Their Applications*, 17 (1), 54–60.

Goodier, C. and Gibb, A., 2005. *The value of the UK market for offsite*. London.

Gorgolewski, M.T., 2005. The Potential for Prefabrication in UK Housing to Improve Sustainability. *In*: J. Yang, P.S. Brandon, and A.C. Sidwell, eds. *Smart & Sustainable Built Environments*. Oxford, UK.: Blackwell Publishing Ltd, 1–8.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012a. Offsite Construction : Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1, 62–73.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012b. Offsite Construction: Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1 (1), 62–73.

Goulding, J.S., Pour Rahimian, F., Arif, M., and Sharp, M.D., 2015. New offsite production and business models in construction: priorities for the future research agenda. *Architectural Engineering and Design Management*, 11 (3), 163–184.

GOV.UK, 2020. Live tables on house building [online]. *Ministry of Housing, Communities & Local Government*. Available from: https://www.gov.uk/government/statistical-data-sets/live-tables-on-house-building [Accessed 1 Feb 2020].

Grani, H.K., 2016. BIM Classification - Giving your Model some Class [online]. *Areo blog - Lifecycle BIM and smart FM*.

Griffith, M. and Jefferys, P., 2013. *Solutions for the housing shortage: How to build the 250.000 homes we need each year*. London.

Gruber, T.R., 1995. Toward principles for the design of ontologies used in knowledge sharing. *International Journal of Human Computer Studies*, 43, 907–928.

Gu, N. and London, K., 2010. Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, 19 (8), 988–999.

Guba, E.G. and Lincoln, Y.S., 1994. Competing Paradigms in Qualitative Research. *In*: N.K. Denzin and Y.S. Lincoln, eds. *Handbook of qualitative research*. 105–117.

Guizzardi, G., 2007. On Ontology, ontologies, Conceptualizations, Modeling Languages, and

(Meta)Models. *In*: O. Vasilecas et al., ed. *Databases and Information Systems IV*. IOS Press.

Gunasekaran, A. and Kobu, B., 2002. Modelling and analysis of business process reengineering. *International Journal of Production Research*, 40 (11), 2521–2546.

Gunasekaran, A. and Sarhadi, M., 1998. Implementation of activity-based costing in manufacturing. *Intern. Journal of Production Economics*, 56–57 (1998), 231–242.

Gunaydın, H.M. and Dogan, S.Z., 2004. A neural network approach for early cost estimation of structural systems of buildings. *International Journal of Project Management*, 22 (2004), 595–602.

Gunduz, M., Ugur, L.O., and Ozturk, E., 2011. Parametric cost estimation system for light rail transit and metro trackworks. *Expert Systems with Applications*, 38 (3), 2873–2877.

Gurcanli, G.E., Bilir, S., and Sevim, M., 2015. Activity based risk assessment and safety cost estimation for residential building construction projects. *Safety Science*, 80 (112), 1–12.

Hairstans, R. and Smith, R.E., 2018. Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK. *Architectural Engineering and Design Management*, 14 (1–2), 60–77.

Haron, N.A., Abdul-Rahman, H., Wang, C., and Wood, L.C., 2015. Quality function deployment modelling to enhance industrialised building system adoption in housing projects. *Total Quality Management and Business Excellence*, 26 (7–8), 703–718.

Hashemi, A., 2015. Offsite Manufacturing: A Survey on the Current Status and Risks of Offsite Construction in Iran, 9, 141–152.

Hashemi, A. and Hadjri, K., 2014. Offsite Construction, a Potential Answer to the Iranian Housing Shortages. *In*: *Construction Technology and Management CTM 2014 International Scientific Conference*. 189–199.

Hause, M., 2006. The SysML Modelling Language. *In*: *Fifteenth European Systems Engineering Conference*. 12.

HM Government, 2013. *Construction 2025. Industrial Strategy: Government and industry in partnership*.

Holten, M. and Ferdinand, G., 2020. BOT : the Building Topology Ontology of the W3C Linked Building Data Group. *Semantic Web*, 12 (1), 143–161.

Höök, M. and Stehn, L., 2008. Lean principles in industrialized housing production : the need for a cultural change Lean culture. *Lean Construction Journal 2008*, (April), 20–33.

Horrocks, I., 2002. DAML+OIL: a Description Logic for the Semantic Web. *Bulletin of the Technical Committee on Data Engineering*, 25 (1).

Horrocks, I. and Sattler, U., 2001. Ontology reasoning in the SHOQ(D) description logic. *IJCAI International Joint Conference on Artificial Intelligence*, 199–204.

Howell, G. and Ballard, G., 1998. Implimenting construction: understanding and action. *Proceedings International Group for Lean Construction*, 0, 9.

Howell, G.A., 1999. What is Lean Construction. *In*: I.D. Tommelein, ed. *IGLC 2012 - 20th Conference of the International Group for Lean Construction*. UNIVERSITY OF CALIFORNIA BERKELEY, CALIFORNIA, USA.

Hueber, C., Horejsi, K., and Schledjewski, R., 2016. Review of cost estimation: methods and models for aerospace composite manufacturing. *Advanced Manufacturing: Polymer and Composites Science*, 2 (1), 1–13.

Hyde, K.F., 2000. Recognising deductive processes in qualitative research. *Qualitative Market Research: An International Journal*, 3 (2), 82–90.

Ijomah, W.L. and Childe, S.J., 2007. A model of the operations concerned in remanufacture. *International Journal of Production Research*, 45 (24), 5857–5880.

Jabar, I. laili, Ismail, F., and Mustafa, A.A., 2013. Issues in Managing Construction Phase of IBS Projects. *Procedia - Social and Behavioral Sciences*, 101, 81–89.

Jaillon, L. and Poon, C.S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment : a Hong Kong case study. *Construction Management and Economics*, 26 (9), 953–966.

Jaillon, L. and Poon, C.S., 2009. The evolution of prefabricated residential building systems in Hong Kong : A review of the public and the private sector. *Automation in Construction*, 18 (3), 239–248.

Jaillon, L., Poon, C.S., and Chiang, Y.H., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management*, 29 (1), 309–320.

Jarkas, A.M. and Bitar, C.G., 2012. Factors Affecting Construction Labor Productivity in

Kuwait. *Journal of Construction Engineering and Management*, 138 (7), 811–820.

Ji, S., Park, M., and Lee, H., 2011. Cost estimation model for building projects using case-based reasoning. *Canadian Journal of Civil Engineering*, 38, 570–581.

Jones, D., Bench-capon, T., and Visser, P., 1998. Methodologies for Ontology Development. *In*: *Proc. IT&KNOWS Conference of the 15th IFIP World Computer Congress*. Budapest.

Jonsson, H. and Rudberg, M., 2014. Classification of production systems for industrialized building : a production strategy perspective. *Construction Management and Economics*, 32 (1–2), 53–69.

Jung, J., 2002. Manufacturing cost estimation for machined parts based on manufacturing features. *Journal of Intelligent Manufacturing*, 13, 227–238.

Kalemi, E.V., Cheung, F., Tawil, A., Patlakas, P., and Alyania, K., 2020. ifcOWL-DfMA a new ontology for the offsite construc- tion domain. *In*: *Proceedings of the7578th Linked Data in Architecture and Construction Workshop - LDAC2020 ifcOWL-DfMA*. 105–117.

Kamar, K.A., Abd Hamid, Z., Azman, M.N.A., and Ahamad, M.S.S., 2011. Industrialized Building System (IBS): Revisiting Issues of Definition and Classification. *International Journal of Emerging. Sciences*, 1 (2), 120–132.

Karhu, V., 2000. Formal Languages for Construction Process Modelling. *Construction Information Technology 2000, Taking the construction industry into the 21st century, CIB W78.*, 525–534.

Kenley, R., 2014. Productivity improvement in the construction process Productivity improvement in the construction process. *Construction Management and Economics*, 32 (6), 489–494.

Kenley, R., Kanjanabootra, S., Ouyang, C., and Wynn, M., 2012. Procuring OSM: base-line models of off-site manufacture business processes in Australia. *In*: *16th Pacific Association of Quantity Surveyors Congress-Innovation and Sustaining: Challenges and Opportunities*. 1–10.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., and Holmstrom, J., 2019. Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7, 147406–147419.

Khosrowshahi, F. and Kaka, A.P., 1996. Estimation of Project Total Cost and Duration for

Housing Projects in the U.K. *Building and Environment*, 31 (4), 373–383.

Kifer, M., 2008. Rule Interchange Format: The Framework. *In*: N. Bassiliades, G. Governatori, and A. Paschke, eds. *International Symposium, RuleML 2008*. Berlin: Springer-Verlag.

Kim, C.H., Weston, R.H., Hodgson, A., and Lee, K.H., 2003. The complementary use of IDEF and UML modelling approaches. *Computers in Industry*, 50 (1), 35–56.

Kim, S. and Shim, J.H., 2014. Combining case-based reasoning with genetic algorithm optimization for preliminary cost estimation in construction industry. *Canadian Journal of Civil Engineering*, 41 (November 2013), 65–73.

Kim, Y.-W., 2017. *Activity Based Costing for Construction Companies*. First Edit. West Sussex: John Wiley & Sons Ltd.

Kim, Y. and Ballard, G., 2001. Activity-based costing and its application to lean construction. *International Group for Lean Construction*, (January), 1–13.

Kim, Y. and Ballard, G., 2002. Case Study - overhead costs analysis. *In*: *Proceedings IGLC-10*. Gramado, Brazil, 1–13.

Kolo, S.J., Rahimian, F.P., and Goulding, J.S., 2014. Housing delivery in Nigeria and the opportunity for offsite manufacturing. *In*: *Creative Construction Conference*. 85–90.

Koskela, L., 1992. *Application of the new production philosophy to construction*. Stanford, CA.

KPMG, 2016. *Smart construction - How offsite manufacturing can transform our industry*.

Lang, R., Goodier, C., and Glass, J., 2016. Are housebuilders' production strategies a barrier to offsite construction uptake in the UK? *Proceedings of the 32nd Annual ARCOM Conference, ARCOM 2016*, 1245–1253.

Larsson, J. and Simonsson, P., 2012. Barriers and drivers for increased use of off-site bridge construction in Sweden. *In*: *28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 751–761.

Latham, M., 1994. *Constructing the Team*. Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry.

Lawson, M., Ogden, R., and Goodier, C., 2010. *Design in Modular Construction*. Taylor & Francis Group.

Lee, S., Kim, K., and Yu, J., 2014. Automation in Construction BIM and ontology-based approach for building cost estimation. *Automation in Construction*, 41, 96–105.

Leishman, C. and Warren, F., 2006. Private housing design customization through house type substitution. *Construction Management and Economics*, 24, 149–158.

Lemaignan, S., Siadat, A., Dantan, J.-Y., and Semenenko, A., 2006. MASON : A proposal for an ontology of manufacturing domain. *In*: *Proceedings of the IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications (DIS'06) 0-7695-2589-X/06*.

Lere, J.C., 2000. Activity-based costing: A powerful tool for pricing. *Journal of Business and Industrial Marketing*, 15 (1), 23–33.

Lessing, J., Stehn, L., and Ekholm, A., 2015. Industrialised house-building – development and conceptual orientation of the field. *Construction Innovation*, 15 (3), 378–399.

Li, Z.C., Hong, J., Xue, F., Shen, G.Q., Xu, X., and Luo, L., 2016. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. *Habitat International*, 57, 74–87.

Liao, S., 2004. Expert system methodologies and applications - a decade review from 1995 to 2004. *Expert Systems with Applications*, 1–11.

Lim, E.C. and Alum, J., 1995. Construction productivity: Issues encountered by contractors in Singapore. *International Journal of Project Management*, 13 (1), 51–58.

Lin, Y.C., Wang, L.C., and Tserng, H.P., 2006. Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan. *Automation in Construction*, 15 (6), 693–705.

Liu, H., Lu, M., and Al-hussein, M., 2016. Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry. *Advanced Engineering Informatics*, 30 (2), 190–207.

Liu, X., Li, Z., and Jiang, S., 2016. Ontology-Based Representation and Reasoning in Building Construction Cost Estimation in China. *Future Internet*, 8 (39).

Liu, Z., Osmani, M., Demian, P., and Baldwin, A.N., 2011. The potential use of BIM to aid construction waste minimalisation. *In*: –Sophia Antipolis, ed. *Proceedings of the CIB W78-W102 2011*. France.

Lou, Y.-I., Wang, H.C., and Lan, J.-S., 2017. Design and Implement the Activity-Based Costing in Taiwan Firm. *IOSR Journal of Business and Management*, 19 (01), 41–46.

Lovett, P.J., Ingram, A., and Bancroft, C.N., 2000. Knowledge-based engineering for SMEs - a methodology. *Journal of Materials Processing Technology*, 107, 384–389.

Lu, Q., Xie, X., Heaton, J., Parlikad, A.K., and Schooling, J., 2020. From BIM towards digital twin: Strategy and future development for smart asset management. *Studies in Computational Intelligence*, 853, 392–404.

Lucko, G. and Rojas, E.M., 2010. Research Validation: Challenges and Opportunities in the Construction Domain. *Journal of Construction Engineering and Management*, 136 (1).

Luo, L., Mao, C., Shen, L., and Li, Z., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system. *Engineering, Construction and Architectural Management*, 22 (6), 622–643.

Ma, Z.M. and Wang, X., 2012. Rule interchange in the semantic web. *Journal of Information Science and Engineering*, 28 (2), 393–406.

Mao, C., Shen, Q., Shen, L., and Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods : Two case studies of residential projects. *Energy & Buildings*, 66, 165–176.

McKay, L.J., 2010. The effect of offsite construction on occupational health and safety. *A Doctoral Thesis Submitted In Partial Fulfilment Of The Requirements For The Award Of Doctor Of Philosophy*. Loughborough University.

Meiling, J., Backlund, F., and Johnsson, H., 2012a. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Meiling, J., Backlund, F., and Johnsson, H., 2012b. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Melão, N. and Pidd, M., 2000. A conceptual framework for understanding business processes and business process modelling. *Information Systems Journal*, 10 (2), 105–129.

Melton, T., 2005. The benefits of lean manufacturing: What lean thinking has to offer the process industries. *Chemical Engineering Research and Design*, 83 (6 A), 662–673.

Miah, S.J. and Genemo, H., 2016. A Design Science Research Methodology for Expert Systems Development. *Australasian Journal of Information Systems*, 20, 1–29.

Miles, J. and Whitehouse, N., 2013. *Offsite Housing Review*. London.

Milton, N., 2008. *Knowledge Technologies*. Italy: Polimetrica ®.

Mizoguchi, R. and Ikeda, M., 1998. Towards ontology engineering. *Journal-Japanese Society for Artificial Intelligence*, 13 (1), 259–266.

Montali, J., Overend, M., Pelken, P.M., and Sauchelli, M., 2018. Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends. *Architectural Engineering and Design Management*, 14 (1–2), 78–94.

Morgan, D.L., 2007. Paradigms Lost and Pragmatism Regained: Qualitative and Quantitative Methods. *Journal of Mixed Methods Research*, 1 (48), 48–76.

Mossman, A., 2009. Creating value: A sufficient way to eliminate waste in lean design and lean production. *Lean Construction Journal*, 2009, 13–23.

Mostafa, S., Chileshe, N., and Abdelhamid, T., 2016. Lean and agile integration within offsite construction using discrete event simulation. *Construction Innovation*, 16 (4), 483–525.

Motawa, I. and Almarshad, A., 2013. A knowledge-based BIM system for building maintenance. *Automation in Construction*, 29, 173–182.

Mtech Group, 2007. *Offsite Construction Industry Survey 2006*. BuildOffsite. London.

Murtaza, M.B., Fisher, D.J., and Skibniewski, M.J., 1993. Knowledge-Based Approach to Modular Construction Decision Support. *Journal of Construction Engineering and Management*, 119, 115–130.

Murugaiah, U., Benjamin, S.J., and Marathamuthu, M.S., 2010. Scrap loss reduction using the 5-whys analysis. *International Journal of Quality & Reliability Management*, 27 (5), 527–540.

Musa, M.F., Mohammad, M.F., Yusof, M.R., and Mahbub, R., 2015. The Way Forward for Industrialised Building System (IBS) in Malaysia. *In*: *InCIEC 2014*. Singapore: Springer, pp 163-175.

Nadim, W. and Goulding, J.S., 2011. Offsite production : a model for building down barriers. *Engineering, Construction and Architectural Management*, 18 (1), 82–101.

Nahmens, I. and Ikuma, L.H., 2012. Effects of Lean Construction on Sustainability of Modular Homebuilding. *Journal of Architectural Engineering*, 18 (2), 155–163.

Nasereddin, M., Mullens, M.A., and Cope, D., 2007. Automated simulator development : A strategy for modeling modular housing production. *Automation in Construction*, 16, 212–223.

Naufal, A., Jaffar, A., Yusoff, N., and Hayati, N., 2012. Development of kanban system at local manufacturing company in Malaysia-Case study. *Procedia Engineering*, 41 (Iris), 1721–1726.

Nawari, N.O., 2012. BIM Standard in Off-Site Construction. *Journal of Architectural Engineering*, 18 (2).

NBS, 2015. Uniclass 2015 [online]. *National Building Specification (NBS)*. Available from: https://www.thenbs.com/our-tools/uniclass-2015 [Accessed 2 Jan 2019].

Nepal, M.P., Staub-French, S., Pottinger, R., and Zhang, J., 2013. Ontology- based feature modeling for construction information extraction from a build- ing information model. *Journal of Computing in Civil Engineering*, 27 (5), 555–569.

Neuman, L.W., 2014. *Social Research Methods: Qualitativr and Quantitative Approaches*. Seventh Ed. Essex, England: Pearson Education Limited.

Niazi, A. and Dai, J.S., 2006. Product Cost Estimation : Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, 128 (May).

Nicholls, D., 2017. Qualitative research. Part 2: Methodologies. *International Journal of Therapy and Rehabilitation*, 24 (2), 71–77.

Nikakhtar, A., Hosseini, A.A., Wong, K.Y., and Zavichi, A., 2015. Application of lean construction principles to reduce construction process waste using computer simulation: A case study. *International Journal of Services and Operations Management*, 20 (4), 461–480.

Nurcan, S., Etien, A., Kaabi, R., Zoukar, I., and Rolland, C., 2005. A strategy driven business process modelling approach. *Business Process Management Journal*, 11 (6), 628–649.

O’Connor, M., Knublauch, H., Tu, S., Grosof, B., Dean, M., Grosso, W., and Musen, M., 2005. Supporting rule system interoperability on the semantic Web with SWRL. *In*: Y. Gil et al., ed. *ISWC 2005*. Berlin: Springer-Verlag, 974–986.

Ochieng, E.G. and Price, A.D.F., 2009. Managing cross-cultural communication in multicultural construction project teams : The case of Kenya and UK. *International Journal of Project Management ·*, (July).

Ofori, G., 2000. Challenges of Construction Industries in Developing Countries : Lessons from Various Countries. *In*: *2nd International Conference on Construction in Developing Countries: Challenges Facing the Construction Industry in Developing Countries*. Gabarone, 1–13.

Ogunlana, S.O., 1989. Accuracy in design cost estimating.

Ong, N.S., 1995. Manufacturing cost estimation for PCB assembly : An activity-based approach. *International Journal of Production Economics*, 38, 159–172.

Ormerod, R.J., 2010. Rational inference: Deductive, inductive and probabilistic thinking. *Journal of the Operational Research Society*, 61 (8), 1207–1223.

Ou-Yang, C. and Lin, T.S., 1997. Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. *International Journal of Advanced Manufacturing Technology*, 13, 618–629.

Ozaki, R., 2003. Customer-focused approaches to innovation in housebuilding. *Construction Management and Economics*, 21, 557–564.

Ozbayrak, M., Akgun, M., and Turker, A.K., 2004. Activity-based cost estimation in a push / pull advanced manufacturing system. *International Journal of Production Economics*, 87, 49–65.

Pan, W., Dainty, A.R.J., and Gibb, A.G.F., 2012. Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, 138 (11), 1239–1250.

Pan, W., Gibb, A.G.F., and Dainty, A.R.J., 2008. *Leading UK housebuilders' utilisation of offsite modern methods of construction*. Building Research & Information.

Pan, W. and Goodier, C., 2012. House-Building Business Models and Off-Site Construction Take-Up. *Journal of Architectural Engineering*, 18 (2), 84–93.

Pan, W. and Sidwell, R., 2011. Demystifying the cost barriers to offsite construction in the UK. *Construction Management & Economics*, 29, 1081–1099.

Pasquire, C., Gibb, A., and Blismas, N., 2005. What should you really measure if you want to compare prefabrication with traditional construction? *In*: *Proceedings IGLC*. Sydney, Australia, 481–491.

Pasquire, C.L. and Connolly, G.E., 2002. Leaner construction through off-site manufacturing. *In*: *Proceedings 10th of the Internationa Group of Lean Construction Conference, Gramado, Brazil*. 1–13.

Pauwels, P. and Terkaj, W., 2016. EXPRESS to OWL for construction industry : Towards a recommendable and usable ifcOWL ontology. *Automation in Construction*, 63, 100–133.

Pearce, A., Pons, D., and Neitzert, T., 2018. Implementing lean—Outcomes from SME case studies. *Operations Research Perspectives*, 5, 94–104.

Persson, S., Malmgren, L., and Johnsson, H., 2009. Information management in industrial housing design and manufacture. *Electronic Journal of Information Technology in Construction*, 14 (June), 110–122.

Pheng, L.S. and Leong, C.H.Y., 2000. Cross-Cultural project management for international construction in China. *International Journal of Project Management*, 18 (5), 307–316.

Post, 2003. *Modern methods of house building*. Parliamentary Office of Science and Technology. London.

Pulido, J.R.G., Ruiz, M.A.G., Herrera, R., Cabello, E., Legrand, S., and Elliman, D., 2006. Ontology languages for the semantic web: A never completely updated review. *Knowledge-Based Systems*, 19 (7), 489–497.

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., and Zimmerman, J.B., 2012. Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*, 16 (2), 243–254.

Rahani, A. and Muhammad, A.-A., 2012. Production Flow Analysis through Value Stream Mapping : A Lean Manufacturing Process Case Study. *Procedia Engineering - International Symposium on Robotics and Intelligent Sensors*, 41 (Iris), 1727–1734.

Rahman, N.A.A., Sharif, S.M., and Esa, M.M., 2013. Lean Manufacturing Case Study with Kanban System Implementation. *Procedia Economics and Finance*, 7 (Icebr), 174–180.

Rahman, S., Perera, S., Odeyinka, H., and Bi, Y., 2008. A Conceptual Knowledge-Based Cost Model for Optimizing the Selection of Materials and Technology for Building Design. *24th Annual ARCOM Conference*, (September), 217–225.

Raz, T. and Elnathan, D., 1999. Activity based costing for projects. *International Journal of Project Management*, 17 (1), 61–67.

Rezgui, Y., Hopfe, C.J., and Vorakulpipat, C., 2010. Generations of knowledge management in the architecture , engineering and construction industry : An evolutionary perspective. *Advanced Engineering Informatics*, 24 (2), 219–228.

Richard, R.B., 2005. Industrialised building systems: Reproduction before automation and robotics. *Automation in Construction*, 14 (4), 442–451.

RICS, 2012a. *NRM1: Order of Cost Estimating and Cost Planning for Capital Building Works*. 2nd Editio. Coventry UK: Royal Institution of Chartered Surveyors (RICS).

RICS, 2012b. *NRM 2: Detailed Measurement for Building Works*. 1st Editio. Coventry: Royal Institution of Chartered Surveyors (RICS).

La Rocca, G., 2012. Knowledge based engineering : Between AI and CAD . Review of a language based technology to support engineering design. *Advanced Engineering Informatics*, 26 (2), 159–179.

Roy, A.U.K., Roy, M., and Saha, P.S., 2007. Mass-Industrialized Housing to Combat Consistent Housing Shortage in Developing Countries : Towards an Appropriate System for India. *In*: *World Congress on Housing National Housing Programmes- New Visions November 03-07, Kolkota, India*. Kolkata, India, 1–7.

Roy, R., Souchoroukov, P., and Shehab, E., 2011. Detailed cost estimating in the automotive industry : Data and information requirements. *Intern. Journal of Production Economics*, 133 (2), 694–707.

Rožanec, J.M., Jinzhi, L., Košmerlj, A., Kenda, K., Dimitris, K., Jovanoski, V., Rupnik, J., Karlovčec, M., and Fortuna, B., 2020. Towards actionable cognitive digital twins for manufacturing. *CEUR Workshop Proceedings*, 2615, 1–12.

Rundora, R., Ziemerink, T., and Oberholzer, M., 2013. Activity-based costing in small manufacturing firms: South African study. *Journal of Applied Business Research*, 29 (2), 485–498.

Saad, A. and Shaharin, S., 2016. The Methodology for Ontology Development in Lesson Plan Domain. *International Journal of Advanced Computer Science and Applications (IJACSA)*, 7 (4), 557–562.

Sabol, L., 2008. *Challenges in Cost Estimating with Building Information Modeling*. Washington, DC.

Sarvimaki, M., 2017. *Case Study Strategies for Architects and Designers : Integrative Data Research Methods: Integrative Data Research Methods*. London: Taylor & Francis Group.

Saunders, M., Lewis, P., and Thornhill, A., 2009. *Research Methods for Business Students*. New York: Pearson.

Schell, C., 1992. *The Value of the Case Study as a Research Strategy*.

Schreiber, A.T., Akkermans, J.M., Anjewierden, A.A., de Hoog, R., Shadbolt, N.R., Velde, W. Van de, and Wielinga, B.J., 2001. *Knowledge Engineering and Management - The CommonKADS Methodology*. Cambridge,Massachusetts: MIT Press.

Schuh, K.L. and Barab, S.A., 2008. Philosophical Perspectives. *In*: J. David, S.J. Michael, D. Marcy, M. David, and M. Jeroen, eds. *Handbook of Research on Educational Communications*. New York: Taylor & Francis, 67–82.

Schwitter, R., 2010. Controlled natural languages for knowledge representation. *In*: *Coling 2010 - 23rd International Conference on Computational Linguistics, Proceedings of the Conference*. Beijing, 1113–1121.

Secretary of State for Communities and Local Government, 2017. *Fixing our broken housing market*. Department for Communities and Local Government. London: Crown.

Shadbolt, N. and Milton, N., 1999. From Knowledge Engineering to Knowledge Management. *British Journal of Management*, 10, 309–322.

Shamsuddin, S.M., Zakaria, R., and Mohamed, S.F., 2013. Economic Attributes in Industrialised Building System in Malaysia. *Procedia - Social and Behavioral Sciences*, 105, 75–84.

Shang, G. and Sui Pheng, L., 2014. Barriers to lean implementation in the construction industry in China. *Journal of Technology Management in China*, 9 (2), 155–173.

Shi, J.J., Lee, D.E., and Kuruku, E., 2008. Task-based modeling method for construction business process modeling and automation. *Automation in Construction*, 17 (5), 633–640.

Shostak, L. and Houghton, J., 2008. The credit crunch and the housing shortage - Time for a radical new approach to building affordable homes. *Local Economy*, 23 (3), 121–126.

Sivakumar, R. and Arivoli, P.V., 2011. Ontology Visualization Protégé Tools - A Review. *International Journal of Advanced Information Technology*, 1 (4), 39–39.

Smith, A.E. and Mason, A.K., 1996. Cost Estimation Predictive Modeling : Regression versus Neural Network. *The Engineering Economist*.

Sobh, R. and Perry, C., 2006. Research design and data analysis in realism research. *European Journal of Markerting*, 40 (11), 1194–1209.

Sodikov, J., 2005. COST ESTIMATION OF HIGHWAY PROJECTS IN DEVELOPING COUNTRIES : ARTIFICIAL NEURAL NETWORK APPROACH. *Journal of the Eastern Asia Society for Transportation Studies*, 6, 1036–1047.

Soiferman, L.K., 2010. Compare and Contrast Inductive and Deductive Research Approaches. *Inductive and Deductive Research Approaches*, (April), 1–23.

Song, J., Fagerlund, W.R., Haas, C.T., Tatum, C.B., and Vanegas, J.A., 2005. Considering Prework on Industrial Projects. *Journal of Construction Engineering and Management*, 131 (6), 723–733.

Spens, K.M. and Kovács, G., 2006. A content analysis of research approaches in logistics research. *International Journal of Physical Distribution and Logistics Management*, 36 (5), 374–390.

Spyns, P., Meersman, R., and Jarrar, M., 2002. Data modelling versus ontology engineering. *ACM SIGMOD Record*, 31 (4), 12–17.

Staub-french, S., Fischer, M., Kunz, J., Paulson, B., and Ishii, K., 2002. *A Feature Ontology to Support Construction Cost Estimating*.

Steinhardt, D., Manley, K., and Miller, W.F., 2014. Reshaping housing using prefabricated systems. *Proceedings of World Sustainable Building Conference (SB14)*.

Studer, R., Benjamins, V.R., and Fensel, D., 1998. Knowledge Engineering : Principles and methods. *Data & Knowledge Engineering*, 25, 161–197.

Sundar, R., Balaji, A.N., and Satheesh Kumar, R.M., 2014. A review on lean manufacturing implementation techniques. *Procedia Engineering*, 97, 1875–1885.

Szuba, J.S., Grabska, E.G., and Borkowski, A., 1999. Graph Visualization in ArchiCAD. *In*: *Proceedings of the International Workshop on Applications of Graph Transformations with Industrial Relevance*. 241–246.

Tam, V.W.Y., Tam, C.M., Zeng, S.X., and Ng, W.C.Y., 2007. Towards adoption of prefabrication in construction. *Building and Environment*.

Tang, J., Zhang, M., Tang, H., and Chen, Y., 2015. Research on Cost Management of Construction Project based on Activity-based Costing. *In*: *International Conference on Civil, Materials and Environmental Sciences (CMES 2015)*. 51–54.

Taylor, S., 2009. *Offsite Production in the UK Construction Industry, abrief overview*. HSE.

Tennant, S., McCarney, M., Tong, M.K., and Tennant, G., 2012. Re-Engineering the Construction Supply Chain: Transferring on-Site Activity, Off- Site. *In*: *Procs 28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 3–5.

Terkaj, W. and Urgo, M., 2014. Ontology-based modeling of production systems for design and performance evaluation. *Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014*, 748–753.

Thanoon, W.A., Peng, L.W., AbdulKadir, M.R., Jaafar, M.S., and Salit, M.S., 2003. The Essential Characteristics of Industrialised Building System. *In*: *International Conference on Industrialised Building Systems*. 10–11.

Thomas, G., 2011. Qualitative Inquiry A Typology for the Case Study in Social Science Following a Review of Definition , Discourse , and Structure. *Qualitative Inquiry*, 17 (6), 511 –521.

Tran, V. and Tookey, J., 2007. Labour Productivity in the New Zealand Construction Industry : A Thorough Investigation. *Australasian Journal of Construction Economics and Building*, 11 (1), 41–60.

Trehan, V., Chapman, C., and Raju, P., 2015. Informal and formal modelling of engineering processes for design automation using knowledge based engineering. *Journal of Zhejiang University: Science A*, 16 (9), 706–723.

Tsai, W.H., Yang, C.H., Chang, J.C., and Lee, H.L., 2014. An Activity-Based Costing decision model for life cycle assessment in green building projects. *European Journal of Operational Research*, 238 (2), 607–619.

Vakaj, E., F., C., H., T.A.-R., Pauwels, P., and Patlakas, P., 2021. Semanic representation of DfMA offsite housing.

Venables, T., Barlow, J., and Gann, D., 2004. *Manufacturing Excellence - UK Offsite Capacity in Off-Site Manufacturing*. Constructing Excellence.

Verhagen, W., Bermell-Garcia, P., Mariot, P., Cotton, J.-P., Ruiz, D., Redon, R., and Curran, R., 2010. (Costing) Knowledge-Based Cost Modelling of Composite Wing Structures. *International Journal of Computer Integrated Manufacturing*, pp.1.

Vernikos, V.K., Nelson, R., Goodier, C.I., and Robery, P.C., 2013. Implementing an offsite construction strategy: a UK contracting organisation case study. *In*: *Proceedings of the 29th Annual ARCOM Conference*. Reading, UK, 667–677.

Vibaek, K.S., 2014. *Architectural System and Structures - Integrating design complexity in industralised construction*. London: Routledge.

Volk, R., Stengel, J., and Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, 38 (October 2017), 109–127.

Voss, E., Jin, Q., and Overend, M., 2013. A BPMN-based process map for the design and construction of façades. *Journal of Facade Design and Engineering*, 1 (1–2), 17–29.

Wagner, A. and Uwe, R., 2019. BPO : The Building Product Ontology for Assembled Products. *In*: *Proceedings of the 7th Linked Data in Architecture and Construction Workshop - LDAC2019*. 106–119.

Wahab, A.N.A., Mukhtar, M., and Sulaiman, R., 2013. A Conceptual Model of Lean Manufacturing Dimensions. *Procedia Technology*, 11 (Iceei), 1292–1298.

Waissi, G.R., Demir, M., Humble, J.E., and Lev, B., 2015. Automation of strategy using IDEF0 - A proof of concept. *Operations Research Perspectives*, 2, 106–113.

Warszawski, A., 1999. *Industrialised and automated building systems*. First edit. London: E & FN Spon.

Willis, J.W., 2007. *World Views, Paradigms, and the Practice of Social Science Research*. London: Sage.

Wilson, L., 2010. *How to Implement Lean Manufacturing*. New York: McGrawHill.

Wong, R., Hao, J., and Ho, C., 2003. Prefabricated building construction systems adopted in Hong Kong. *In*: *Proc. of the International Association for Housing Science on Word Congress of Housing: Process and Product*. Canada.

Wu, S., Wood, G., Ginige, K., and Jong, S.W., 2014. A technical review of bim based cost estimating in UK quantity surveying practice, standards and tools. *Journal of Information Technology in Construction*, 19 (March), 535–563.

Xu, Y., Elgh, F., Erkoyuncu, J.A., Bankole, O., Goh, Y., Cheung, W.M., Baguley, P., Wang, Q., Arundachawat, P., Shehab, E., Newnes, L., and Roy, R., 2011. Cost engineering for manufacturing : current and future research. *International Journal of Computer Intergrated Manufacturing*, 25 (4–5), 300–314.

Xu, Z., Abualdenien, J., Liu, H., and Kang, R., 2020. An IDM-Based Approach for Information Requirement in Prefabricated Construction. *Advances in Civil Engineering*, 2020, 21.

Yaman, H. and Tas, E., 2007. A building cost estimation model based on functional elements. *ITU Journal of Faculty of Architecture,* 4 (1), 73–87.

Yang, H., Yeung, J.F.Y., Chan, A.P.C., Chiang, Y.H., and Chan, D.W.M., 2010. A critical review of performance measurement in construction. *Journal of Facilities Management*, 8 (4), 269–284.

Yi, W. and Chan, A.P.C., 2014. Critical Review of Labor Productivity Research in Construction Journals. *Journal of Management in Engineering*, 30 (2), 214–225.

Yin, R.K., 1994. *Case Study Research: Design and Methods*. Second. Bervely Hills: Sage Publishing.

Yin, R.K., 2009. *Case Study Reserach: Design and methods*. Fourth. London: SAGE Publications.

Yin, R.K., 2016. *Qualitative Research from Start to Finish*. Second Edi. London: Guilford Publications.

Yitmen, I., 2007. The challenge of change for innovation in construction : A North Cyprus perspective. *Building and Environment*, 42, 1319–1328.

Young, B., Harty, C., Lu, S., and Davies, R., 2015. Developing Temporary Manufacturing Facilities for Residential Building : a Case of the Modern Flying Factory. *Procs 31st Annual ARCOM Conference, 7-9 September 2015,* (September), 1033–1042.

Yunus, R. and Yang, J., 2012. Critical Sustainability Factors in Industrialised Building Systems Abstract. *Construction Innovation*, 12 (4), 447–463.

Zainal, Z., 2007. Case study as a research method. *Jurnal Kemanusiaan,* 9.

Zakaria, S.A., Gajendran, T., Rose, T., and Brewer, G., 2018. Contextual, structural and behavioural factors influencing the adoption of industrialised building systems: a review. *Architectural Engineering and Design Management*, 14 (1–2), 3–26.

Zhai, X., Reed, R., and Mills, A., 2014. Addressing sustainable challenges in China. *Smart and Sustainable Built Environment*, 3 (3), 261–274.

Zhang, S., Boukamp, F., and Teizer, J., 2015. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, 52, 29–41.

Zhang, X. and Skitmore, M., 2012. Industrialized housing in China: a coin with two sides. *International Journal of Strategic Property Management*, 16 (2), 143–157.

Zhang, Y., Fan, G., Lei, Z., Han, S., Raimondi, C., Al-Hussein, M., and Bouferguene, A., 2016. Lean-based diagnosis and improvement for offsite construction factory manufacturing facilities. *In*: *ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction*. 1090–1098.

Zhang, Y., Lei, Z., Han, S., Bouferguene, A., and Al-Hussein, M., 2020. Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance. *Journal of Construction Engineering and Management*, 146 (9).

Zhong, B.T., Ding, L.Y., Love, P.E.D., and Luo, H.B., 2015. An ontological approach for technical plan definition and verification in construction. *Automation in Construction*, 55, 47–57.

Zhuang, C., Miao, T., Liu, J., and Xiong, H., 2021. The connotation of digital twin, and the construction and application method of shop-floor digital twin. *Robotics and Computer-Integrated Manufacturing*, 68 (September 2020), 102075.

APPENDICES

Appendix A – Ethical clearance form

CEBE Faculty Academic Ethics Committee

BIRMINGHAM CITY University

STAGE ONE ETHICAL REVIEW FORM

This form needs to be completed by **everyone** undertaking research (including staff studying in other Faculties or at other institutions). It must be completed **before** the project starts, and be submitted with a copy of the research project proposal. It will be used by the module coordinator (in the case of student projects)/ Faculty Academic Ethics Committee (in the case of staff/postgraduate research students projects) to identify whether a fuller application for ethical approval needs to be submitted or whether the research can proceed without this."

Name: Kudirat Ayinla

Student/Staff ID Number: 17102250

School/Course: CEBE/Built Environment

Please circle the capacity in which you are completing this form:
Undergraduate Taught
Postgraduate Taught
Postgraduate Research ☑
Staff – Non-funded Research
Staff – Funded Research

1. Potential physical or psychological harm, discomfort or stress

(a) Is there a significant foreseeable potential for psychological harm or stress? YES/~~NO~~
(b) Is there a significant foreseeable potential for physical harm or discomfort? YES/~~NO~~
(c) Is there a significant foreseeable risk to the researcher? YES/~~NO~~

2. Protection of research subject confidentiality
Are there any issues of ***confidentiality*** *which are* ***not*** *adequately addressed by the following actions:*
(a) Non-attribution of individual responses;
(b) Individuals and organisations to be anonymised in publications and presentations, or to give consent to be named;
(c) Specific agreements with respondents regarding any feedback to collaborators and relating to any publications.
YES/~~NO~~

3. Data protection and consent
Are there any issues of ***data handling*** *and* ***informed consent*** *which are not dealt with by established procedures? This would entail ensuring:*
(a) Compliance with the Data Protection Act with reference to safe/secure storage of data and its management on completion of the project.
(b) That respondents have giving consent regarding the collection of personal data by completing a Consent Form (please attach form)
(c) That there are no special issues arising concerning confidentiality/informed consent.
YES/~~NO~~
(d) Is there any difficulty providing your participants with a participant information sheet?
YES/~~NO~~

4. Moral issues and Researcher/Institutional Conflicts of Interest
Are there any special moral issues and/or conflicts of interest identified? YES/~~NO~~
(a) An example of conflict of interest would be the researcher compromising research objectivity or independence in return for financial or non-financial benefit for him/herself or for a relative or friend.
(b) Particular moral issues or concerns could arise, for example, where the purposes of research are concealed, where respondents are unable to provide informed consent, or where research findings would impinge negatively/differentially upon the interests of participants.

5. Vulnerable participants
Are any of participants or interviewees in the research vulnerable, e.g. children and young people, people with disabilities, vulnerable adults etc.? YES/~~NO~~

6. Animals
Are any animals involved in the proposed research? YES/~~NO~~

7. Bringing the University into disrepute
Is there any aspect of the proposed research which might bring the University into disrepute? YES/~~NO~~

8. Does your research concern groups which may be construed as terrorist or extremist?

YES/~~NO~~

To assist your response to the question please note the following definitions of "terrorism" and "extremism" from the Prevent Strategy which are contained in the FAEC *Procedures*:

The current UK definition of ***terrorism*** *is given in the Terrorism Act 2000 (TACT 2000). In summary this defines terrorism as an action that endangers or causes serious violence to a person/people; causes serious damage to property; or seriously interferes or disrupts an electronic system. The use or threat must be designed to influence the government or to intimidate the public and is made for the purpose of advancing a political, religious or ideological cause.*

Extremism *is vocal or active opposition to fundamental British values, including democracy, the rule of law, individual liberty and mutual respect and tolerance of different faiths and beliefs. We also include in our definition of extremism calls for the death of members of our armed forces, whether in this country or overseas.*

Overall assessment

If all the answers are NO, the self-audit has been conducted and confirms the absence of ethical risks which can be reasonably foreseen.

If one or more answers are YES then risks have been identified which require that a **Stage Two form will need to be completed. If the answer to question 8 is YES the completion of additional forms 2A and 2B will also be required along with the Stage Two form.**

DECLARATION

- ☐ *I can confirm that I have read the Faculty Ethics Procedures and will adhere to them in my research*
- ☐ *I can confirm I have read and reviewed this form and there are no issues*
- ☐ *I can confirm I have read and reviewed this form. I have identified issues and understand that I now need to complete a Stage Two form.*

Signed by applicant Kudirat Ayinla

*Approved by*__________________________

Appendix B – Expert validation form

Research Title: Development of a knowledge-based production process analysis tool for offsite manufacturing method of construction

Dear Participant.

Thank you for agreeing to participate in the expert validation process. The researcher intends to validate the Offsite Manufacturing Production Workflow (OPW) ontology developed and your feedback is a part of expert validation which will help ensure that the knowledge modelled in the ontology is applicable to real-life problems and is novel in nature.

About the tool:

The aim of the knowledge-based engineering tool is to enable offsite housebuilders/manufacturers to analyse their processes. It will facilitate the retrieval of qualitative and quantitative data on aspects like, cost, time, waste, process sequences, resource consumption etc. to support informed decision making and continuous improvement.

The ontology is intended and designed to answer the following competency questions:

Question 1: *What activities are involved in manufacturing a house using various systems of OSM and what resources are involved in each process?*

Question 2: *What is the cost of each activity involved in producing a house using the OSM method?*

Question 3: *What is the time spent on each activity and workstations involved in producing a house using the OSM method?*

Question 4: *What proportions of the activities involved in the production process of different methods are value-adding and/or non-value adding?*

Question 5: *Compare the process information for different production methods i.e. the cost and time spent on the various categories of activities in the various OSM production methods?*

I would appreciate if you could take a few minutes to share your expert opinions about the work conducted. Your input and participation in the study will be kept confidential and at no point will your true identity be disclosed. Personal details are not required for the feedback.

Please complete and return this form at the end of the full presentation.

Thank you.

Expert Validation & Feedback Form

Assessment Criteria 1: Accuracy & Clarity

(○ Circle, whichever is applicable)

	Strongly Disagree				Strongly Agree
1. The estimates seem to be reliable in a variance of 0 - 10%	1	2	3	4	5
2. The terminologies used are clear and practical	1	2	3	4	5
3. The methodology design and structuring are logical	1	2	3	4	5

Assessment Criteria 2: Usefulness & Adaptability

(○ Circle, whichever is applicable)

4. The tool proves to be advanced and beneficial to users	1	2	3	4	5
5. The designed tool finds application in real-life scenarios	1	2	3	4	5
6. The OSM production workflow tool covers a wide scope	1	2	3	4	5
7. The knowledge base developed is flexible and transferable	1	2	3	4	5

Assessment Criteria 3: Completeness (☒ Cross whichever is applicable)

8. This work, its application and results are: ☐simple ☐intermediate ☐advanced ☐expert

9. The knowledge-based tool :☐requires more rework ☐ is capable ☐is good ☐is excellent

Fill in the details as applicable:

What is your overall opinion on the usefulness of the research and ontology developed? Any suggestions for improvement?

Background and Details:

What is the name of the Organisation you work for?...

What is your current role in the Organisation? ....

How many years of professional experience do you have in relation to offsite method of construction? ___years ___months

Thank you!

Please return this form to the presenter at the end of the full presentation or email it to Kudirat.ayinla@mail.bcu.ac.uk.

Appendix C – OPW Ontology Data Analysis Results

Table 11.1: Process analysis for production line with 50% of annual capacity (Year 1 – 70 Unit Houses)

Static Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.4	Material delivery	NVA	10		10		7.42		7.42	
5.5	Sorting steel sections	NVA	10		10		6.25		6.25	
5.6	Nut and bolt Frame	VA	35	30	5		21.87	21.87		
5.7	Quality inspection	NNVA	5			5	1.04			1.04
5.8	Rework on frames	NVA	10		10		6.25		6.25	
5.9	Measuring and Cutting CP Board	VA	15	15			9.37	9.37		
5.10	Check alignment	NVA	2		2		1.25		1.25	
5.11	Load CP Board on frame	NVA	7		7		4.37		4.37	
5.12	Screw board to frame	VA	20	15	5		12.50	12.50		
5.13	Quality inspection on fixings	NNVA	5			5	0.83			0.83
5.14	Rework on failed joints	NVA	5		5		3.12		3.12	
5.29	Load finished panels to transport trolley	NVA	3		3		2.23		2.23	
Total Time (Min)/Cost (£)			127	60	57	10	£76.52	£43.75	£30.90	£1.88
Total Time/Cost (%)			100	47	45	8	100	57	40	2.5

Table 11.2: Process analysis for production line with 60% of annual capacity (Year 1 – 84 Unit Houses)

Static Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.4	Material delivery	NVA	10		10		7.42		7.42	
5.5	Sorting steel sections	NVA	10		10		6.04		6.04	
5.6	Nut and bolt Frame	VA	35	30	5		21.14	21.14		
5.7	Quality inspection	NNVA	5			5	1.04			1.04
5.8	Rework on frames	NVA	10		10		6.04		6.04	
5.9	Measuring and Cutting CP Board	VA	15	15			9.06	9.06		
5.10	Check alignment	NVA	2		2		1.21		1.21	
5.11	Load CP Board on frame	NVA	7		7		4.23		4.23	
5.12	Screw board to frame	VA	20	15	5		12.08	12.08		
5.13	Quality inspection on fixings	NNVA	5			5	0.83			0.83
5.14	Rework on failed joints	NVA	5		5		3.02		3.02	
5.29	Load finished panels to transport trolley	NVA	3		3		2.23		2.23	
Total Time (Min)/Cost (£)			127	60	57	10	£74.33	£42.27	£30.18	£1.88
Total Time/Cost (%)			100	47	45	8	100	57	41	2.5

Table 11.3: Process analysis for production line with 75% of annual capacity (Year 3-6 – 105 Unit Houses)

Static Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.4	Material delivery	NVA	10		10		7.42		7.42	
5.5	Sorting steel sections	NVA	10		10		5.83		5.83	
5.6	Nut and bolt Frame	VA	35	30	5		20.41	20.41		
5.7	Quality inspection	NNVA	5			5	1.04			1.04
5.8	Rework on frames	NVA	10		10		5.83		5.83	
5.9	Measuring and Cutting CP Board	VA	15	15			8.75	8.75		
5.10	Check alignment	NVA	2		2		1.17		1.17	
5.11	Load CP Board on frame	NVA	7		7		4.08		4.08	
5.12	Screw board to frame	VA	20	15	5		11.66	11.66		
5.13	Quality inspection on fixings	NNVA	5			5	0.83			0.83
5.14	Rework on failed joints	NVA	5		5		2.92		2.92	
5.29	Load finished panels to transport trolley	NVA	3		3		2.23		2.23	
Total Time (Min)/Cost (£)			127	60	57	10	£72.17	£40.82	£29.48	£1.88
Total Time/Cost (%)			100	47	45	8	100	57	41	2.6

Table 11.4: Process analysis for production line with 85% of annual capacity (Year 7&8 – 120 Unit Houses)

Static Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.4	Material delivery	NVA	10		10		7.42		7.42	
5.5	Sorting steel sections	NVA	10		10		5.73		5.73	
5.6	Nut and bolt Frame	VA	35	30	5		20.07	20.07		
5.7	Quality inspection	NNVA	5			5	1.04			1.04
5.8	Rework on frames	NVA	10		10		5.73		5.73	
5.9	Measuring and Cutting CP Board	VA	15	15			8.60	8.60		
5.10	Check alignment	NVA	2		2		1.15		1.15	
5.11	Load CP Board on frame	NVA	7		7		4.01		4.01	
5.12	Screw board to frame	VA	20	15	5		11.47	11.47		
5.13	Quality inspection on fixings	NNVA	5			5	0.83			0.83
5.14	Rework on failed joints	NVA	5		5		2.87		2.87	
5.29	Load finished panels to transport trolley	NVA	3		3		2.23		2.23	
Total Time (Min)/Cost (£)			127	60	57	10	£71.15	£40.14	£29.14	£1.88
Total Time/Cost (%)			100	47	45	8	100	56	41	2.6

Table 11.5: Process analysis for production line with 95% of annual capacity (Year 9 – 134 Unit Houses)

Static Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.4	Material delivery	NVA	10		10		7.42		7.42	
5.5	Sorting steel sections	NVA	10		10		5.66		5.66	
5.6	Nut and bolt Frame	VA	35	30	5		19.80	19.80		
5.7	Quality inspection	NNVA	5			5	1.04			1.04
5.8	Rework on frames	NVA	10		10		5.66		5.66	
5.9	Measuring and Cutting CP Board	VA	15	15			8.48	8.48		
5.10	Check alignment	NVA	2		2		1.13		1.13	
5.11	Load CP Board on frame	NVA	7		7		3.96		3.96	
5.12	Screw board to frame	VA	20	15	5		11.31	11.31		
5.13	Quality inspection on fixings	NNVA	5			5	0.83			0.83
5.14	Rework on failed joints	NVA	5		5		2.83		2.83	
5.29	Load finished panels to transport trolley	NVA	3		3		2.23		2.23	
Total Time (Min)/Cost (£)			127	60	57	10	£70.35	£39.60	£28.88	£1.88
Total Time/Cost (%)			100	47	45	8	100	56	41	2.7

Table 11.6: Process analysis for production line with 100% of annual capacity (Year 10 – 140 Unit Houses)

Static Production Line			Time (min)				Cost (£)			
Activity Code	Activity	Type	Cycle time (CT)	VA Time	NVA Time	NNVA Time	Cost per Activity (ABC)	VA Cost	NVA Cost	NNVA Cost
5.4	Material delivery	NVA	10		10		7.42		7.42	
5.5	Sorting steel sections	NVA	10		10		5.62		5.62	
5.6	Nut and bolt Frame	VA	35	30	5		19.68	19.68		
5.7	Quality inspection	NNVA	5			5	1.04			1.04
5.8	Rework on frames	NVA	10		10		5.62		5.62	
5.9	Measuring and Cutting CP Board	VA	15	15			8.44	8.44		
5.10	Check alignment	NVA	2		2		1.12		1.12	
5.11	Load CP Board on frame	NVA	7		7		3.94		3.94	
5.12	Screw board to frame	VA	20	15	5		11.25	11.25		
5.13	Quality inspection on fixings	NNVA	5			5	0.83			0.83
5.14	Rework on failed joints	NVA	5		5		2.81		2.81	
5.29	Load finished panels to transport trolley	NVA	3		3		2.23		2.23	
Total Time (Min)/Cost (£)			127	60	57	10	£70.01	£39.36	£28.77	£1.88
Total Time/Cost (%)			100	47	45	8	100	56	41	2.7

Table 11.7: Process analysis for production line with 10% of annual capacity (Year 1 – 60 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		4.41		4.41	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA				0.2	0.41			0.41
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	1.02			1.02
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			13.81	13.81		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		1.02		1.02	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	1.02			1.02
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	1.02			1.02
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		2.04		2.04	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	8.78			8.78
5.46	Datum frame and Clamp frame in place	VA	1	1			2.04	2.04		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			13.81	13.81		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	1.02			1.02
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	1.02			1.02

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17		
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33		
5.52	Load CP board	NVA	1		1		2.37		2.37		
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	1.02			1.02	
5.54	Screw CP board to frame	VA	7.33	7.33			14.93	14.93			
5.55	Visual Inspection on connections	NNVA	0.5			0.5	1.02			1.02	
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17		
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	1.59			1.59	
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	10.39			10.39	
5.59	Load panels on transport trolley	NVA	2		2		0.67		0.67		
Total Time (Min)/Cost (£)			58	22	21	15	£86.50	£44.59	£13.45	£28.46	
Total Time/Cost (%)			100	38	37	26	100	52	16	33	

Table 11.8: Process analysis for production line with 20% of annual capacity (Year 2 – 120 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	Activity	Type	Cycle time (CT)	VA Time	NVA Time	NNVA Time	Cost per Activity (ABC)	VA Cost	NVA Cost	NNVA Cost
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		2.37		2.37	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA	0.2			0.2	0.20			0.20
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	0.51			0.51
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			6.91	6.91		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		0.51		0.51	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	0.51			0.51
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	0.51			0.51
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		1.02		1.02	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	4.39			4.39
5.46	Datum frame and Clamp frame in place	VA	1	1			1.02	1.02		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			6.91	6.91		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	0.51			0.51
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	0.51			0.51

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17	
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33	
5.52	Load CP board	NVA	1		1		1.38		1.38	
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	0.51			0.51
5.54	Screw CP board to frame	VA	7.33	7.33			7.47	7.47		
5.55	Visual Inspection on connections	NNVA	0.5			0.5	0.51			0.51
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17	
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	0.79			0.79
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	5.19			5.19
5.59	Load panels on transport trolley	NVA	2		2		0.67		0.67	
Total Time (Min)/Cost (£)			58	22	21	15	£45.50	£22.29	£8.90	£14.31
Total Time/Cost (%)			100	38	37	26	100	49	20	31

Table 11.9: Process analysis for production line with 30% of annual capacity (Year 3 – 180 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		1.69		1.69	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA	0.2			0.2	0.14			0.14
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	0.34			0.34
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			4.60	4.60		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		0.34		0.34	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	0.34			0.34
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	0.34			0.34
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		0.68		0.68	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	2.93			2.93
5.46	Datum frame and Clamp frame in place	VA	1	1			0.68	0.68		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			4.60	4.60		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	0.34			0.34
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	0.34			0.34

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17	
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33	
5.52	Load CP board	NVA	1		1		1.01		1.01	
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	0.34			0.34
5.54	Screw CP board to frame	VA	7.33	7.33			4.98	4.98		
5.55	Visual Inspection on connections	NNVA	0.5			0.5	0.34			0.34
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17	
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	0.53			0.53
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	3.46			3.46
5.59	Load panels on transport trolley	NVA	2		2		0.67		0.67	
Total Time (Min)/Cost (£)			58	22	21	15	£31.79	£14.86	£7.34	£9.59
Total Time/Cost (%)			100	38	37	26	100	47	23	30

Table 11.10: Process analysis for production line with 40% of annual capacity (Year 4 – 240 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		1.35		1.35	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA	0.2			0.2	0.10			0.10
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	0.25			0.25
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			3.45	3.45		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		0.25		0.25	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	0.25			0.25
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	0.25			0.25
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		0.51		0.51	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	2.19			2.19
5.46	Datum frame and Clamp frame in place	VA	1	1			0.51	0.51		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			3.45	3.45		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	0.25			0.25
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	0.51			0.51

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17	
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33	
5.52	Load CP board	NVA	1		1		0.84		0.84	
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	0.25			0.25
5.54	Screw CP board to frame	VA	7.33	7.33			3.73	3.73		
5.55	Visual Inspection on connections	NNVA	0.5			0.5	0.25			0.25
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17	
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	0.40			0.40
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	2.60			2.60
5.59	Load panels on transport trolley	NVA	2		2		0.67		0.67	
Total Time (Min)/Cost (£)			58	22	21	15	£25.22	£11.15	£6.58	£7.50
Total Time/Cost (%)			100	38	37	26	100	44	26	30

Table 11.11: Process analysis for production line with 50% of annual capacity (Year 5 – 300 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	Activity	Type	Cycle time (CT)	VA Time	NVA Time	NNVA Time	Cost per Activity (ABC)	VA Cost	NVA Cost	NNVA Cost
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		1.15		1.15	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA	0.2			0.2	0.08			0.08
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	0.20			0.20
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			2.76	2.76		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		0.20		0.20	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	0.20			0.20
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	0.20			0.20
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		0.41		0.41	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	1.76			1.76
5.46	Datum frame and Clamp frame in place	VA	1	1			0.41	0.41		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			2.76	2.76		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	0.20			0.20
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	0.20			0.20

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17	
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33	
5.52	Load CP board	NVA	1		1		0.74		0.74	
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	0.20			0.20
5.54	Screw CP board to frame	VA	7.33	7.33			2.99	2.99		
5.55	Visual Inspection on connections	NNVA	0.5			0.5	0.20			0.20
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17	
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	0.32			0.32
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	2.08			2.08
5.59	Load panels on transport trolley	NVA	2		2		0.67		0.67	
Total Time (Min)/Cost (£)			58	22	21	15	£20.86	£8.92	£6.12	£5.83
Total Time/Cost (%)			100	38	37	26	100	43	29	28

Table 11.12: Process analysis for production line with 75% of annual capacity (Year 6 – 450 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	Activity	Type	Cycle time (CT)	VA Time	NVA Time	NNVA Time	Cost per Activity (ABC)	VA Cost	NVA Cost	NNVA Cost
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		0.88		0.88	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA	0.2			0.2	0.05			0.05
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	0.14			0.14
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			1.84	1.84		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		0.14		0.14	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	0.14			0.14
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	0.14			0.14
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		0.27		0.27	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	1.17			1.17
5.46	Datum frame and Clamp frame in place	VA	1	1			0.27	0.27		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			1.84	1.84		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	0.14			0.14
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	0.14			0.14

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17	
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33	
5.52	Load CP board	NVA	1		1		0.60		0.60	
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	0.14			0.14
5.54	Screw CP board to frame	VA	7.33	7.33			1.99	1.99		
5.55	Visual Inspection on connections	NNVA	0.5			0.5	0.14			0.14
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17	
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	0.21			0.21
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	1.39			1.39
5.59	Load panels on transport trolley	NVA	2		2		0.67		0.67	
Total Time (Min)/Cost (£)			58	22	21	15	£15.40	£5.95	£5.51	£3.94
Total Time/Cost (%)			100	38	37	26	100	39	36	26

Table 11.13: Process analysis for production line with 85% of annual capacity (Year 7 – 510 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		0.81		0.81	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA	0.2			0.2	0.05			0.05
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	0.12			0.12
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			1.62	1.62		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		0.12		0.12	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	0.12			0.12
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	0.12			0.12
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		0.24		0.24	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	1.03			1.03
5.46	Datum frame and Clamp frame in place	VA	1	1			0.24	0.24		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			1.62	1.62		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	0.12			0.12
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	0.12			0.12

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17	
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33	
5.52	Load CP board	NVA	1		1		0.57		0.57	
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	0.12			0.12
5.54	Screw CP board to frame	VA	7.33	7.33			1.76	1.76		
5.55	Visual Inspection on connections	NNVA	0.5			0.5	0.12			0.12
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17	
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	0.19			0.19
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	1.22			1.22
5.59	Load panels on transport trolley	NVA	2		2		0.67		0.67	
Total Time (Min)/Cost (£)			58	22	21	15	£14.10	£5.24	£5.36	£3.49
Total Time/Cost (%)			100	38	37	26	100	37	38	25

Table 11.14: Process analysis for production line with 100% of annual capacity (Year 8 to10 – 600 Unit Houses)

Semi-Automated Production Line			Time (min)				Cost (£)			
Activity Code	**Activity**	**Type**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**	**Cost per Activity (ABC)**	**VA Cost**	**NVA Cost**	**NNVA Cost**
5.33	Material delivery	NVA	2		2		0.67		0.67	
5.34	Tool set-up for batch	NVA	2		2		0.74		0.74	
5.35	Sorting frames	NVA	8.73		8.73		1.46		1.46	
5.36	Verify and Inspect Set-up	NNVA	1			1	0.17			0.17
5.37	Clamp section in place	NNVA	0.2			0.2	0.04			0.04
5.38	Transfer to fixing station 1	NNVA	0.5			0.5	0.10			0.10
5.39	Insert TEK Screw to hold sections	VA	6.78	6.78			1.38	1.38		
5.40	Transfer frame to inspection and rework station	NVA	0.5		0.5		0.10		0.10	
5.41	Visual Inspection on Frame	NNVA	0.5			0.5	0.10			0.10
5.42	Manual rework on failed joints	NVA	1		1		0.17		0.17	
5.43	Tooling and frame moves to turnover and transfer system	NNVA	0.5			0.5	0.10			0.10
5.44	Automatically unclamp frame and Lift frame off tooling	NVA	1		1		0.20		0.20	
5.45	Turnover frame and transfer to fixing station 2	NNVA	4.31			4.31	0.88			0.88
5.46	Datum frame and Clamp frame in place	VA	1	1			0.20	0.20		
5.47	Insert TEK Screw to hold sections together	VA	6.78	6.78			1.38	1.38		
5.48	Frame transfers to CP Board and Rework Station	NNVA	0.5			0.5	0.10			0.10
5.49	Visual inspection on frame connection	NNVA	0.5			0.5	0.10			0.10

5.50	Manually Rework on failed joints	NVA	1		1		0.17		0.17		
5.51	Deliver CP Board in kits to loading area	NVA	1		1		0.33		0.33		
5.52	Load CP board	NVA	1		1		0.54		0.54		
5.53	Transfer frame to CP Board Screw station	NNVA	0.5			0.5	0.10			0.10	
5.54	Screw CP board to frame	VA	7.33	7.33			1.49	1.49			
5.55	Visual Inspection on connections	NNVA	0.5			0.5	0.10			0.10	
5.56	Manually rework on framed joints	NVA	1		1		0.17		0.17		
5.57	Frame transfers to Unload station	NNVA	0.78			0.78	0.16			0.16	
5.58	Tilt frame to 90degrees and lift off line	NNVA	5.1			5.1	1.04			1.04	
5.59	Load panels on transport trolley	NVA	2		2		0.66		0.66		
		Total Time (Min)/Cost (£)	58	22	21	15	£12.65	£4.46	£5.20	£3.00	
		Total Time/Cost (%)	100	38	37	26	100	35	41	24	

Appendix D – Process Maps for OSM Production Process

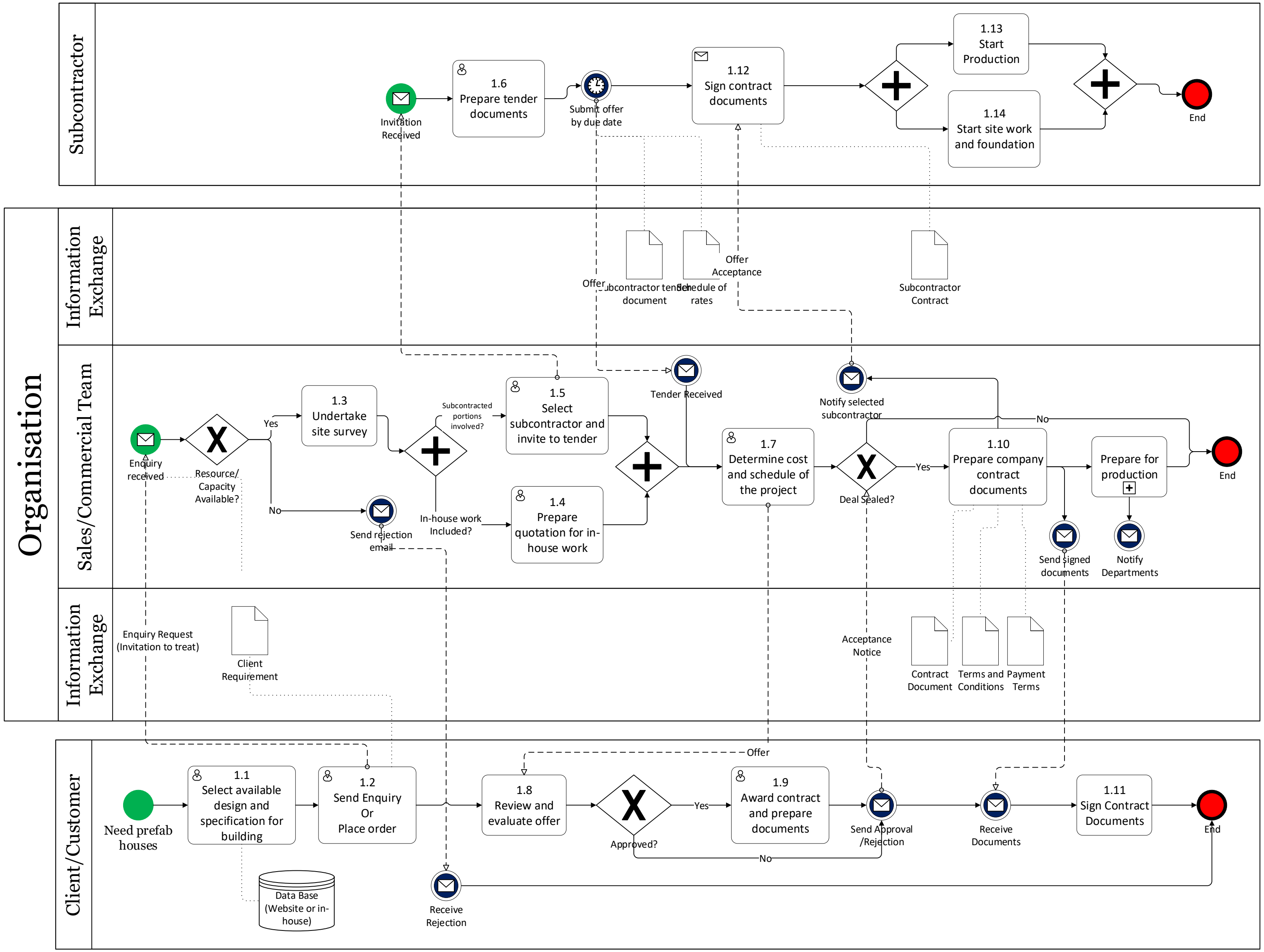


Figure 11.1: Offsite Business Organisation Level Process Map (Level 1)

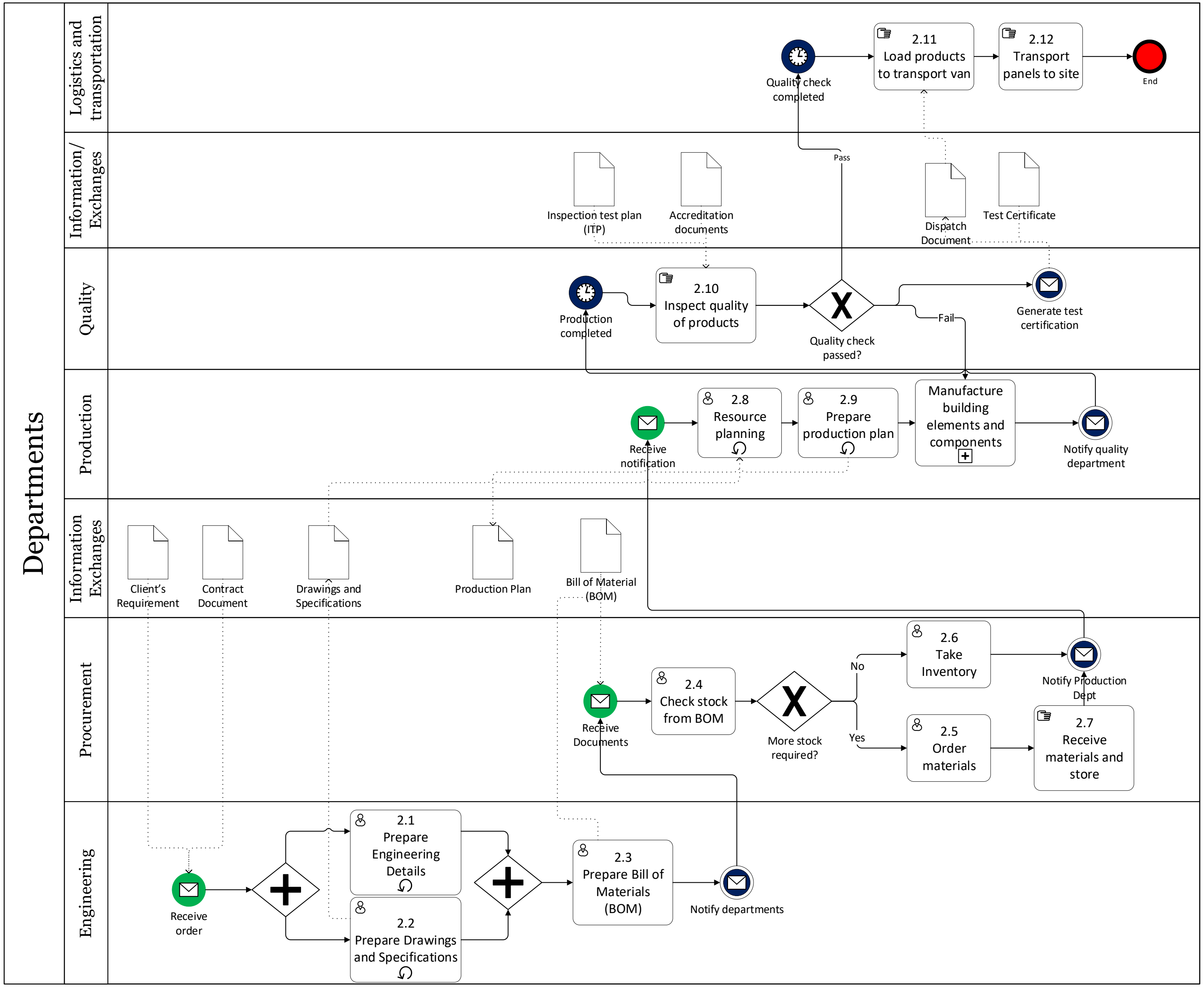


Figure 11.2: Offsite Departmental Level Process Map (Level 2)

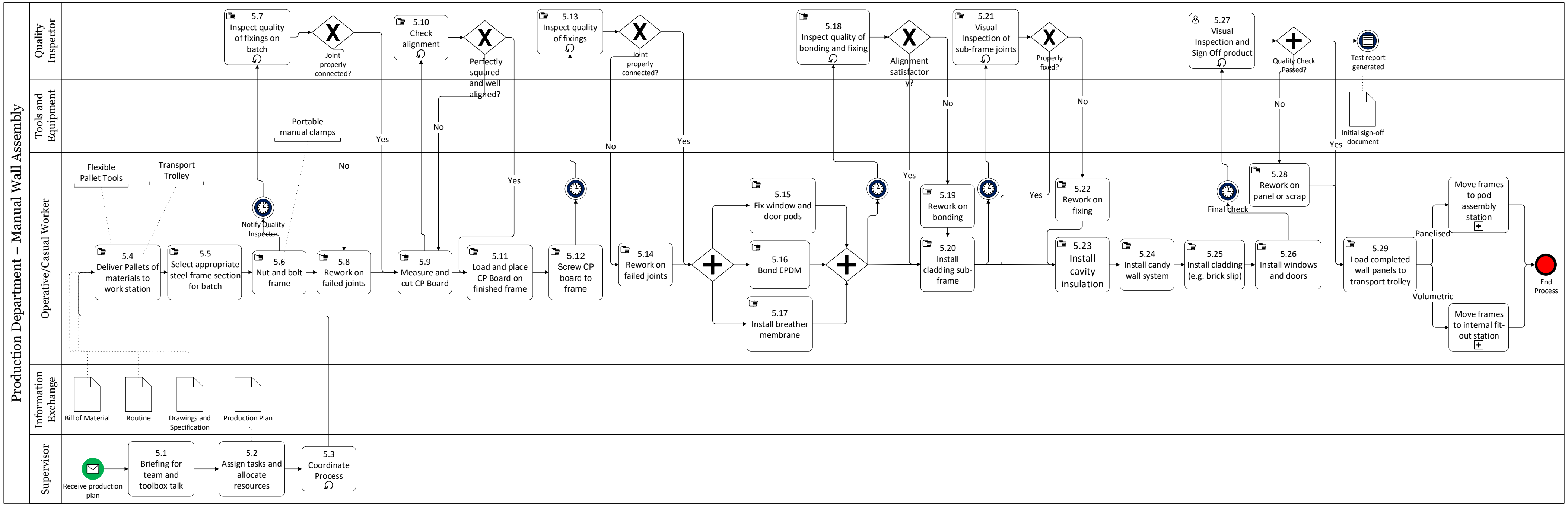


Figure 11.3: Manual frame and cladding assembly process map for the static production method

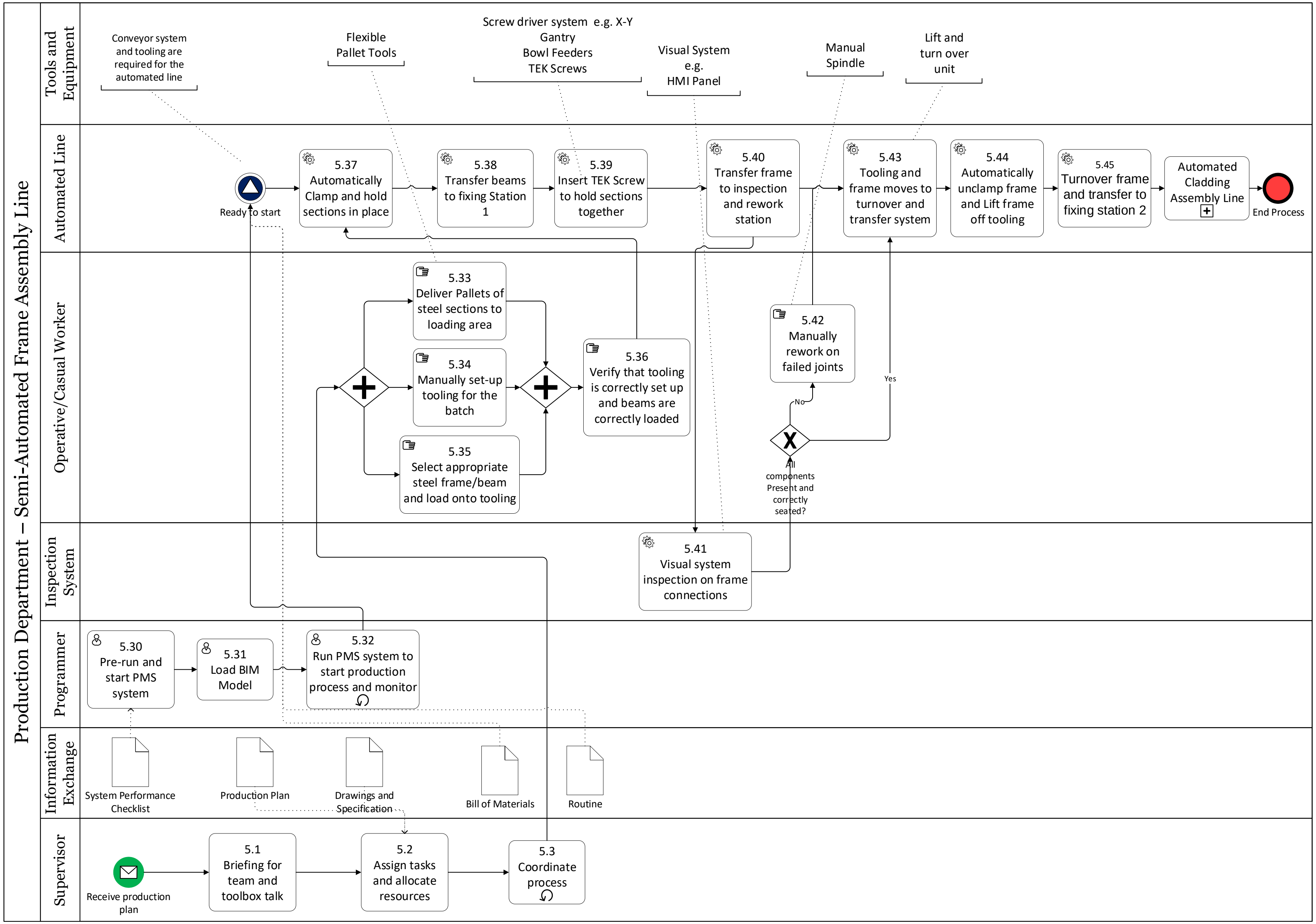


Figure 11.4: Automated frame assembly process map for semi-automated linear method

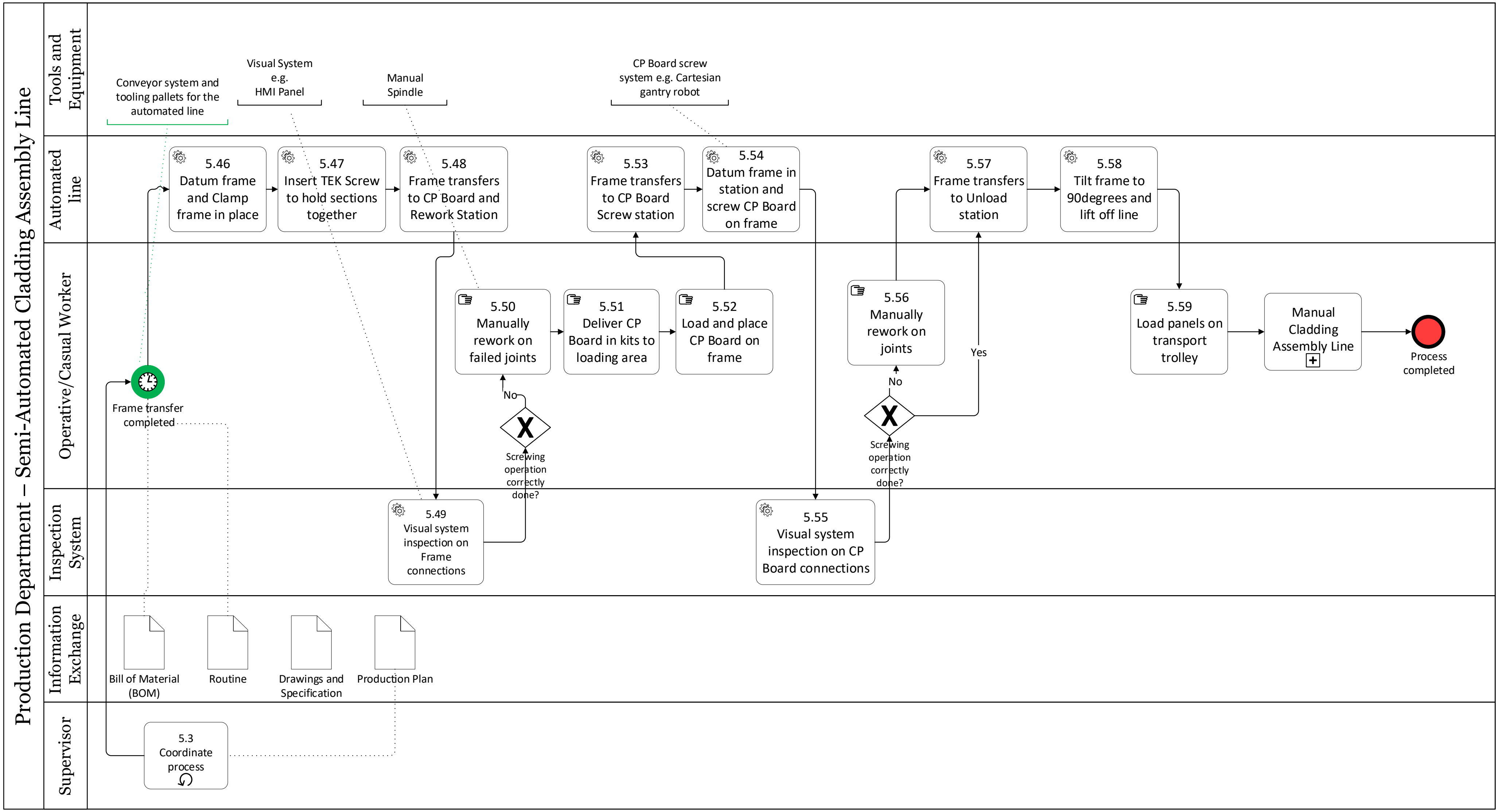


Figure 11.5: Automated cladding assembly process map for semi-automated linear method

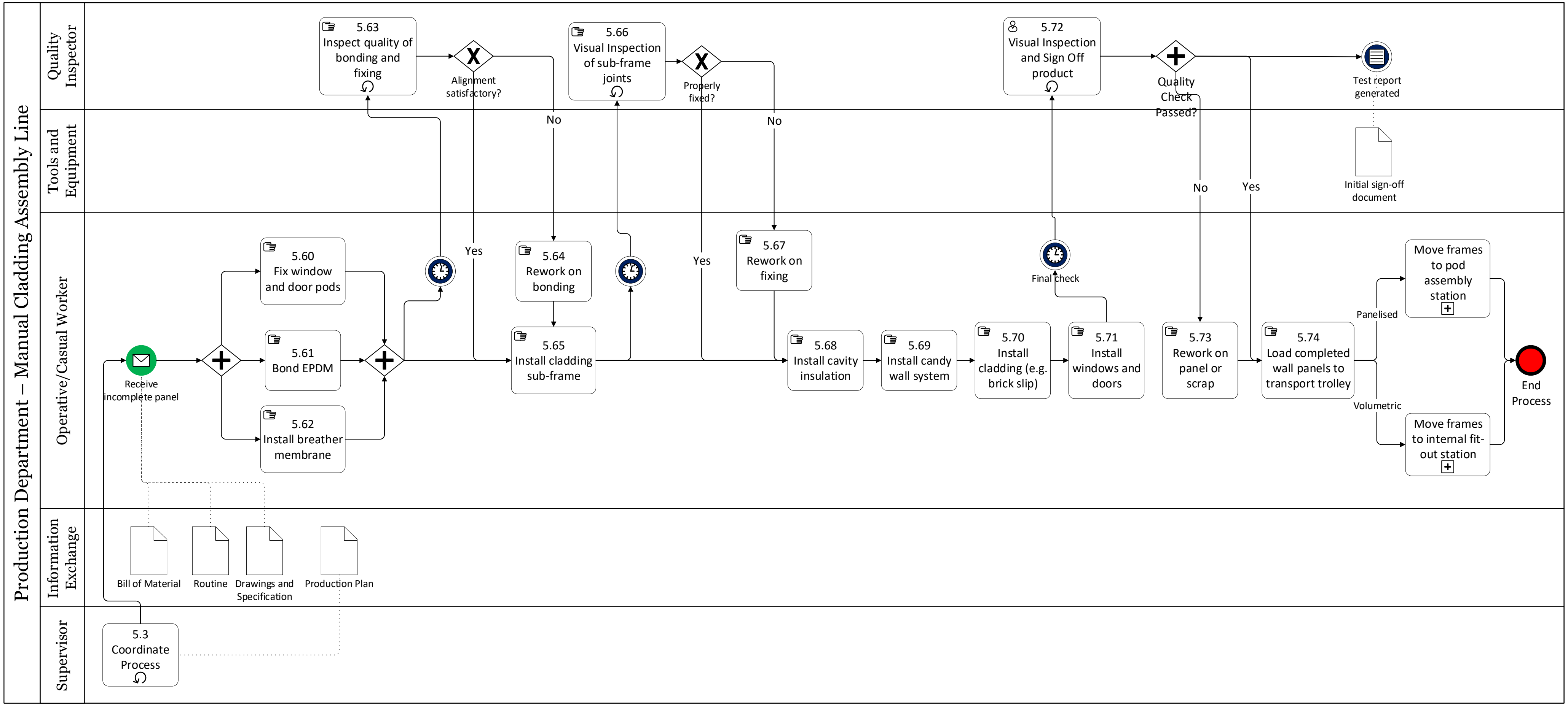


Figure 11.6: Manual cladding assembly process map for semi-automated linear method

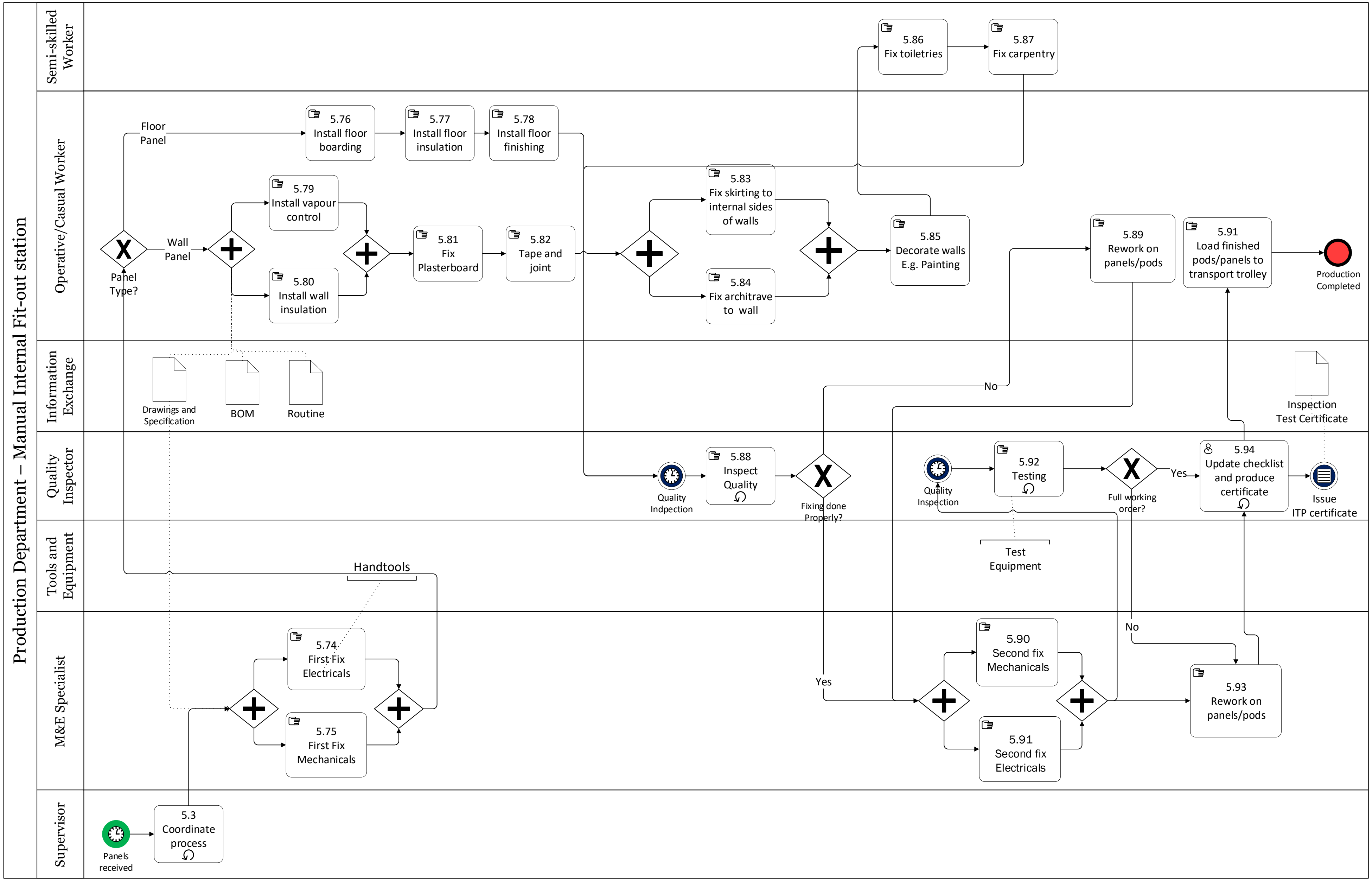


Figure 11.7: Manual Internal fit-out Process Map

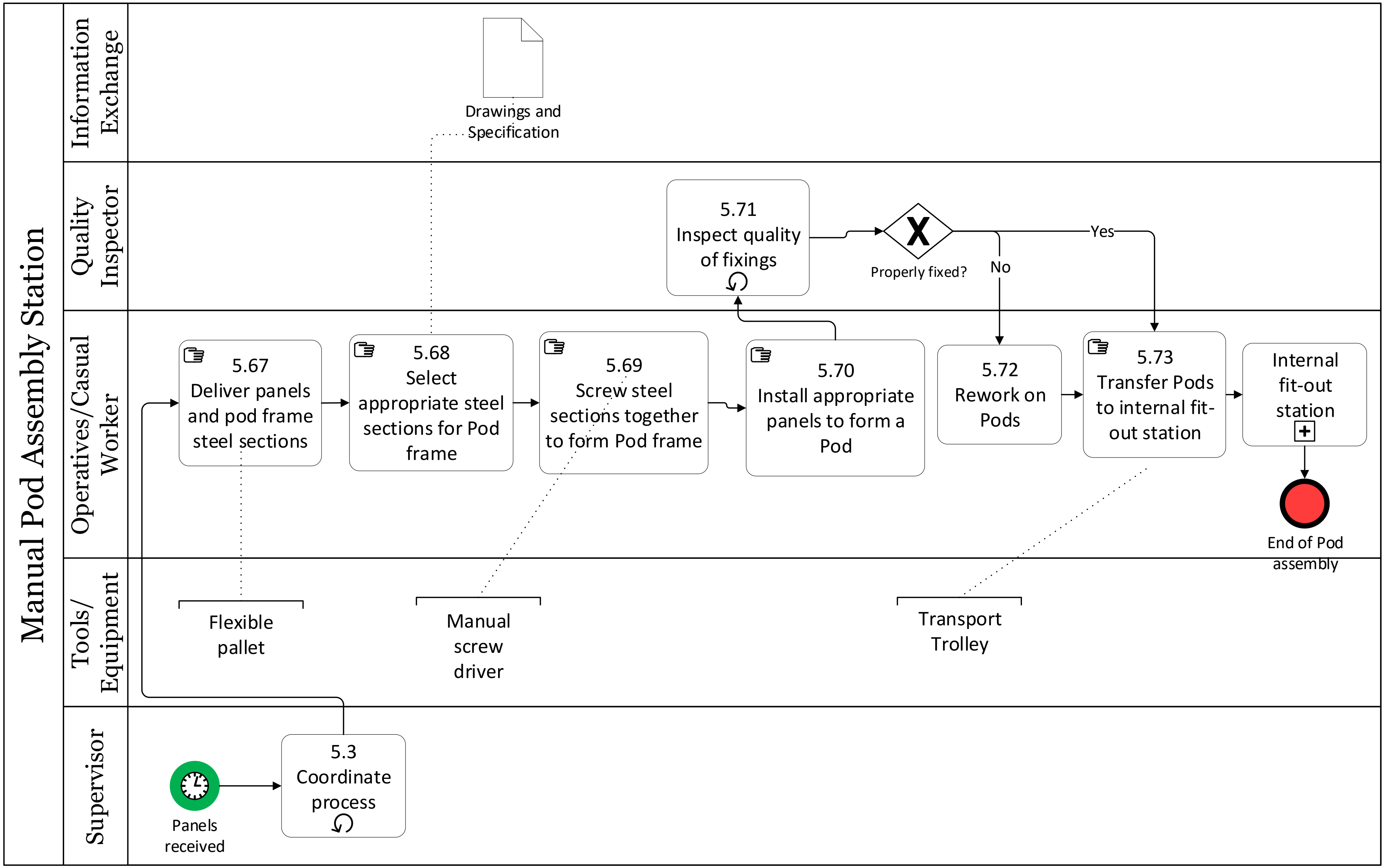


Figure 11.8: Manual Volumetric Pod Assembly Process Map

Appendix E – Publications

TOWARDS AN ONTOLOGY-BASED APPROACH TO MEASURING PRODUCTIVITY FOR OFFSITE MANUFACTURING METHOD

Kudirat Ayinla[1], Franco Cheung[2] and Abdel-Rahman Tawil[3]

[1&2] School of Engineering and the Built Environment, Birmingham City University, Millennium Point, Birmingham, West Midlands, B4 7XG, UK

[3] School of Computing and Digital Technology, Birmingham City University, Millennium Point, Birmingham, West Midlands, B4 7XG, UK

The steady decline of manual and skilled trades in the construction industry has increased the recognition of offsite manufacturing (OSM), an aspect of Design for Manufacture and Assembly (DFMA) methods as one way to boost productivity and performance. However, existing productivity estimation approaches are carried out in isolation thus limiting the sort of result obtained from such systems. Also, there is yet to be a holistic approach that enables productivity estimation using different metrics and integrates experts' knowledge to predict productivity and guide decision making at the early development stage of a project. This study aims to develop a method that can be used to generate multiple estimations for all these metrics simultaneously through linking their relationships. An ontology-based knowledge modelling approach for estimating productivity at the production stage for OSM projects is proposed. A case study of panel system offsite is used as a proof-of-concept for data collection and knowledge modelling in an ontology. Results from the study through the use of rules and semantic reasoning retrieved cost estimates and time schedule for a panel system production with considerations for different design choices. It is thus proven that systemising the production process knowledge of OSM methods enables practitioners to make informed choices on product design to best suit productivity requirements. The developed method helps to reduce the level of uncertainty by encouraging measurable evidence and allows for better decision-making on productivity.

Keywords: DFMA, estimating, offsite-manufacturing, ontology, productivity.

INTRODUCTION

The improvement of productivity and performance has long been an area of interest in the construction sector. Labour productivity in construction is reported to be low compared to that of other sectors, e.g. manufacturing (Eastman and Sacks 2008), which has led to several questions including whether productivity is accurately measured in the first place. This is mostly linked to the long-standing inefficiency associated with conventional methods of construction. The impact of low productivity is significant as it affects economic growth and welfare of a country. For instance, the level of productivity has been linked directly to the affordability of housing (Tran and Tookey 2007). Traditionally, the performance measurement of construction works is based on project time, cost and quality. More recently, other indicators such as client satisfaction and environmental requirements, etc. have been included (Bassioni et al. 2004, Robinson et al. 2005). The use of performance benchmarking through key performance indicators (KPIs) are very common in the industry (Robinson et al. 2005, Yang et al. 2010). These criteria are mostly qualitative and can be subjective. More importantly, there is arguably a lack of productivity measurement, including estimating and measuring the actual productivity with the use of KPIs. There are also views that the construction industry in many countries are not doing well in terms of measuring productivity (Tran and Tookey 2007, Kenley 2014) due to the craft-based nature of the industry.

Since the recent propagation of cross-industry learning from other sectors (e.g. manufacturing) to construction in the UK (Pan and Sidwell 2011), the industry has started to implement production processes similar to that of manufacturing. An example is through the implementation of Design for Manufacture and Assembly (DFMA) concepts such as offsite manufacturing (OSM). OSM presents a way to reduce the number of on-site personnel by moving some major aspects of the construction process to a controlled environment and is continuously getting recognised as a way to boost the productivity of the construction industry (Huang et al. 2009). As construction operations are being moved to manufacturing in OSM, it gives the industry an opportunity to consider approaches being used in manufacturing such as the use of knowledge-based approaches through ontology knowledge modelling to estimate, measure and improve productivity. An ontology is used to formally represent knowledge in a particular domain and supports rules and reasoning in order to facilitate computer processing and knowledge sharing. The development of ontology can enable automated productivity estimation, which can be essential to facilitate continuous improvement as it can provide real-time estimates as feedback for design development.

In this study, a review of existing productivity measurement methods and frameworks commonly used in the construction sector is carried out in order to acquire an understanding of their applications, limitations, and to identify opportunities for improvement. The potential for the use of ontology in modelling the knowledge of the product development stage of OSM projects for estimating productivity is revealed using the case of a panel system manufactured off-site. A framework to represent the ontology for cost and time productivity estimation is proposed and implemented using the ontology editor (Protégé) to facilitate reasoning and computation. This is supported with semantic rules to enable estimation of the production cost and time for offsite manufacturing method.

PRODUCTIVITY IN A CONSTRUCTION CONTEXT

Performance and productivity are sometimes used interchangeably by practitioners. However, these words are different and are measured using a set of different criteria. Performance measurement is said to involve a process of establishing a set of parameters/criteria of desired results at which actual results are measured against (Yang et al. 2010). Productivity, on the other hand, is defined as the level of efficiency in terms of using resources in the production of goods and services (Tran and Tookey 2007). Productivity is calculated as a measure of an output of a process to the corresponding input over a given period of time (Cox et al. 2003). Performance measurement includes a more comprehensive analysis of some indicators which can be both financial (e.g. turnovers, cash flow, profit and share price) and non-financial(e.g., client satisfaction, client changes, motivation, business performance and health and safety) (Cox et al. 2003). Hence, productivity is an aspect of performance or can be described as a measure of 'process performance'.

According to previous researches (Kenley 2014, Yi and Chan 2014), the productivity in the construction industry has different meanings across the disciplines. Although it is mostly measured as the ratio of input and output, the expected type of input and output differs based on disciplines. A common approach in measuring construction productivity is to observe from different levels. Kenley (2014) categorised it using three levels: (i) onsite productivity - measured according to labour output, activity scheduling and resource management (as the classification may not have taken into account off-site activities, a more appropriate expression would be project level productivity) (ii) firm productivity - measured best practices, innovativeness and management ability across projects, (iii) industry productivity measured according to research, training, standards, investments and skills. At each level, productivity has different methods of measurement. This study looks at a more finite level than project level, i.e. offsite production level. The measurement at the offsite production level is described in the next section.

Measuring construction productivity with respect to time, cost and quality

A commonly used technique for measuring productivity at an offsite production level is the evaluation of the 'man hour per unit'. This approach is used to measure labour productivity by determining the ratio of the input to output (i.e. input/output). Usually, a lower value indicates better result (Park et al. 2005, Malisiovas 2010). The measurement metric for this method is the labour time taken to produce an output. Although simple and direct, the limitation of this method is its inability to measure accurately when the unit output encompasses more work efforts that are not easily quantifiable (Cox et al. 2003). This could be partly because the relationships between variables cannot be determined with this method. Other time-based models include experienced-based models and work sampling method. Experience-based method is one of the oldest methods that have existed before the development of technology-based approaches, where productivity is mainly measured based on expert's experience and compared to previous similar projects (Malisiovas 2010). The reliability of this method is not guaranteed due to the uniqueness of construction projects and the subjectivity of personal judgement. Work sampling method uses a statistical sampling theory to measure the time involved to complete various activities. It identifies productive work hours from the overall work hours by collecting data through methods such as video recording, observation tour, time-lapse photography and many more (Thomas et al. 1990). The limitation of these time-based models for control is that they ultimately focus on measuring the time taken to produce an output alone, which can be at the expense of controlling other factors such as cost and quality. Reducing the time taken does not equate to obtaining the best quality and optimum cost.

There exist also some cost-based models that utilise cost as a measure of productivity. A common and simple approach is the evaluation of 'cost/unit' i.e. the pounds' value associated with producing one unit of work. This is an aggregation of cost variables such as the material, labour, plant, and waste. Similar to the 'man-hour per unit' method, this approach also fails to give an accurate measure for a more complicated unit of output. Another method using cost metric is the cost reporting method used to monitor productivity rate by benchmarking and comparing cost against past projects. This is mostly used internally by organisations and requires historical data from past projects (Malisiovas 2010). Data collection can be very time consuming and prone to error. Also, possible causes of low productivity cannot be determined hence, limited opportunity for improvement. Lastly, productivity can be measured using the quality of work as the metric of measurement. The 'quality control/rework' method measures productivity by calculating the change in time and cost (i.e. man-hours and aggregated cost) for an output due to a repair work (Cox et al. 2003). Reducing the amount of rework on a job reduces the unit cost and thus profit for a specific task is increased.

The discussed methods all present a good means of measuring the productivity of a process. However, they are limited to the use of just one metric at a time for measuring productivity as typically, cost, time, or quality productivity matrices are estimated and measured independently. Also, there is a challenge in collecting relevant information for estimation and comparison. For instance, an increase in output may not lead to an improvement in quality. Likewise, reduced time may reduce the cost associated with labour, it does not change other cost variables such as materials, plant, waste, and rework. Therefore, there is a need to develop an approach that can be used to generate multiple measurements for all the metrics simultaneously through linking their relationships. The multiple productivity measurements will give a greater opportunity to improve design decisions.

Ontology-based productivity measurement for DMFA project

Ontology is the act of 'formally' representing 'explicit' knowledge based on a shared 'conceptualization' (Gruber 1995). It is used to formalise the shared world view (idea or knowledge) of a community so as to aid understanding and communication. Ontologies are capable of modelling knowledge in a domain as well as their interrelationship and features as an advancement of locally-based knowledge repositories as it enables the use of artificial intelligence to facilitate automated expert advice (Cutting-Decelle et al. 2007). The development of rules in an ontology facilitates reasoning which is used to generate results that mimic an expert's decision. Given these functions, ontology can be applied in facilitating multiple productivity measurements. This is particularly important in terms of generating multiple units of productivity measurements simultaneously in a factory production line setting.

OSM involves different variables and input that can be measured in terms of productivity. Compared to conventional construction methods which are labour intensive and workforces are the dominant productive resources (Yi and Chan 2014), OSM involves moving construction operation to a closed environment and the use of methods similar to manufacturing. Hence, reduced human labour is needed to complete a task in OSM. The productive resources for a manufacturing method are both the tools (robotics, machines) and the workforces (onsite and offsite) as the construction method is not craft-based. Therefore, whereas labour input is the most measured factor for the conventional method, there is arguably a need to include other inputs in the case of manufacturing. For DFMA projects, these inputs will typically include product related features (such as the size, weight, structural stability), production and assembly factors (in terms of sequence, activities, and resources). Therefore, systemising knowledge of the different stages of OSM through creating an accurate representation of the relationships between productivity metrics with an ontology can facilitate automatic generation of multiple measurements of productivity.

The ontology development in this study aims to represent the underlying principles and concepts of OSM as well as their interrelationships to enable productivity measurement. Experts' knowledge is also modelled in the knowledge-base so as to facilitate reasoning and improve the output from the computation.

METHODOLOGY

In order to fulfil the aim of the research (to understand the production process of OSM so as to estimate the productivity of the process) a case study approach is selected. This method is considered the best match in fulfilling the aim of the research because a holistic in-depth exploration and understanding of OSM production process is required (Yin 2009). This sort of data (primary data) required for developing the ontology is not readily available in literature and most likely gathered through an in-depth study of the phenomenon (OSM) in its real-life context. A single-case design is adopted as the study seeks to develop a proof-of-concept and one case is deemed acceptable to prove or disprove the idea (Yin 2009). The choice of case study is guided by (i) availability of data on different types of product and processes (ii) use of advanced methods production process (robots) that allows time metric to be measured automatically. The selected case fulfils these criteria.

The use case features a light steel frame (LSF) panelised offsite production process on a manufacturing line in the factory for a 2-storey semi-detached house. Multiple sources of data are used to develop the ontology for real-time productivity estimation. Data collection was done in two phases, first is through document review (technical documents including as-built drawings, process flow documents, cost and time schedule documents, and quality reports). The data from this stage is used to populate the product and process ontology (i.e. concepts generation and classifications) and compilation of information about the production and assembly sequences, resource allocations, and cost and time schedules. The second phase of data collection was done through focus groups and discussions with professionals (the design and production team). The purpose is to capture expert knowledge regarding design decisions that influences productivity and also to verify the ontology developed. The last stage verification also features a validation process where expert result is compared to the result from the ontology.

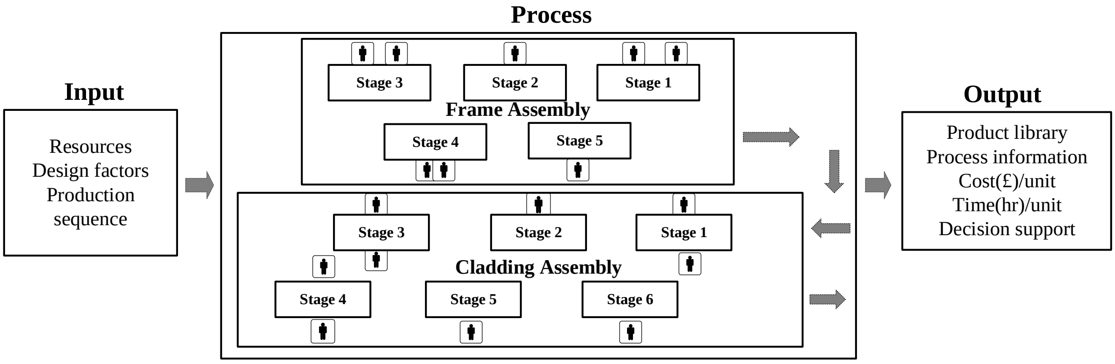


Figure 9: LSF panel system semi-automated linear production process

The production method modelled in this case is a 'semi-automated linear production process' where stages are sequential and some of the processes are automated (Figure 1). The breakdown of the production sequence on the line is identified and the corresponding task at each stage modelled. The 2-storey semi-detached house is separated into panels - wall panels, floors panels, etc. Each of these is further broken down into a number of smaller units panels (up to 32 external units) as output from the production line. The factory production process consists of two major stages – frame assembly (building skeleton) and cladding assembly (building enclosure). The materials, upon reaching the factory move through these stages (which are further broken down into tasks) until each unit is completed (Figure 1). The ontology thus models the knowledge of the input and the process to measure the output. Rules and queries included in the ontology are those that enable the answers on productivity and design factor implication to be retrieved.

The ontology development process follows Meth-ontology approach, one of the ontology development methods widely encouraged by researchers because it thoroughly analyses the lifecycle of an ontology (Fernandez et al. 1997, Corcho et al. 2003). The Meth-ontology guideline steps followed are: (i) the specification of objectives (ii) gathering information from a case study (iii) the conceptualisation - development of a semi-formal representation of the knowledge (iv) the formalisation - representing the knowledge formally using an ontology builder/editor (Protégé) (v) the implementation - representing the ontology in a machine-readable language (Web Ontology Language - OWL) (vi) the evaluation of results. Due to the interest in cost and time estimation, the high-level classification and properties used to describe the products is according to the UK standards based on the New Rules of Measurement 2 (RICS 2012). For lower level classification, there is not enough granularity in NRM2 to classify the complex offsite concepts. Thus, a bottom-up approach according to how experts are classifying components and aggregating cost per unit is adopted based on the case study to develop the ontology.

ANALYSIS AND RESULTS

The analysis and results follow the MethOntology approach explained in the previous section. The first two stages have been covered in the methodology section.

(i) Conceptualisation – this stage features the development of a semi-formal representation of the knowledge gathered. Figure 2 shows the architecture of the system which is designed such that information on specific intended questions (i.e. related to cost/unit or time/unit) can be retrieved. Their relationships follow as: panelised production system (PanelSystemProduction) is composed of some production stages (ProductionStages) and has outputs in the form of panels (Products). The products are composed of some materials (Material), and the production stages are composed of some activities (JobTask) which requires operatives (Labour) and tools (Tools) to be executed.

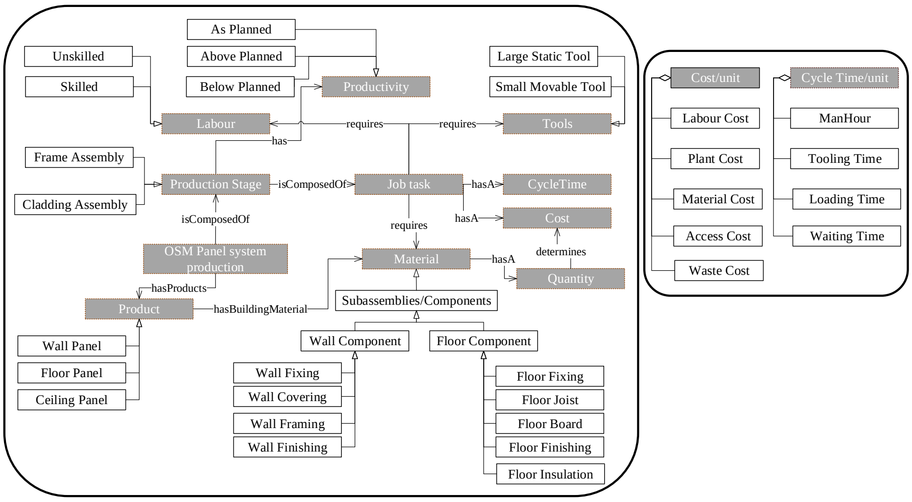


Figure 10: Structure of the OSM Panel System Productivity

(ii) Formalisation – the knowledge from the conceptual design is further developed formally in an ontology builder/editor (Protégé). Each class is populated with subclasses and property assertions is used to build relationships between the instances of a class or to link an instance to a data value. Object properties are included to describe the relationship between a product and its resources or production process (Figure 3). Data-type properties are included to allow the computation of values used to determine productivity such as length, width, height, area, quantity, counts, etc. The productivity in terms of cost/unit is determined through aggregation of labour, material, plant, transportation and waste costs. Similarly, the time/unit is determined through an aggregation of the man-hour (work done by operatives), tooling time (for robots operations), loading time (putting the panels in position) and waiting time (from one station to another). To allow the ontology to compute the cost/unit and time/unit for each panel, Semantic Web Rule Language (SWRL) rules are included to facilitate reasoning and enable inferences about an instance.

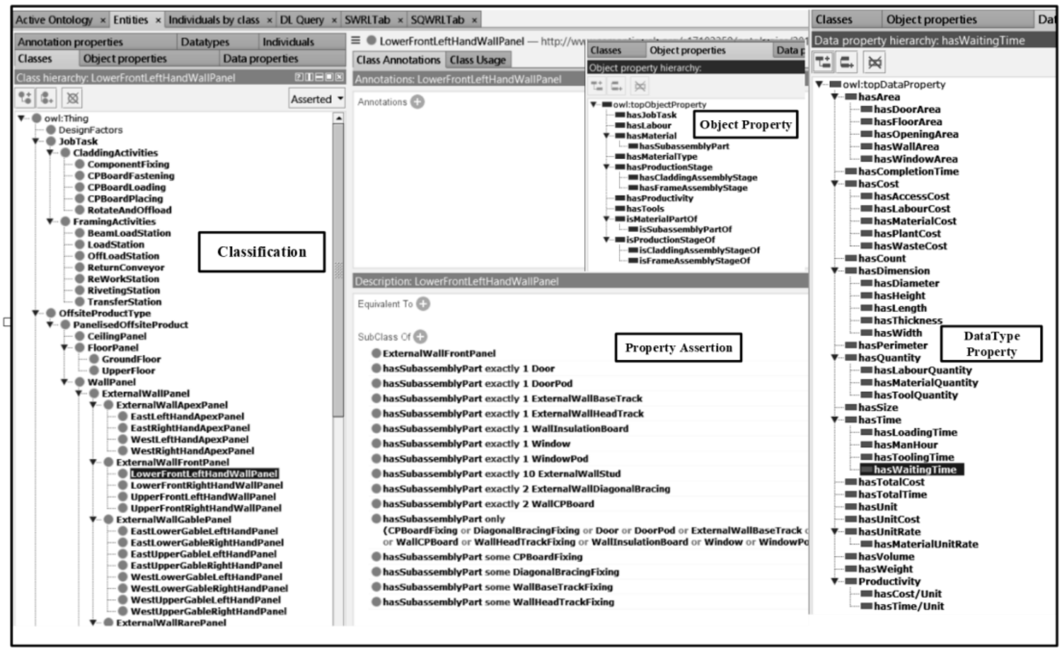


Figure 11: Modelled concepts in the ontology with Protégé

(iii) Implementation - the ontology is represented in a machine-readable language (Web Ontology Language - OWL) to enables rich set of modelling constructors. Rules are built into so as to query the ontology to retrieve information such duration of activities/task, type and number of operatives for a task, materials for a panel etc. In order to calculate cost, quantities must first be calculated. For wall panels, the quantity of cladding material for each wall panel is first calculated and this is multiplied by the corresponding unit rate. The SWRL rule to calculate the quantity and then the cost are as follows:

WallCladdingComponents(?wc) ∧ hasLength(?wc, ?l) ∧ hasHeight(?wc, ?h) ∧ swrlb:multiply(?ca, ?l, ?h) -> hasWallArea(?wc, ?ca)

WallCladdingComponents(?c) ∧ hasWallArea(?c, ?a) ∧ hasUnitCost(?c, ?u) ∧ swrlb:multiply(?q, ?a, ?u) -> hasMaterialCost(?c, ?q)

For this rule, an instance of a wall cladding (e.g. Cement Board) with an already specified length and height (in the ontology) is invoked and the SWRL built-in function – swrlb:multiply is used to relate these data in order to compute the quantity of the material. This results from running the rule are then picked up by the reasoner and fed back into the ontology as inferred properties (see Figure 3). However, swrl built-ins are not able to create expressions for obtaining a sum of a set of instances (i.e. nx) due to the open world reasoning assumption. Therefore, the SQWRL's operators are used to query the ontology in order to retrieve information for this purpose. A query is this used to select the duration (time) of the production stage of a panel as follows:

WallPanel(?p) ^ hasProductionStage(?p, ?pr) ^ hasLoadingTime(?pr, ?lt) ^ hasWaitingTime(?pr, ?wt) ^ hasManHour(?pr, ?mh) ^ hasToolingTime(?pr, ?tt) ^ swrlb:add(?t, ?lt, ?tt, ?wt, ?mh) . sqwrl:makeBag(?b, ?t) . sqwrl:size(?n, ?b) -> sqwrl:select(?p, ?pr, ?n, ?lt, ?wt, ?tt, ?mh, ?t)

From the query result (Figure 4), the total time for all activities for the wall unit (panel 4) can be calculated by summing up the retuned values. This gives an estimate of cycletime/unit (t) for that product through an aggregation of the sum of the man-hour (mh), tooling time (tt), loading time (lt) and waiting time (wt).

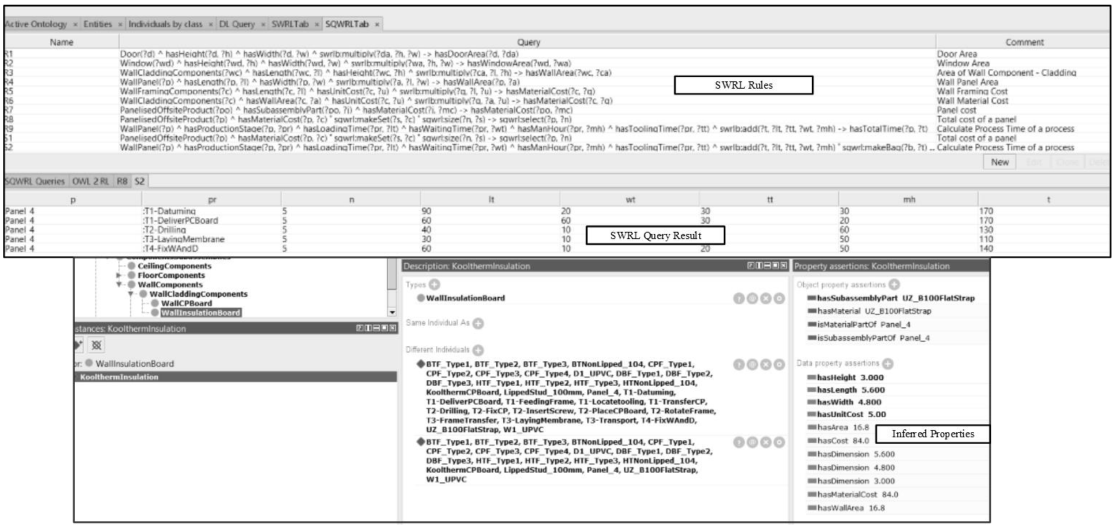


Figure 4: SWRL rules to enhance reasoning and computation in the ontology

Also, the results from Figure 4 includes some design decisions specified on the product and process. Evaluations of the implications of design changes on products (e.g. size, weight and geometry of the panels) and process changes (e.g. reduced/increase labour for a particular operation and/or the introduction of robots to automate some activities) are captured in the knowledge-based system. An example is implemented in the ontology through a rule to evaluate the implication of panel sizing on cost and time per unit. The rule is included in the ontology to classify an instance of a wall panel with an area greater than 30m2 as big and thus consequently increase the number of operatives (for handling) in all stations by one.

WallPanel(?x) ^ hasWallArea(?x, ?a) ^ swrlb:greaterThan(?a, 30) -> LargePanel(?x)

LargePanel(?lp) ^ hasOperativeCount(?p, ?c) ^ swrlb:add(?b, ?c, 1) -> hasLabour(?lp, ?b)

For this rule, an instance of a wall panel with an area greater than 30m2 is considered big and thus consequently, an increase of plus one on the number of operatives at all stations in order to give allowance for handling. This rule is to guide decisions and inform choices regarding considerations of alternatives where possible.

DISCUSSION

The results from the analysis show that there is a possibility of estimating both cost and time metrics of productivity simultaneously. The SWRL rules enabled inclusion of mathematical expressions and formula to calculate the cost of the products by determining the quantities of materials and subsequently the costs of labour, materials, and machining for each offsite panel. After running the rules and invoking the reasoner, the cost of materials, labour and plant for each component of a panel are generated (Figure 4). Similarly, the rules developed are used to estimate the production time for each panel, the result from the reasoner generates the material loading time, tooling time, waiting time and man-hour (Figure 4). This presents a way to generate cost and time metrics and combine previous measurement approaches commonly used in the industry such as cost/unit (Cox et al. 2003) and time/unit (Malisiovas 2010). Also, experts' knowledge on design implications and production sequence captured in the ontology influences the result from the reasoning process.

The challenge with the use of the knowledge-based system and the rule development is that it is limited to some simple mathematical expressions. For instance, generating the overall total cost/unit and time/unit for all 32 panels is challenging because of the limited capabilities of SWRL and summing up the results from individual panels needs to be done manually or using other systems (e.g. Excel). This implies that there is a need to achieve these other tasks using other means. Using an external user interface and system can come handy in performing these tasks. An Application Programme Interface (API) such as OWL-API can be used to link the knowledge-base with an external application to perform these operations. OWL-API can interact with the ontology to fetch data needed to generate estimates for cost/unit and time/unit.

Also, compared to the onsite construction method, one of the challenges encountered in formalising the knowledge is that offsite processes vary in products, process, and equipment used for manufacturing; e.g., timber offsite production varies significantly in products, processes, and techniques from that of steel or concrete. Similarly, compared to manufacturing, construction projects are often times unique and sometimes have non-repetitive operations thus limits the effort in measuring productivity of the process. The ontology will need to be expanded in its capacity so as to capture changing conditions that happen frequently in construction. Continuous changes or alterations in the OSM processes or operations are necessary to cope with the market requirements, and largely influenced by individual project requirement.

CONCLUSIONS

The study presents an ontology-based approach to estimating cost and time metrics for measuring the productivity of the manufacturing process of offsite method using a panel system OSM as a proof-of-concept. It is proven that an ontology-based estimation is effective in allowing more than one metric of productivity measurement to be obtained such as cost and time. The study concludes that the development of an ontology to capture the knowledge of the OSM products and processes although will not directly improve productivity, can help with decision support on product and process design at the PD stage which can influence productivity significantly. The use of an ontology to model alternatives choices at the PD stage will be able to give a clearer picture of output for every change in input through the estimation of the process performance indicators. Given that the use of rules (i.e. SWRL) is limited to some mathematical expressions, further work on communicating with the ontology through an Application Programme Interface (API) such as OWL-API and linking with other systems will need to be explored to perform these operations.

REFERENCES

AAQS, 2016. *Guide to Elemental Cost Estimating & Analysis for Building Works 2016*. Second.

Abanda, F.H., Tah, J.H.M., and Cheung, F.K.T., 2017. BIM in off-site manufacturing for buildings. *Journal of Building Engineering*, 14 (September), 89–102.

Abanda, F.H., Taj, J.H.M., Pettang, C., and Manjia, M.B., 2011. An ontology-driven building construction labour cost estimation in Cameroon. *Journal of Information Technology in Construction (ITcon)*, 16, 617–634.

Abdullah, M.. and Egbu, C.., 2010. Selection criteria frameword for choosing industrialized building systems for housing projects. *In*: C. Egbu, ed. *Procs 26th Annual ARCOM Conference, 6-8 September 2010*. Leeds: Association of Researchers in Construction Management.

Abdullah, M.R. and Egbu, C.O., 2009. *Industrialised building system in Malaysia: Issues for research in a changing financial and property market*. Proceedings of the BUHU 9th International Post Graduate Research Conference.

Abdulmalek, F.A. and Rajgopal, J., 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of Production Economics*, 107 (1), 223–236.

Abosoad, H., Underwood, J., and Boreny, S., 2009. Towards an Information System Representation of off Site Manufacturing (OSM) in Facilitating the Virtual Prototyping of Housing Design. *In*: *9th International Postgraduate Research Conference (IPGRC)', University of Salford, Salford, UK*. 509–520.

Adamides, E.D. and Karacapilidis, N., 2006. A knowledge centred framework for collaborative business process modelling. *Business Process Management Journal*, 12 (5), 557–575.

Adeli, H. and Wu, M., 1998. Regularization neural network for construction cost estimation. *Journal of Construction Engineering and Management*, 124 (1), 18–23.

Afsari, K. and Eastman, C.M., 2016. A Comparison of Construction Classification Systems Used for Classifying Building Product Models. *In*: *52nd ASC Annual International Conference Proceedings*. Associated Schools of Construction.

Aguilar-Savén, R.S., 2004. Business process modelling: Review and framework. *International Journal of Production Economics*, 90 (2), 129–149.

Ahmed, V., Opoku, A., and Aziz, Z., 2016. *Research Methodology in the Built Environment: A selection of case studies*. New York: Routledge.

Akasah, Z.A., Amirudin, R., and Alias, M., 2010. Maintenance management process model for school buildings: An application of IDEF 0 modelling methodology . *Australian Journal of Civil Engineering*, 8 (1), 1–12.

Akintoye, A. and Fitzgerald, E., 2000. A survey of current cost estimating practices in the UK A. *Construction Management & Economics*, 18, 161–172.

Akyol, D.E., Tuncel, G., and Bayhan, G.M., 2007. An Analysis of Activity-Based Costing in a Manufacturing System. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, 1 (11), 1040–1043.

Aldridge, G., Pasquire, C., Gibb, A., and Blismas, N., 2001. Methods for Measuring the

"Unmeasurable": Evaluating the Benefits of Pre-Assembly and Standardization in Construction. *In*: *17th Annual ARCOM Conference, 5-7 September 2001, University of Salford. Association of Researchers in Construction Management*. 311–9.

Almeida, A. and Cunha, J., 2017. The implementation of an Activity-Based Costing (ABC) system in a manufacturing company. *Procedia Manufacturing*, 13, 932–939.

Alonso, R., Borras, M., Koppelaar, R.H.E.M., Lodigiani, A., Loscos, E., and Yöntem, E., 2019. SPHERE: BIM Digital Twin Platform. *Proceedings*, 20 (1), 9.

Arafa, M. and Alqedra, M., 2011. Early Stage Cost Estimation of Building Construction Projects using Artificial Neural Networks. *Journal of Artificial Intelligence*, 4 (1), 63–75.

Arbizzani, E. and Civiero, P., 2013. Technical solutions and industrialised construction systems for advanced sustainable buildings. *In*: *PORTUGAL SB13 - CONTRIBUTION OF SUSTAINABLE BUILDING TO MEET EU 20-20-20 TARGETS*. 371–378.

Arditi, D. and Mochtar, K., 2000. Trends in productivity improvement in the US construction industry. *Construction Management & Economics*, 18 (1), 15–27.

Arif, M. and Egbu, C., 2010. Making a case for offsite construction in Making a case for offsite construction in China. *Engineering Construction & Architectural Management*, 17 (6), 536–548.

Assaf, S.A. and Al-Hejji, S., 2006. Causes of delay in large construction projects. *International Journal of Project Management*, 24, 349–357.

Awuzie, B. and McDermott, P., 2017. An abductive approach to qualitative built environment research: A viable system methodological exposé. *Qualitative Research Journal*, 17 (4), 356–372.

Ayachit, A.C., Attarde, P.M., and Kulkarni, S., 2014. Activity Based Costing in Construction. *International Journal of Advanced Engineering Research and Studies*, 4 (1), 9–14.

Ayinla, K.O., Cheung, F., and Tawil, A.R., 2019. Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system. *Construction Innovation*, 20 (2), 223–246.

Badir, Y.F., Kadir, M.R.A., and Hashim, A.H., 2002. Industrialized Building Systems Construction in Malaysia. *Journal of Architectural Engineering*, 8 (1).

Baghchesaraei, A., Kaptan, M.V., and Baghchesaraei, O.R., 2015. Using prefabrication systems in building construction. *International Journal of Applied Engineering Research*, 10 (24), 44258–44262.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., and Wong, I., 2006. Designing out waste in high-rise residential buildings : analysis of precasting and methods and traditional construction. *In*: *The International Conference on Asia-European Sustainable Urban Development*. Chongqing, China.

Baloi, D., 2003. Sustainable construction: Challenges And Opportunities. *In*: *19th Annual ARCOM Conference*. 289–97.

Barber, K.D., Dewhurst, F.W., Burns, R.L.D.H., and Rogers, J.B.B., 2003. Business-process modelling and simulation for manufacturing management: A practical way forward. *Business Process Management Journal*, 9 (4), 527–542.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertran, N., and Brown, S.V., 2017. *Reinventing construction through a productivity revolution*.

Bari, N.A.A., Abdullah, N.A., Yusuff, R., Ismail, N., and Jaapar, A., 2012. Environmental Awareness and Benefits of Industrialized Building Systems (IBS). *Procedia - Social and Behavioral Sciences*, 50 (July), 392–404.

Baxter, P. and Jack, S., 1990. Qualitative case study methodology: study design and implementation for novice researchers. *The Qualitative Report*, 13 (4), 544–559.

Baxter, P. and Jack, S., 2008. Qualitative Case Study Methodology : Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13 (4), 544–559.

Ben-Arieh, D. and Qian, L., 2003. Activity-based cost management for design and development stage. *International Journal of Production Economics*, 83 (2), 169–183.

Bertelsen, S., 2005. Modularization – a third approach to making construction lean? *In*: *13th annual conference in the International Group for Lean Construction*. Sydney, Australia, 1–11.

Blismas, N., Pasquire, C., and Gibb, A., 2006a. Bene t evaluation for o ff-site production in construction. *Construction Management & Economics*, 24 (2), 121–130.

Blismas, N., Pasquire, C., and Gibb, A., 2006b. Benefit evaluation for off - site production in construction. *Construction Management and Economics*, 24 (2), 121–130.

Blismas, N. and Wakefield, R., 2007. Drivers constraints and the future of off-site manufacture in Australia. *Construction Innovation Special Edition*.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114 (January), 103179.

Bottom, D., Gann, D., Groak, S., and Meikle, J., 1996. *Innovation in Japanese Prefabricated House-Building Industries: Department of Trade and Industry Overseas Science and Technology Expert Mission Visit Report*. Construction Industry Research and Information Association.

Brockmans, S., Haase, P., Hitzler, P., and Studer, R., 2006. A Metamodel and UML Profile for Rule-extended OWL DL Ontologies. *In*: Y. Sure and J. Domingue, eds. *ESWC 2006*. Berlin Heidelberg: Springer-Verlag, 303–316.

Bryman, A., 2012. *Social Research Methods*. 4th editio. New York: Oxford University Press.

buildingSMART, 2016. IFC4 Add2 - Addendum 2 [online]. *buildingSMART International Ltd.* Available from: http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/ [Accessed 2 Jan 2019].

Cabinet Office, 2011. *Government Construction Strategy*. London.

Caputo, A.C. and Pelagagge, P.M., 2005. Parametric and Neural Methods for Cost Estimation Of Process Vessels. *In*: *18th International Congress of Mechanical Engineering*.

Carli, G. and Canavari, M., 2013. Introducing Direct Costing and Activity based Costing in a Farm Management System: A Conceptual Model. *Procedia Technology*, 8 (Haicta), 397–405.

Carr, R.I., 1989. Cost - Estimating Principles. *Journal of Construction Engineering and Management*.

Chan, C.W. and Johnstonb, M., 1996. Knowledge modelling for constructing an expert system to support reforestation decisions. *Knowledge-Based Systems*, 9, 41–59.

Chan, E.H.W. and Tse, R.Y.C., 2003. Cultural Considerations in Cultural Considerations in International Construction Contracts. *Journal of Construction Engineering and Management*, 129 (4), 375–381.

Chau, K.W., 1995. The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs : empirical evidence from Hong Kong. *Construction*

Management and Economics, 13 (1), 15–21.

Chau, K.W. and Anson, M., 2002. A Knowledge-Based System for Constr uction Site Level Facilities Layout, 2358, 393–402.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010a. Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction*, 19 (2), 235–244.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010b. Automation in Construction Decision support for construction method selection in concrete buildings : Prefabrication adoption and optimization. *Automation in Construction*, 19, 665–667.

Cheng-Leong, A., Pheng, K.L., and Leng, G.R.K., 1999. IDEF: A comprehensive modelling methodology for the development of manufacturing enterprise systems. *International Journal of Production Research*, 37 (17), 3839–3858.

Cheung, F.K.T., Kurul, E., and Oti, A.H., 2016. A case study of hybrid strategies to create value for a contracting business in the education sector in England and Wales. *Construction Management and Economics*, 34 (4–5), 335–352.

Chevallier, Z., Finance, B., and Boulakia, B.C., 2020. A reference architecture for smart building digital twin. *CEUR Workshop Proceedings*, 2615, 1–12.

Chiang, Y.H., Hon-Wan Chan, E., and Ka-Leung Lok, L., 2006. Prefabrication and barriers to entry-a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, 30 (3), 482–499.

Chou, J.-S., Yang, I.-T., and Chong, W.K., 2009. Probabilistic simulation for developing likelihood distribution of engineering project cost. *Automation in Construction*, 18 (August), 570–577.

Chou, J.S., 2011. Cost simulation in an item-based project involving construction engineering and management. *International Journal of Project Management*, 29 (6), 706–717.

Corcho, O., Fernandez-Lopez, M., and Gomez-Perez, A., 2003. Methodologies , tools and languages for building ontologies . Where is their meeting point ? *Data & Knowledge Engineering*, 46, 41–64.

Corcho, O. and Gómez-Pérez, A., 2000a. Evaluating Knowledge Representation and Reasoning Capabilities of Ontology Specification Languages. *In*: *Applications of*

Ontologies and Problem Solving Methods 14th European Conference on Artificial Intelligence (ECAI'00). 3.1 – 3.9.

Corcho, O. and Gómez-Pérez, A., 2000b. A roadmap to ontology specification languages. *In*: R. Dieng and O. Corby, eds. *EKAW*. Berlin Heidelberg: Springer-Verlag Berlin, 80–96.

Cox, R.F., Issa, R.R.A., Asce, M., and Ahrens, D., 2003. Management ' s Perception of Key Performance Indicators for Construction. *Journal of Construction Engineering & Management*, 129 (2), 142–151.

Creswell, J.W., 2009. *Research Design_ Qualitative, Quantitative, and Mixed Methods Approaches*. Third edit. London: SAGE Publications.

Cutting-Decelle, A.-F., Young, B.I., Das, B.P., Case, K., Rahimifard, S., Anumba, C.J., and Bouchlaghem, D.M., 2007. A Review of Approaches to Supply Chain Communications: From Manufacturing to Construction. *ITcon*, 12, 73–102.

Datta, P.P. and Roy, R., 2009. Cost Modelling Techniques for Availability Type Service Support Contracts : a Literature Review and Empirical Study. *In*: *Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2)*. 216.

Dave, B., Koskela, L., and Kiviniemi, A., 2013. *Implementing Lean in construction: Lean construction and BIM*. CIRIA Guide C725 - Construction Industry Research and Information Association. London: CIRIA.

Delany, S., 2015. Classification [online]. *National Building Specification (NBS) BIM Toolkit*. Available from: https://toolkit.thenbs.com/articles/classification#classificationtables [Accessed 4 Feb 2019].

Denzin, N.K. and Lincoln, Y.S., 2000. *Handbook of Qualitative Research*. Second. London: SAGE Publications.

Djurić, D., Gašević, D., and Devedžić, V., 2005. Ontology modeling and MDA. *Journal of Object Technology*, 4 (1), 109–128.

Doomun, R. and Jungum, N.V., 2008. Business process modelling, simulation and reengineering: Call centres. *Business Process Management Journal*, 14 (6), 838–848.

Doran, D. and Giannakis, M., 2011. An examination of a modular supply chain : a construction sector perspective. *An International Journal of Supply Chain Management*, 16 (4), 260–270.

Dubois, A. and Gadde, L.-E., 1999. Case studies in business market research: An abductive approach. *In*: M. Damien and C. Horan, eds. *Proceedings of the 15th Annual IMP Conference*. Dublin, 1–20.

Duncheva, T. and Bradley, F.F., 2016. A comparison between Volumetric Timber Manufacturing Strategies in the UK and mainland Europe. *In*: *2016 Modular and Offsite Construction (MOC) Summit*. Edmonton, Alberta, Canada, 10–17.

Durdyev, S. and Mbachu, J., 2011. On-site Labour Productivity of New Zealand Construction Industry : Key Constraints and Improvement Measures. *Australasian Journal of Construction Economics and Building*, 11 (3), 18–33.

Duverlie, P. and Castelain, J.M., 1999. Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method. *The International Journal of Advanced Manufacturing Technology*, 15, 895–906.

Eastman, C.M. and Sacks, R., 2008. Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134 (7), 517–526.

Egan, J., 1998. *Rethinking Construction*. The Report of the Construction Task Force.

El-Diraby, T.A., Lima, C., and Feis, B., 2005. Domain Taxonomy for Construction Concepts : Toward a Formal Ontology for Construction Knowledge. *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, 19 (4), 394–406.

El-Gohary, N.M. and El-Diraby, T.E., 2015. Domain Ontology for Processes in Infrastructure and Construction. *Journal of Construction Engineering and Management ASCE*, (January).

Elhag, T.M.S. and Boussabaine, A.H., 1998. An Artificial Neural System for Cost Estimation Of Construction Projects. *In*: *14th Annual ARCOM Conference*. 219–226.

Elnaas, E., 2014. The Decision To Use Off-Site Manufacturing (OSM) Systems for House Building Projects in the UK. University of Brighton. UK.

Elo, S. and Kyngäs, H., 2008. The qualitative content analysis process. *Journal of Advanced Nursing*, 62 (1), 107–115.

Enshassi, A., Mohamed, S., and Abushaban, S., 2009. Factors affecting the performance of construction projects in the Gaza strip. *Journal of Civil Engineering and Management*, 15

(2), 269–280.

Farmer, M., 2016. *Modernise or die: The Framer Review of the UK construction labour market*. The Farmer Review of the UK Construction Labour Model.

Fellows, R.F. and Liu, A.M.M., 2015. *Research Methods for Construction*. Fourth Edi. West Sussex: John Wiley & Sons Ltd.

Fensel, D., 2000. Relating Ontology Languages and Web Standards Ontology Languages.

Fernández-solís, J.L., 2009. How the Construction Industry does differ from manufacturing ? *In*: *Associated Schools of Construction International Proceedings of the 45th Annual Conference*. Gainesville.

Fernández, L.M., 1999. Overview Of Methodologies For Building Ontologies. *Proceedings of the IJCAI99 Workshop on Ontologies and ProblemSolving Methods Lessons Learned and Future Trends CEUR Publications*, 1999 (2), 1–13.

Fernandez, M., Gomez-Perez, A., and Juristo, N., 1997. *METHONTOLOGY : From Ontological Art Towards Ontological Engineering*.

Finnimore, B., 1989. *Houses from the Factory: System Building and the Welfare State*. California: Rivers Oram Press.

Flick, U., 2007. *Designing Qualitative Research*. London: SAGE Publications.

Flick, U., 2014. *The SAGE Handbook of Qualitative Data Analysis*. London: SAGE Publications.

Formoso, C.T., 1991. A Knowledge-based Framework for Planning House Building Projects. University of Salford.

Forsberg, A. and Saukkoriipi, L., 2007. Measurement of waste and productivity in relation to lean thinking. *In*: *Lean Construction: A New Paradigm for Managing Capital Projects - 15th IGLC Conference*. 67–76.

Fortineau, V., Paviot, T., Louis-Sidney, L., and Lamouri, S., 2012. SWRL as a rule language for ontology-based models in power plant design. *IFIP Advances in Information and Communication Technology*, 388 AICT, 588–597.

Froese, T., 2003. FUTURE DIRECTIONS FOR IFC-BASED INTEROPERABILITY. *ITcon*, 8 (December 2002), 231–246.

Future Focus, 2017. *Offsite and Modular Building Market Research*.

Gann, D.M., 1996. Construction as a manufacturing process ? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics*, 14 (5), 437–450.

Gbadamosi, A.Q., Mahamadu, A.M., Oyedele, L.O., Akinade, O.O., Manu, P., Mahdjoubi, L., and Aigbavboa, C., 2019. Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, 215, 1180–1190.

Giacobbi, P.R., Poczwardowski, A., and Hager, P., 2005. A pragmatic research philosophy for applied sport psychology. *Sport Psychologist*, 19 (1), 18–31.

Gibb, A.G.F., 1999. *Off-site fabrication: Prefabrication, Pre-assembly and Modularisation*. New York: John Wiley & Sons.

Gibb, A.G.F., 2001. Standardization and pre-assembly – distinguishing myth from reality using case study research. *Construction Management and Economics*, 19, 307–315.

Gibb, A.G.F. and Isack, F., 2003. Re-engineering through pre-assembly : client expectations and drivers. *Building Research & Information*, 31 (2), 146–160.

Girmscheid, G. and Scheublin, F., 2010. New perspective in industrialisation in construction - a state of the art report. *International Council For Research And Innovation In Building And Construction (CIB)*, (May).

Golbreich, C., 2004. Combining Rule and Ontology Reasoner for the Semantic Web. *In*: Grigoris Antoniou and H. Boley, eds. *Third International Workshop, RuleML 2004*. Berlin: Springer, ??? ????

Gómez-Pérez, A. and Corcho, O., 2002. Ontology languages for the semantic web. *IEEE Intelligent Systems and Their Applications*, 17 (1), 54–60.

Goodier, C. and Gibb, A., 2005. *The value of the UK market for offsite*. London.

Gorgolewski, M.T., 2005. The Potential for Prefabrication in UK Housing to Improve Sustainability. *In*: J. Yang, P.S. Brandon, and A.C. Sidwell, eds. *Smart & Sustainable Built Environments*. Oxford, UK.: Blackwell Publishing Ltd, 1–8.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012a. Offsite Construction : Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1, 62–73.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012b. Offsite Construction: Strategic

Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1 (1), 62–73.

Goulding, J.S., Pour Rahimian, F., Arif, M., and Sharp, M.D., 2015. New offsite production and business models in construction: priorities for the future research agenda. *Architectural Engineering and Design Management*, 11 (3), 163–184.

GOV.UK, 2020. Live tables on house building [online]. *Ministry of Housing, Communities & Local Government*. Available from: https://www.gov.uk/government/statistical-data-sets/live-tables-on-house-building [Accessed 1 Feb 2020].

Grani, H.K., 2016. BIM Classification - Giving your Model some Class [online]. *Areo blog - Lifecycle BIM and smart FM*.

Griffith, M. and Jefferys, P., 2013. *Solutions for the housing shortage: How to build the 250.000 homes we need each year*. London.

Gruber, T.R., 1995. Toward principles for the design of ontologies used in knowledge sharing. *International Journal of Human Computer Studies*, 43, 907–928.

Gu, N. and London, K., 2010. Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, 19 (8), 988–999.

Guba, E.G. and Lincoln, Y.S., 1994. Competing Paradigms in Qualitative Research. *In*: N.K. Denzin and Y.S. Lincoln, eds. *Handbook of qualitative research*. 105–117.

Guizzardi, G., 2007. On Ontology, ontologies, Conceptualizations, Modeling Languages, and (Meta)Models. *In*: O. Vasilecas et al., ed. *Databases and Information Systems IV*. IOS Press.

Gunasekaran, A. and Kobu, B., 2002. Modelling and analysis of business process reengineering. *International Journal of Production Research*, 40 (11), 2521–2546.

Gunasekaran, A. and Sarhadi, M., 1998. Implementation of activity-based costing in manufacturing. *Intern. Journal of Production Economics*, 56–57 (1998), 231–242.

Gunaydın, H.M. and Dogan, S.Z., 2004. A neural network approach for early cost estimation of structural systems of buildings. *International Journal of Project Management*, 22 (2004), 595–602.

Gunduz, M., Ugur, L.O., and Ozturk, E., 2011. Parametric cost estimation system for light rail transit and metro trackworks. *Expert Systems with Applications*, 38 (3), 2873–2877.

Gurcanli, G.E., Bilir, S., and Sevim, M., 2015. Activity based risk assessment and safety cost estimation for residential building construction projects. *Safety Science*, 80 (112), 1–12.

Hairstans, R. and Smith, R.E., 2018. Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK. *Architectural Engineering and Design Management*, 14 (1–2), 60–77.

Haron, N.A., Abdul-Rahman, H., Wang, C., and Wood, L.C., 2015. Quality function deployment modelling to enhance industrialised building system adoption in housing projects. *Total Quality Management and Business Excellence*, 26 (7–8), 703–718.

Hashemi, A., 2015. Offsite Manufacturing: A Survey on the Current Status and Risks of Offsite Construction in Iran, 9, 141–152.

Hashemi, A. and Hadjri, K., 2014. Offsite Construction, a Potential Answer to the Iranian Housing Shortages. *In*: *Construction Technology and Management CTM 2014 International Scientific Conference*. 189–199.

Hause, M., 2006. The SysML Modelling Language. *In*: *Fifteenth European Systems Engineering Conference*. 12.

HM Government, 2013. *Construction 2025. Industrial Strategy: Government and industry in partnership*.

Holten, M. and Ferdinand, G., 2020. BOT : the Building Topology Ontology of the W3C Linked Building Data Group. *Semantic Web*, 12 (1), 143–161.

Höök, M. and Stehn, L., 2008. Lean principles in industrialized housing production : the need for a cultural change Lean culture. *Lean Construction Journal 2008*, (April), 20–33.

Horrocks, I., 2002. DAML+OIL: a Description Logic for the Semantic Web. *Bulletin of the Technical Committee on Data Engineering*, 25 (1).

Horrocks, I. and Sattler, U., 2001. Ontology reasoning in the SHOQ(D) description logic. *IJCAI International Joint Conference on Artificial Intelligence*, 199–204.

Howell, G. and Ballard, G., 1998. Implimenting construction: understanding and action. *Proceedings International Group for Lean Construction*, 0, 9.

Howell, G.A., 1999. What is Lean Construction. *In*: I.D. Tommelein, ed. *IGLC 2012 - 20th Conference of the International Group for Lean Construction*. UNIVERSITY OF CALIFORNIA BERKELEY, CALIFORNIA, USA.

Hueber, C., Horejsi, K., and Schledjewski, R., 2016. Review of cost estimation: methods and models for aerospace composite manufacturing. *Advanced Manufacturing: Polymer and Composites Science*, 2 (1), 1–13.

Hyde, K.F., 2000. Recognising deductive processes in qualitative research. *Qualitative Market Research: An International Journal*, 3 (2), 82–90.

Ijomah, W.L. and Childe, S.J., 2007. A model of the operations concerned in remanufacture. *International Journal of Production Research*, 45 (24), 5857–5880.

Jabar, I. laili, Ismail, F., and Mustafa, A.A., 2013. Issues in Managing Construction Phase of IBS Projects. *Procedia - Social and Behavioral Sciences*, 101, 81–89.

Jaillon, L. and Poon, C.S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment : a Hong Kong case study. *Construction Management and Economics*, 26 (9), 953–966.

Jaillon, L. and Poon, C.S., 2009. The evolution of prefabricated residential building systems in Hong Kong : A review of the public and the private sector. *Automation in Construction*, 18 (3), 239–248.

Jaillon, L., Poon, C.S., and Chiang, Y.H., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management*, 29 (1), 309–320.

Jarkas, A.M. and Bitar, C.G., 2012. Factors Affecting Construction Labor Productivity in Kuwait. *Journal of Construction Engineering and Management*, 138 (7), 811–820.

Ji, S., Park, M., and Lee, H., 2011. Cost estimation model for building projects using case-based reasoning. *Canadian Journal of Civil Engineering*, 38, 570–581.

Jones, D., Bench-capon, T., and Visser, P., 1998. Methodologies for Ontology Development. *In*: *Proc. IT&KNOWS Conference of the 15th IFIP World Computer Congress*. Budapest.

Jonsson, H. and Rudberg, M., 2014. Classification of production systems for industrialized building : a production strategy perspective. *Construction Management and Economics*, 32 (1–2), 53–69.

Jung, J., 2002. Manufacturing cost estimation for machined parts based on manufacturing features. *Journal of Intelligent Manufacturing*, 13, 227–238.

Kalemi, E.V., Cheung, F., Tawil, A., Patlakas, P., and Alyania, K., 2020. ifcOWL-DfMA a new ontology for the offsite construc- tion domain. *In*: *Proceedings of the7578th Linked*

Data in Architecture and Construction Workshop - LDAC2020 ifcOWL-DfMA. 105–117.

Kamar, K.A., Abd Hamid, Z., Azman, M.N.A., and Ahamad, M.S.S., 2011. Industrialized Building System (IBS): Revisiting Issues of Definition and Classification. *International Journal of Emerging. Sciences*, 1 (2), 120–132.

Karhu, V., 2000. Formal Languages for Construction Process Modelling. *Construction Information Technology 2000, Taking the construction industry into the 21st century, CIB W78.*, 525–534.

Kenley, R., 2014. Productivity improvement in the construction process Productivity improvement in the construction process. *Construction Management and Economics*, 32 (6), 489–494.

Kenley, R., Kanjanabootra, S., Ouyang, C., and Wynn, M., 2012. Procuring OSM: base-line models of off-site manufacture business processes in Australia. *In*: *16th Pacific Association of Quantity Surveyors Congress-Innovation and Sustaining: Challenges and Opportunities*. 1–10.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., and Holmstrom, J., 2019. Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7, 147406–147419.

Khosrowshahi, F. and Kaka, A.P., 1996. Estimation of Project Total Cost and Duration for Housing Projects in the U.K. *Building and Environment*, 31 (4), 373–383.

Kifer, M., 2008. Rule Interchange Format: The Framework. *In*: N. Bassiliades, G. Governatori, and A. Paschke, eds. *International Symposium, RuleML 2008*. Berlin: Springer-Verlag.

Kim, C.H., Weston, R.H., Hodgson, A., and Lee, K.H., 2003. The complementary use of IDEF and UML modelling approaches. *Computers in Industry*, 50 (1), 35–56.

Kim, S. and Shim, J.H., 2014. Combining case-based reasoning with genetic algorithm optimization for preliminary cost estimation in construction industry. *Canadian Journal of Civil Engineering*, 41 (November 2013), 65–73.

Kim, Y.-W., 2017. *Activity Based Costing for Construction Companies*. First Edit. West Sussex: John Wiley & Sons Ltd.

Kim, Y. and Ballard, G., 2001. Activity-based costing and its application to lean construction. *International Group for Lean Construction*, (January), 1–13.

Kim, Y. and Ballard, G., 2002. Case Study - overhead costs analysis. *In*: *Proceedings IGLC-10*. Gramado, Brazil, 1–13.

Kolo, S.J., Rahimian, F.P., and Goulding, J.S., 2014. Housing delivery in Nigeria and the opportunity for offsite manufacturing. *In*: *Creative Construction Conference*. 85–90.

Koskela, L., 1992. *Application of the new production philosophy to construction*. Stanford, CA.

KPMG, 2016. *Smart construction - How offsite manufacturing can transform our industry*.

Lang, R., Goodier, C., and Glass, J., 2016. Are housebuilders' production strategies a barrier to offsite construction uptake in the UK? *Proceedings of the 32nd Annual ARCOM Conference, ARCOM 2016*, 1245–1253.

Larsson, J. and Simonsson, P., 2012. Barriers and drivers for increased use of off-site bridge construction in Sweden. *In*: *28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 751–761.

Latham, M., 1994. *Constructing the Team*. Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry.

Lawson, M., Ogden, R., and Goodier, C., 2010. *Design in Modular Construction*. Taylor & Francis Group.

Lee, S., Kim, K., and Yu, J., 2014. Automation in Construction BIM and ontology-based approach for building cost estimation. *Automation in Construction*, 41, 96–105.

Leishman, C. and Warren, F., 2006. Private housing design customization through house type substitution. *Construction Management and Economics*, 24, 149–158.

Lemaignan, S., Siadat, A., Dantan, J.-Y., and Semenenko, A., 2006. MASON : A proposal for an ontology of manufacturing domain. *In*: *Proceedings of the IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications (DIS'06) 0-7695-2589-X/06*.

Lere, J.C., 2000. Activity-based costing: A powerful tool for pricing. *Journal of Business and Industrial Marketing*, 15 (1), 23–33.

Lessing, J., Stehn, L., and Ekholm, A., 2015. Industrialised house-building – development and conceptual orientation of the field. *Construction Innovation*, 15 (3), 378–399.

Li, Z.C., Hong, J., Xue, F., Shen, G.Q., Xu, X., and Luo, L., 2016. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. *Habitat International*, 57, 74–87.

Liao, S., 2004. Expert system methodologies and applications - a decade review from 1995 to 2004. *Expert Systems with Applications*, 1–11.

Lim, E.C. and Alum, J., 1995. Construction productivity: Issues encountered by contractors in Singapore. *International Journal of Project Management*, 13 (1), 51–58.

Lin, Y.C., Wang, L.C., and Tserng, H.P., 2006. Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan. *Automation in Construction*, 15 (6), 693–705.

Liu, H., Lu, M., and Al-hussein, M., 2016. Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry. *Advanced Engineering Informatics*, 30 (2), 190–207.

Liu, X., Li, Z., and Jiang, S., 2016. Ontology-Based Representation and Reasoning in Building Construction Cost Estimation in China. *Future Internet*, 8 (39).

Liu, Z., Osmani, M., Demian, P., and Baldwin, A.N., 2011. The potential use of BIM to aid construction waste minimalisation. *In*: –Sophia Antipolis, ed. *Proceedings of the CIB W78-W102 2011*. France.

Lou, Y.-I., Wang, H.C., and Lan, J.-S., 2017. Design and Implement the Activity-Based Costing in Taiwan Firm. *IOSR Journal of Business and Management*, 19 (01), 41–46.

Lovett, P.J., Ingram, A., and Bancroft, C.N., 2000. Knowledge-based engineering for SMEs - a methodology. *Journal of Materials Processing Technology*, 107, 384–389.

Lu, Q., Xie, X., Heaton, J., Parlikad, A.K., and Schooling, J., 2020. From BIM towards digital twin: Strategy and future development for smart asset management. *Studies in Computational Intelligence*, 853, 392–404.

Lucko, G. and Rojas, E.M., 2010. Research Validation: Challenges and Opportunities in the Construction Domain. *Journal of Construction Engineering and Management*, 136 (1).

Luo, L., Mao, C., Shen, L., and Li, Z., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system. *Engineering, Construction and Architectural Management*, 22 (6), 622–643.

Ma, Z.M. and Wang, X., 2012. Rule interchange in the semantic web. *Journal of Information*

Science and Engineering, 28 (2), 393–406.

Mao, C., Shen, Q., Shen, L., and Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods : Two case studies of residential projects. *Energy & Buildings*, 66, 165–176.

McKay, L.J., 2010. The effect of offsite construction on occupational health and safety. *A Doctoral Thesis Submitted In Partial Fulfilment Of The Requirements For The Award Of Doctor Of Philosophy*. Loughborough University.

Meiling, J., Backlund, F., and Johnsson, H., 2012a. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Meiling, J., Backlund, F., and Johnsson, H., 2012b. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Melão, N. and Pidd, M., 2000. A conceptual framework for understanding business processes and business process modelling. *Information Systems Journal*, 10 (2), 105–129.

Melton, T., 2005. The benefits of lean manufacturing: What lean thinking has to offer the process industries. *Chemical Engineering Research and Design*, 83 (6 A), 662–673.

Miah, S.J. and Genemo, H., 2016. A Design Science Research Methodology for Expert Systems Development. *Australasian Journal of Information Systems*, 20, 1–29.

Miles, J. and Whitehouse, N., 2013. *Offsite Housing Review*. London.

Milton, N., 2008. *Knowledge Technologies*. Italy: Polimetrica ®.

Mizoguchi, R. and Ikeda, M., 1998. Towards ontology engineering. *Journal-Japanese Society for Artificial Intelligence*, 13 (1), 259–266.

Montali, J., Overend, M., Pelken, P.M., and Sauchelli, M., 2018. Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends. *Architectural Engineering and Design Management*, 14 (1–2), 78–94.

Morgan, D.L., 2007. Paradigms Lost and Pragmatism Regained: Qualitative and Quantitative Methods. *Journal of Mixed Methods Research*, 1 (48), 48–76.

Mossman, A., 2009. Creating value: A sufficient way to eliminate waste in lean design and lean production. *Lean Construction Journal*, 2009, 13–23.

Mostafa, S., Chileshe, N., and Abdelhamid, T., 2016. Lean and agile integration within offsite construction using discrete event simulation. *Construction Innovation*, 16 (4), 483–525.

Motawa, I. and Almarshad, A., 2013. A knowledge-based BIM system for building maintenance. *Automation in Construction*, 29, 173–182.

Mtech Group, 2007. *Offsite Construction Industry Survey 2006*. BuildOffsite. London.

Murtaza, M.B., Fisher, D.J., and Skibniewski, M.J., 1993. Knowledge-Based Approach to Modular Construction Decision Support. *Journal of Construction Engineering and Management*, 119, 115–130.

Murugaiah, U., Benjamin, S.J., and Marathamuthu, M.S., 2010. Scrap loss reduction using the 5-whys analysis. *International Journal of Quality & Reliability Management*, 27 (5), 527–540.

Musa, M.F., Mohammad, M.F., Yusof, M.R., and Mahbub, R., 2015. The Way Forward for Industrialised Building System (IBS) in Malaysia. *In*: *InCIEC 2014*. Singapore: Springer, pp 163-175.

Nadim, W. and Goulding, J.S., 2011. Offsite production : a model for building down barriers. *Engineering, Construction and Architectural Management*, 18 (1), 82–101.

Nahmens, I. and Ikuma, L.H., 2012. Effects of Lean Construction on Sustainability of Modular Homebuilding. *Journal of Architectural Engineering*, 18 (2), 155–163.

Nasereddin, M., Mullens, M.A., and Cope, D., 2007. Automated simulator development : A strategy for modeling modular housing production. *Automation in Construction*, 16, 212–223.

Naufal, A., Jaffar, A., Yusoff, N., and Hayati, N., 2012. Development of kanban system at local manufacturing company in Malaysia-Case study. *Procedia Engineering*, 41 (Iris), 1721–1726.

Nawari, N.O., 2012. BIM Standard in Off-Site Construction. *Journal of Architectural Engineering*, 18 (2).

NBS, 2015. Uniclass 2015 [online]. *National Building Specification (NBS)*. Available from: https://www.thenbs.com/our-tools/uniclass-2015 [Accessed 2 Jan 2019].

Nepal, M.P., Staub-French, S., Pottinger, R., and Zhang, J., 2013. Ontology- based feature modeling for construction information extraction from a build- ing information model.

Journal of Computing in Civil Engineering, 27 (5), 555–569.

Neuman, L.W., 2014. *Social Research Methods: Qualitativr and Quantitative Approaches*. Seventh Ed. Essex, England: Pearson Education Limited.

Niazi, A. and Dai, J.S., 2006. Product Cost Estimation : Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, 128 (May).

Nicholls, D., 2017. Qualitative research. Part 2: Methodologies. *International Journal of Therapy and Rehabilitation*, 24 (2), 71–77.

Nikakhtar, A., Hosseini, A.A., Wong, K.Y., and Zavichi, A., 2015. Application of lean construction principles to reduce construction process waste using computer simulation: A case study. *International Journal of Services and Operations Management*, 20 (4), 461–480.

Nurcan, S., Etien, A., Kaabi, R., Zoukar, I., and Rolland, C., 2005. A strategy driven business process modelling approach. *Business Process Management Journal*, 11 (6), 628–649.

O'Connor, M., Knublauch, H., Tu, S., Grosof, B., Dean, M., Grosso, W., and Musen, M., 2005. Supporting rule system interoperability on the semantic Web with SWRL. *In*: Y. Gil et al., ed. *ISWC 2005*. Berlin: Springer-Verlag, 974–986.

Ochieng, E.G. and Price, A.D.F., 2009. Managing cross-cultural communication in multicultural construction project teams : The case of Kenya and UK. *International Journal of Project Management ·*, (July).

Ofori, G., 2000. Challenges of Construction Industries in Developing Countries : Lessons from Various Countries. *In*: *2nd International Conference on Construction in Developing Countries: Challenges Facing the Construction Industry in Developing Countries*. Gabarone, 1–13.

Ogunlana, S.O., 1989. Accuracy in design cost estimating.

Ong, N.S., 1995. Manufacturing cost estimation for PCB assembly : An activity-based approach. *International Journal of Production Economics*, 38, 159–172.

Ormerod, R.J., 2010. Rational inference: Deductive, inductive and probabilistic thinking. *Journal of the Operational Research Society*, 61 (8), 1207–1223.

Ou-Yang, C. and Lin, T.S., 1997. Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. *International Journal of Advanced Manufacturing*

Technology, 13, 618–629.

Ozaki, R., 2003. Customer-focused approaches to innovation in housebuilding. *Construction Management and Economics*, 21, 557–564.

Ozbayrak, M., Akgun, M., and Turker, A.K., 2004. Activity-based cost estimation in a push / pull advanced manufacturing system. *International Journal of Production Economics*, 87, 49–65.

Pan, W., Dainty, A.R.J., and Gibb, A.G.F., 2012. Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, 138 (11), 1239–1250.

Pan, W., Gibb, A.G.F., and Dainty, A.R.J., 2008. *Leading UK housebuilders' utilisation of offsite modern methods of construction*. Building Research & Information.

Pan, W. and Goodier, C., 2012. House-Building Business Models and Off-Site Construction Take-Up. *Journal of Architectural Engineering*, 18 (2), 84–93.

Pan, W. and Sidwell, R., 2011. Demystifying the cost barriers to offsite construction in the UK. *Construction Management & Economics*, 29, 1081–1099.

Pasquire, C., Gibb, A., and Blismas, N., 2005. What should you really measure if you want to compare prefabrication with traditional construction? *In*: *Proceedings IGLC*. Sydney, Australia, 481–491.

Pasquire, C.L. and Connolly, G.E., 2002. Leaner construction through off-site manufacturing. *In*: *Proceedings 10th of the Internationa Group of Lean Construction Conference, Gramado, Brazil*. 1–13.

Pauwels, P. and Terkaj, W., 2016. EXPRESS to OWL for construction industry : Towards a recommendable and usable ifcOWL ontology. *Automation in Construction*, 63, 100–133.

Pearce, A., Pons, D., and Neitzert, T., 2018. Implementing lean—Outcomes from SME case studies. *Operations Research Perspectives*, 5, 94–104.

Persson, S., Malmgren, L., and Johnsson, H., 2009. Information management in industrial housing design and manufacture. *Electronic Journal of Information Technology in Construction*, 14 (June), 110–122.

Pheng, L.S. and Leong, C.H.Y., 2000. Cross-Cultural project management for international construction in China. *International Journal of Project Management*, 18 (5), 307–316.

Post, 2003. *Modern methods of house building*. Parliamentary Office of Science and Technology. London.

Pulido, J.R.G., Ruiz, M.A.G., Herrera, R., Cabello, E., Legrand, S., and Elliman, D., 2006. Ontology languages for the semantic web: A never completely updated review. *Knowledge-Based Systems*, 19 (7), 489–497.

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., and Zimmerman, J.B., 2012. Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*, 16 (2), 243–254.

Rahani, A. and Muhammad, A.-A., 2012. Production Flow Analysis through Value Stream Mapping : A Lean Manufacturing Process Case Study. *Procedia Engineering - International Symposium on Robotics and Intelligent Sensors*, 41 (Iris), 1727–1734.

Rahman, N.A.A., Sharif, S.M., and Esa, M.M., 2013. Lean Manufacturing Case Study with Kanban System Implementation. *Procedia Economics and Finance*, 7 (Icebr), 174–180.

Rahman, S., Perera, S., Odeyinka, H., and Bi, Y., 2008. A Conceptual Knowledge-Based Cost Model for Optimizing the Selection of Materials and Technology for Building Design. *24th Annual ARCOM Conference*, (September), 217–225.

Raz, T. and Elnathan, D., 1999. Activity based costing for projects. *International Journal of Project Management*, 17 (1), 61–67.

Rezgui, Y., Hopfe, C.J., and Vorakulpipat, C., 2010. Generations of knowledge management in the architecture , engineering and construction industry : An evolutionary perspective. *Advanced Engineering Informatics*, 24 (2), 219–228.

Richard, R.B., 2005. Industrialised building systems: Reproduction before automation and robotics. *Automation in Construction*, 14 (4), 442–451.

RICS, 2012a. *NRM1: Order of Cost Estimating and Cost Planning for Capital Building Works*. 2nd Editio. Coventry UK: Royal Institution of Chartered Surveyors (RICS).

RICS, 2012b. *NRM 2: Detailed Measurement for Building Works*. 1st Editio. Coventry: Royal Institution of Chartered Surveyors (RICS).

La Rocca, G., 2012. Knowledge based engineering : Between AI and CAD . Review of a language based technology to support engineering design. *Advanced Engineering Informatics*, 26 (2), 159–179.

Roy, A.U.K., Roy, M., and Saha, P.S., 2007. Mass-Industrialized Housing to Combat Consistent Housing Shortage in Developing Countries : Towards an Appropriate System for India. *In*: *World Congress on Housing National Housing Programmes- New Visions November 03-07, Kolkota, India*. Kolkata, India, 1–7.

Roy, R., Souchoroukov, P., and Shehab, E., 2011. Detailed cost estimating in the automotive industry : Data and information requirements. *Intern. Journal of Production Economics*, 133 (2), 694–707.

Rožanec, J.M., Jinzhi, L., Košmerlj, A., Kenda, K., Dimitris, K., Jovanoski, V., Rupnik, J., Karlovčec, M., and Fortuna, B., 2020. Towards actionable cognitive digital twins for manufacturing. *CEUR Workshop Proceedings*, 2615, 1–12.

Rundora, R., Ziemerink, T., and Oberholzer, M., 2013. Activity-based costing in small manufacturing firms: South African study. *Journal of Applied Business Research*, 29 (2), 485–498.

Saad, A. and Shaharin, S., 2016. The Methodology for Ontology Development in Lesson Plan Domain. *International Journal of Advanced Computer Science and Applications (IJACSA)*, 7 (4), 557–562.

Sabol, L., 2008. *Challenges in Cost Estimating with Building Information Modeling*. Washington, DC.

Sarvimaki, M., 2017. *Case Study Strategies for Architects and Designers : Integrative Data Research Methods: Integrative Data Research Methods*. London: Taylor & Francis Group.

Saunders, M., Lewis, P., and Thornhill, A., 2009. *Research Methods for Business Students*. New York: Pearson.

Schell, C., 1992. *The Value of the Case Study as a Research Strategy*.

Schreiber, A.T., Akkermans, J.M., Anjewierden, A.A., de Hoog, R., Shadbolt, N.R., Velde, W. Van de, and Wielinga, B.J., 2001. *Knowledge Engineering and Management - The CommonKADS Methodology*. Cambridge,Massachusetts: MIT Press.

Schuh, K.L. and Barab, S.A., 2008. Philosophical Perspectives. *In*: J. David, S.J. Michael, D. Marcy, M. David, and M. Jeroen, eds. *Handbook of Research on Educational Communications*. New York: Taylor & Francis, 67–82.

Schwitter, R., 2010. Controlled natural languages for knowledge representation. *In*: *Coling 2010 - 23rd International Conference on Computational Linguistics, Proceedings of the Conference*. Beijing, 1113–1121.

Secretary of State for Communities and Local Government, 2017. *Fixing our broken housing market*. Department for Communities and Local Government. London: Crown.

Shadbolt, N. and Milton, N., 1999. From Knowledge Engineering to Knowledge Management. *British Journal of Management*, 10, 309–322.

Shamsuddin, S.M., Zakaria, R., and Mohamed, S.F., 2013. Economic Attributes in Industrialised Building System in Malaysia. *Procedia - Social and Behavioral Sciences*, 105, 75–84.

Shang, G. and Sui Pheng, L., 2014. Barriers to lean implementation in the construction industry in China. *Journal of Technology Management in China*, 9 (2), 155–173.

Shi, J.J., Lee, D.E., and Kuruku, E., 2008. Task-based modeling method for construction business process modeling and automation. *Automation in Construction*, 17 (5), 633–640.

Shostak, L. and Houghton, J., 2008. The credit crunch and the housing shortage - Time for a radical new approach to building affordable homes. *Local Economy*, 23 (3), 121–126.

Sivakumar, R. and Arivoli, P.V., 2011. Ontology Visualization Protégé Tools - A Review. *International Journal of Advanced Information Technology*, 1 (4), 39–39.

Smith, A.E. and Mason, A.K., 1996. Cost Estimation Predictive Modeling : Regression versus Neural Network. *The Engineering Economist*.

Sobh, R. and Perry, C., 2006. Research design and data analysis in realism research. *European Journal of Markerting*, 40 (11), 1194–1209.

Sodikov, J., 2005. COST ESTIMATION OF HIGHWAY PROJECTS IN DEVELOPING COUNTRIES : ARTIFICIAL NEURAL NETWORK APPROACH. *Journal of the Eastern Asia Society for Transportation Studies*, 6, 1036–1047.

Soiferman, L.K., 2010. Compare and Contrast Inductive and Deductive Research Approaches. *Inductive and Deductive Research Approaches*, (April), 1–23.

Song, J., Fagerlund, W.R., Haas, C.T., Tatum, C.B., and Vanegas, J.A., 2005. Considering Prework on Industrial Projects. *Journal of Construction Engineering and Management*, 131 (6), 723–733.

Spens, K.M. and Kovács, G., 2006. A content analysis of research approaches in logistics research. *International Journal of Physical Distribution and Logistics Management*, 36 (5), 374–390.

Spyns, P., Meersman, R., and Jarrar, M., 2002. Data modelling versus ontology engineering. *ACM SIGMOD Record*, 31 (4), 12–17.

Staub-french, S., Fischer, M., Kunz, J., Paulson, B., and Ishii, K., 2002. *A Feature Ontology to Support Construction Cost Estimating*.

Steinhardt, D., Manley, K., and Miller, W.F., 2014. Reshaping housing using prefabricated systems. *Proceedings of World Sustainable Building Conference (SB14)*.

Studer, R., Benjamins, V.R., and Fensel, D., 1998. Knowledge Engineering : Principles and methods. *Data & Knowledge Engineering*, 25, 161–197.

Sundar, R., Balaji, A.N., and Satheesh Kumar, R.M., 2014. A review on lean manufacturing implementation techniques. *Procedia Engineering*, 97, 1875–1885.

Szuba, J.S., Grabska, E.G., and Borkowski, A., 1999. Graph Visualization in ArchiCAD. *In*: *Proceedings of the International Workshop on Applications of Graph Transformations with Industrial Relevance*. 241–246.

Tam, V.W.Y., Tam, C.M., Zeng, S.X., and Ng, W.C.Y., 2007. Towards adoption of prefabrication in construction. *Building and Environment*.

Tang, J., Zhang, M., Tang, H., and Chen, Y., 2015. Research on Cost Management of Construction Project based on Activity-based Costing. *In*: *International Conference on Civil, Materials and Environmental Sciences (CMES 2015)*. 51–54.

Taylor, S., 2009. *Offsite Production in the UK Construction Industry, abrief overview*. HSE.

Tennant, S., McCarney, M., Tong, M.K., and Tennant, G., 2012. Re-Engineering the Construction Supply Chain: Transferring on-Site Activity, Off- Site. *In*: *Procs 28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 3–5.

Terkaj, W. and Urgo, M., 2014. Ontology-based modeling of production systems for design and performance evaluation. *Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014*, 748–753.

Thanoon, W.A., Peng, L.W., AbdulKadir, M.R., Jaafar, M.S., and Salit, M.S., 2003. The

Essential Characteristics of Industrialised Building System. *In*: *International Conference on Industrialised Building Systems*. 10–11.

Thomas, G., 2011. Qualitative Inquiry A Typology for the Case Study in Social Science Following a Review of Definition , Discourse , and Structure. *Qualitative Inquiry*, 17 (6), 511 –521.

Tran, V. and Tookey, J., 2007. Labour Productivity in the New Zealand Construction Industry : A Thorough Investigation. *Australasian Journal of Construction Economics and Building*, 11 (1), 41–60.

Trehan, V., Chapman, C., and Raju, P., 2015. Informal and formal modelling of engineering processes for design automation using knowledge based engineering. *Journal of Zhejiang University: Science A*, 16 (9), 706–723.

Tsai, W.H., Yang, C.H., Chang, J.C., and Lee, H.L., 2014. An Activity-Based Costing decision model for life cycle assessment in green building projects. *European Journal of Operational Research*, 238 (2), 607–619.

Vakaj, E., F., C., H., T.A.-R., Pauwels, P., and Patlakas, P., 2021. Semanic representation of DfMA offsite housing.

Venables, T., Barlow, J., and Gann, D., 2004. *Manufacturing Excellence - UK Offsite Capacity in Off-Site Manufacturing*. Constructing Excellence.

Verhagen, W., Bermell-Garcia, P., Mariot, P., Cotton, J.-P., Ruiz, D., Redon, R., and Curran, R., 2010. (Costing) Knowledge-Based Cost Modelling of Composite Wing Structures. *International Journal of Computer Integrated Manufacturing*, pp.1.

Vernikos, V.K., Nelson, R., Goodier, C.I., and Robery, P.C., 2013. Implementing an offsite construction strategy: a UK contracting organisation case study. *In*: *Proceedings of the 29th Annual ARCOM Conference*. Reading, UK, 667–677.

Vibaek, K.S., 2014. *Architectural System and Structures - Integrating design complexity in industralised construction*. London: Routledge.

Volk, R., Stengel, J., and Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, 38 (October 2017), 109–127.

Voss, E., Jin, Q., and Overend, M., 2013. A BPMN-based process map for the design and construction of façades. *Journal of Facade Design and Engineering*, 1 (1–2), 17–29.

Wagner, A. and Uwe, R., 2019. BPO : The Building Product Ontology for Assembled Products. *In*: *Proceedings of the 7th Linked Data in Architecture and Construction Workshop - LDAC2019*. 106–119.

Wahab, A.N.A., Mukhtar, M., and Sulaiman, R., 2013. A Conceptual Model of Lean Manufacturing Dimensions. *Procedia Technology*, 11 (Iceei), 1292–1298.

Waissi, G.R., Demir, M., Humble, J.E., and Lev, B., 2015. Automation of strategy using IDEF0 - A proof of concept. *Operations Research Perspectives*, 2, 106–113.

Warszawski, A., 1999. *Industrialised and automated building systems*. First edit. London: E & FN Spon.

Willis, J.W., 2007. *World Views, Paradigms, and the Practice of Social Science Research*. London: Sage.

Wilson, L., 2010. *How to Implement Lean Manufacturing*. New York: McGrawHill.

Wong, R., Hao, J., and Ho, C., 2003. Prefabricated building construction systems adopted in Hong Kong. *In*: *Proc. of the International Association for Housing Science on Word Congress of Housing: Process and Product*. Canada.

Wu, S., Wood, G., Ginige, K., and Jong, S.W., 2014. A technical review of bim based cost estimating in UK quantity surveying practice, standards and tools. *Journal of Information Technology in Construction*, 19 (March), 535–563.

Xu, Y., Elgh, F., Erkoyuncu, J.A., Bankole, O., Goh, Y., Cheung, W.M., Baguley, P., Wang, Q., Arundachawat, P., Shehab, E., Newnes, L., and Roy, R., 2011. Cost engineering for manufacturing : current and future research. *International Journal of Computer Intergrated Manufacturing*, 25 (4–5), 300–314.

Xu, Z., Abualdenien, J., Liu, H., and Kang, R., 2020. An IDM-Based Approach for Information Requirement in Prefabricated Construction. *Advances in Civil Engineering*, 2020, 21.

Yaman, H. and Tas, E., 2007. A building cost estimation model based on functional elements. *ITU Journal of Faculty of Architecture*, 4 (1), 73–87.

Yang, H., Yeung, J.F.Y., Chan, A.P.C., Chiang, Y.H., and Chan, D.W.M., 2010. A critical review of performance measurement in construction. *Journal of Facilities Management*, 8 (4), 269–284.

Yi, W. and Chan, A.P.C., 2014. Critical Review of Labor Productivity Research in Construction Journals. *Journal of Management in Engineering*, 30 (2), 214–225.

Yin, R.K., 1994. *Case Study Research: Design and Methods*. Second. Bervely Hills: Sage Publishing.

Yin, R.K., 2009. *Case Study Reserach: Design and methods*. Fourth. London: SAGE Publications.

Yin, R.K., 2016. *Qualitative Research from Start to Finish*. Second Edi. London: Guilford Publications.

Yitmen, I., 2007. The challenge of change for innovation in construction : A North Cyprus perspective. *Building and Environment*, 42, 1319–1328.

Young, B., Harty, C., Lu, S., and Davies, R., 2015. Developing Temporary Manufacturing Facilities for Residential Building : a Case of the Modern Flying Factory. *Procs 31st Annual ARCOM Conference, 7-9 September 2015*, (September), 1033–1042.

Yunus, R. and Yang, J., 2012. Critical Sustainability Factors in Industrialised Building Systems Abstract. *Construction Innovation*, 12 (4), 447–463.

Zainal, Z., 2007. Case study as a research method. *Jurnal Kemanusiaan*, 9.

Zakaria, S.A., Gajendran, T., Rose, T., and Brewer, G., 2018. Contextual, structural and behavioural factors influencing the adoption of industrialised building systems: a review. *Architectural Engineering and Design Management*, 14 (1–2), 3–26.

Zhai, X., Reed, R., and Mills, A., 2014. Addressing sustainable challenges in China. *Smart and Sustainable Built Environment*, 3 (3), 261–274.

Zhang, S., Boukamp, F., and Teizer, J., 2015. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, 52, 29–41.

Zhang, X. and Skitmore, M., 2012. Industrialized housing in China: a coin with two sides. *International Journal of Strategic Property Management*, 16 (2), 143–157.

Zhang, Y., Fan, G., Lei, Z., Han, S., Raimondi, C., Al-Hussein, M., and Bouferguene, A., 2016. Lean-based diagnosis and improvement for offsite construction factory manufacturing facilities. *In*: *ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction*. 1090–1098.

Zhang, Y., Lei, Z., Han, S., Bouferguene, A., and Al-Hussein, M., 2020. Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance. *Journal of Construction Engineering and Management*, 146 (9).

Zhong, B.T., Ding, L.Y., Love, P.E.D., and Luo, H.B., 2015. An ontological approach for technical plan definition and verification in construction. *Automation in Construction*, 55, 47–57.

Zhuang, C., Miao, T., Liu, J., and Xiong, H., 2021. The connotation of digital twin, and the construction and application method of shop-floor digital twin. *Robotics and Computer-Integrated Manufacturing*, 68 (September 2020), 102075.

Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system

Kudirat Olabisi Ayinla

School of Engineering and the Built Environment, Birmingham City University, Birmingham, UK and School of Architecture, Computing and Engineering, University of East London, London, UK

Franco Cheung

School of Engineering and the Built Environment, Birmingham City University, Birmingham, UK, and

Abdel-Rahman Tawil

School of Computing and Digital Technology, Birmingham City University, Birmingham, UK

Abstract

Purpose: Offsite manufacturing (OSM) is continuously getting recognised as a way to increase efficiency and boost productivity of the construction industry in many countries. However, the knowledge of OSM varies across different countries, construction practices and individual experts thus resulting into major misconceptions. The lack of consensus of what OSM is and what constitutes its methods creates a lot of misunderstanding across AEC industry professionals hence, inhibiting a global view and understanding for multicultural collaboration. Therefore, there is a need to revisit these issues with the aim of developing a deeper understanding of the concepts and to ascertain what is deemed inclusive or exclusive.

Approach: A state-of-the-art review and analysis of literature on OSM was conducted to observe trends in OSM definitions and classifications. The paper identifies gaps in existing methods and proposes a future direction.

Findings: Findings suggest that classifications are mostly aimed towards a particular purpose and existing classification system are not robust enough to cover all aspects. Therefore, there is need to extend these classification systems to be fit for various purposes.

Originality: This paper contributes to the body of literature on offsite concepts, definition and classification, and provides knowledge on the broader context on the fundamentals of OSM.

Keywords: Offsite manufacturing; prefabrication; definition; classification; literature review

1. Introduction

The construction industry has for a long time been associated with inefficiencies, which is argued to be mostly facilitated by the traditional procurement and method of construction (Barbosa *et al.* 2017). This together with the increasing expectations of clients and end users creates pressure and opportunities for the industry to improve. Many governments, particularly those from the developed countries have created various incentives to encourage cross-industry learning from other industries such as automotive, aerospace and manufacturing with focuses on developing more efficient alternative construction methods through accommodating automation and standardisation of processes (Pan and Sidwell 2011, Hairstans and Smith 2018). In the UK, for instance, the government commissioned reports such as Latham (1994) and Egan (1998) have previously identified the needs and barriers for technologically-driven innovations. Offsite manufacturing (OSM) is seen as the approach to improve the products from the industry (Cabinet Office, 2011; HM Government, 2013), and a requisite to changing the craft-based and labour-intensive nature of the construction industry (Gibb and Isack 2003, Miles and Whitehouse 2013).

However, despite the recent increasing propagation of OSM, its diffusion and acceptance is still quite low in both developed and developing countries (Goulding *et al*> 2015). So far, apparent observation gathered from various publications on OSM shows a significant amount of issues inhibiting its wider acceptance in the construction industry of various countries. To start with, there is a lack of consensus or coordinated effort with regards to agreeing what shall be included in its definition (Yunus and Yang 2012, Baghchesaraei *et al.* 2015). The lack of consensus further compounds the issue of how to appraise various OSM methods and compare them with traditional construction method (Song *et al.* 2005, Blismas *et al.* 2006b, Yitmen 2007, Pan *et al.* 2008, Abdullah and Egbu 2010, Arif and Egbu 2010, Yunus and Yang 2012, Haron *et al.* 2015). Other issues reported involves the unavailability of documented sources of information about modularization (Murtaza *et al.* 1993, Aldridge *et al.* 2001, Pasquire *et al.* 2005).

Although there are a lot of publications on OSM, the knowledge is not well structured and described as being fragmented (Blismas and Wakefield 2007, Jabar *et al.* 2013). Some previous studies have reviewed the concept of OSM and developed different classification systems. Most of these classification systems are either based on the type of finished product (Gibb 2001, Gibb and Isack 2003, Jaillon and Poon 2009), the process of manufacture (Lawson *et al.* 2010), the geometrical configuration of the product (Badir *et al.* 2002, Thanoon *et al.* 2003), or even the location of production (Mostafa *et al.* 2016). Kamar et al., (2011) reviewed the concept of Industrialised Building Systems (IBS) with the aim to develop a common definition and classification. However, the study is limited in terms of analysis and synthesis for recognising the commonalities and differences in definitions. Also, the classification system developed is only based on OSM products and missing other aspects like process and people captured in other literature materials.

This study aims to further the work of these researchers by synthesizing existing knowledge on OSM in construction through systematically evaluating the concepts of OSM from reviewed publications, and developing a more inclusive working definition and a comprehensive formalised classification of offsite vocabularies to enable common basis of evaluation and improve communication. The review includes (i) an evaluation of the definitions of OSM evolved over time (ii) an analysis of OSM taxonomies according to literature and other UK classification systems, (iii) development of a working definition and classification system for various purposes.

2. Methodology: Literature review analysis

A systematic analysis of exiting literature on OSM published since the 90s was carried out to identify its development and application in the construction industry. The review was conducted through four stages as illustrated in Figure 1: planning, screening and extraction, analysis and discussion, and documentation.

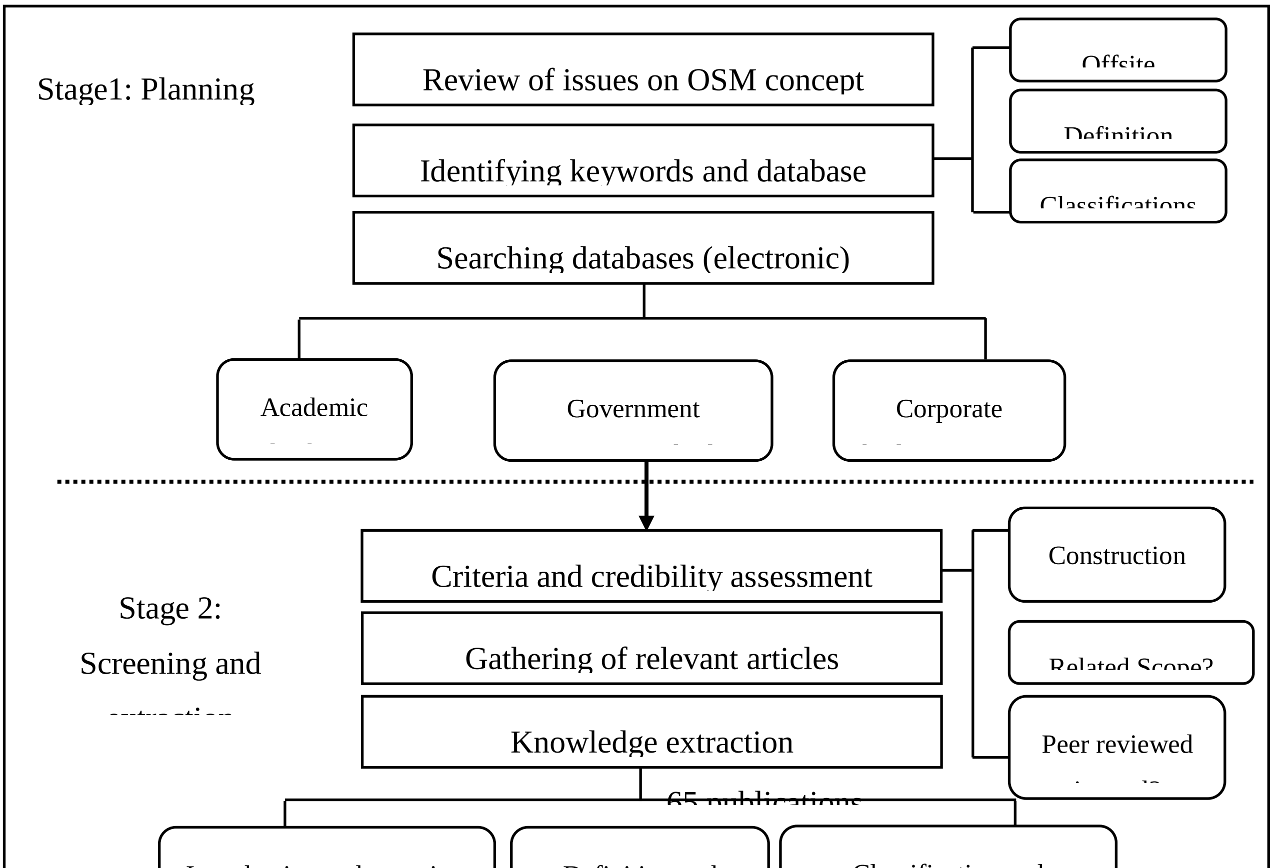


Figure 1: Research methodology and process flow chart

Stage 1: Planning

A search strategy was adopted to gather relevant publications on the subject area. Firstly, a set of relevant keyword phrases were identified for the search using the electronic database - ScienceDirect; some of which include ‘offsite construction’, ‘prefabrication in construction’, ‘offsite manufacturing’, ‘offsite fabrication’, ‘industrialised building systems’, ‘system buildings’, ‘modern methods of construction’, ‘modular construction’, building classification system etc. Use of keyword phrases is considered more application due to the need of ensuring that an exhaustive coverage by means of including as much work relevant for developing a comprehensive list of different definitions and classifications of OSM is achieved.

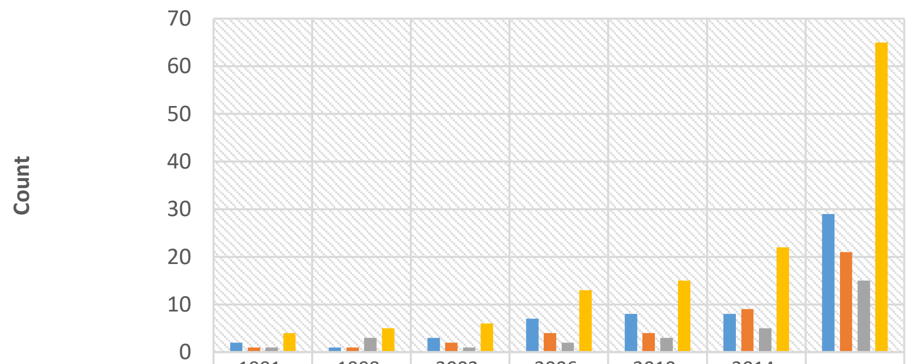
Supplementary searches were also carried out using other popular academic databases including Google Scholar, ASCE Library, Wiley, IEEE and Scopus. To include literature of OSM regarding its applications in practice, relevant government publications, industry standards and guidelines for OSM were also reviewed, e.g. published articles by corporate bodies such as BuildOffsite, National Building Specification (NBS), buildingSMART, Construction Industry Council (CIC), International Council for Research and Innovation in Building and Construction (CIB) and OffsiteHub) on offsite research and classification systems. The search resulted into a huge number of articles being retrieved.

Stage 2: Screening and extraction

The initial keyword search generated thousands of articles. To narrow the number of articles down, publications that are not construction related were eliminated. Further screening exercise was conducted where each article was skimmed through (for instance their abstract and conclusion) to examine their suitability to the analysis of the individual subjects. Articles with focus on peripheral subjects of OSM were considered out of scope and therefore excluded in the review. Remaining articles were then further screened out based on the criteria of (i) the credibility of such publications i.e. whether they are published in a peer reviewed journal or at least examined through a peer-review process, or widely recognised for industrial reports and textbooks and (ii) the type and source of such article. Overall, 65 journal papers/conference papers/books/reports were found suitable (Figure 2) and reviewed ranging from the 90s (although there was no restriction based on the year of publication during the screening exercise). . Reviewed publications were subsequently organised into themes according to the objectives of this study (Figure 3).

Stage 3: Analysis and synthesis of information

The selected papers were analysed and synthesised according to their similarities and differences in order to develop an insight on the topic and also identify gaps in current knowledge. This led to a high-level classification based on product, process and people which is followed up by an explanation of how they can be applied.



	1991-1997	1998-2001	2002-2005	2006-2009	2010-2013	2014-2019	Total
Journal Papers	2	1	3	7	8	8	29
Conference papers	1	1	2	4	4	9	21
Others	1	3	1	2	3	5	15
Total	4	5	6	13	15	22	65

Figure 2: Frequency and distinction of reviewed publications over a period of 28 years

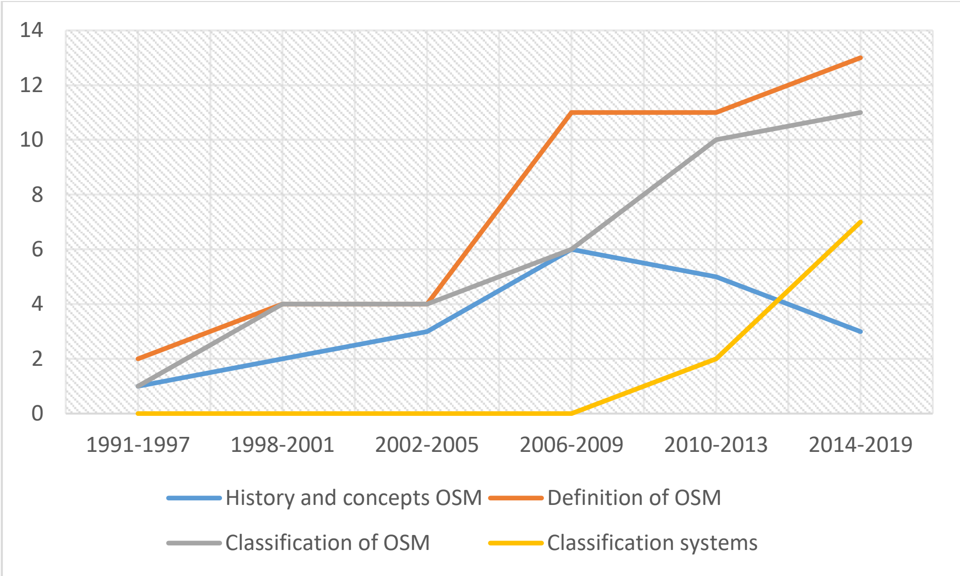


Figure 3: Number of reviewed publications yearly on different themes in the offsite domain

3. Defining offsite manufacturing (OSM) method

Definitions of OSM from 18 references are reviewed. Table 1 extracts and groups the definitions according to 4 categories - (i) *Pre* (as in *pre*fab, *pre*fabrication and *pre*assembly), (ii) *Building* (as in industrialised *building* system and system building), (iii) *Offsite* (as in *offsite* construction and *offsite* manufacturing), and (iv) *Modern methods* (as in *modern method* of construction and *modern method* of house building - defined by Pan et al. (2012) and highlights the common aspects of the definitions.

Table 1: Definitions of terms

Category	**Term**	**Some key definitions**	**Source**
'Pre'	Preassembly	"a ***process*** of ***manufacturing and assembly*** of building ***components*** in a ***factory environment*** prior to ***transportation*** … for installation."	(Gibb and Isack 2003)
	Prefabrication	"describe the ***manufacturing process*** of ***components*** in a ***controlled environment*** … are ***assembled*** together to form components parts for ***installation***"	(Jaillon and Poon 2009)
		"a ***manufacturing process*** and ***transporting*** to a site … to be ***erected or assembled***."	(Baghchesar*aei et al>* 2015)
		"… ***process of building components or full modules*** in … a ***factory environment***…."	(Richard 2005)

		"… **a *manufacturing process***, generally taking place at a ***specialized facility*** and involves joining different materials to form a ***component*** part of the final ***installation***"	(Jaillon and Poon 2008)
		"The ***manufacture*** of housing ***components*** offsite in a ***factory setting***"	(Steinh*ardt et al*> 2014)
		"… a ***manufacturing and preassembly process*** in which joining of materials to forma ***component*** part takes place at a ***specified facility***"	(Chiang *et al*> 2006)
'Building'	Industrialised building system (IBS)	"… a construction process that involves the use of ***standardised mass produced building components*** in a ***factory or on site, transported and assembled*** into a structure using appropriate machinery"	(Musa *et al*> 2015)
		"… it requires the integration of smaller ***components and subsystems*** into an overall process/product with a full utilisation of ***industrialised production, transportation and assembly techniques***"	(Roy *et al*> 2007)
	System building (SB)	"…adopts the concept of ***mass production*** of ***building components* in a *controlled environment*** either onsite or offsite"	(Kamar *et al.*, 2011)
	Industrialised house building (IHB)	"… is used for describing a strategically different ***process- and product-oriented*** alternative to traditional project-oriented house-building methods and principles"	(Lessing *et al.* 2015)
'Offsite'	Offsite industrialisation (OI)	"… a process of moving construction operations traditionally undertaken on site to a ***manufacturing environment*** prior to ***final installation*** in required position"	(Zhai *et al.* 2014)
	Offsite construction (OSC)	"… the creation of built environment in a ***factory environment*** such that part of the construction ***process*** …	(Mtech Group 2007)
	Offsite manufacturing (OSM)	"…a ***process*** that requires a higher percentage of the ***value-adding*** activities being carried out offsite (in a ***controlled environment***) with just ***installation and finishing*** done onsite."	(Jonsson and Rudberg 2014)
		"… a unique mix of general construction procedures integrated into a ***production flow line*** ..."	(Naseereddin *et al.* 2007)
	Offsite manufacturing (OSM), offsite construction (OSC)	"collectively used to describe a method of production and delivery through ***factory manufacture and assembly***"	(Miles and Whitehouse 2013)

	and offsite fabrication (OSF)		
'Modern methods'	Modern method of house building	"manufacture of homes in factories with potential benefits"	(Post 2003)
	Modern method of construction (MMC)	"as a description of new products, techniques and technologies in construction"	(Miles and Whitehouse 2013)
		"… industrialisation as the use of advanced technology (mechanical tools, computerised systems) in a continuous process to improve efficiency in terms of ***standardisation, modularisation and mass production***"	(Girmscheid and Scheublin 2010)

Observing from Table 1, the definitions seem to focus on either the nature of the finished product or outcome that is obtained (Musa et al. 2015, Roy et al. 2007, Li et al. 2016), the process of carrying out the construction (Mohd Kamar *et al.*, 2011; Zhai et al. 2014; Lessing et al. 2015), or both (Miles and Whitehouse 2013, Baghchesaraei *et al.* 2015, Lessing *et al.* 2015). The common concept found in a number of definitions from the *Pre* and *Offsite* groups is the adoption of a manufacturing process, in which part of the production as components are assembled in a controlled working environment. The *Building* group contain the same fundamental concept together with standardisation or mass production as an additional element in the definitions, which arguably is a main contribution of the "higher percentage of the value-adding activities" in Jonsson and Rudberg (2014). The *Modern methods* group appears not limited to methods that integrate a manufacturing process and thus are more inclusive as alternative methods to traditional construction. (McKay 2010, Tennant *et al.* 2012, Kolo *et al.* 2014). For instance, some *Modern methods* techniques are used in conjunction with onsite work hence forming a hybrid systems construction without any manufacturing process involved (e.g. Arbizzani and Civiero, 2013), which cannot be classified to be under the *Offsite* or *Pre* group. Thus, the other three groups can be considered as a sub-set of *Modern methods* and hence the authors do not consider *Modern methods* to be interchangeable with the other three groups.

According to Table 1, it is established that OSM terminologies in the Pre, Building and Offsite categories can be used interchangeably. However, the term 'modern methods' is a broader terms, which using the definition for OSM will not be considered satisfactory. OSM used in this paper is thus described as:

> *'the creation of a value-adding built environment through a combination of conventional construction procedures and production processes (as in product manufacturing) in which components for construction are produced in a controlled environment, and are transported and installed in the final position onsite.'*

It is important to note that the controlled environment referred to in the above definition is not limited to activities outside of a construction site. In the situation where a site is big enough to accommodate a factory or yard for production purpose, the production process can actually be onsite as seen in Young et al., (2015). Nevertheless, the finished components are required to be transported and installed to the final positions disregarding whether the production process is onsite or offsite. Also, the definition follows that of Jonsson and Rudberg's (2014) in capturing “value-adding” as the main rationale for offsite manufacturing processes as contrast to the counterpart of conventional onsite processes. It is then implied that value can be added through the adoption of standardisation, mass production, mass customisation and lean methodology as concepts found and applied in manufacturing processes.

4. Taxonomy of offsite manufacturing

4.1 Review and analysis of classification systems – based on literature

One general acknowledged classification for OSM adopted by most researchers (Gibb 2001, Gibb and Isack 2003, Jaillon and Poon 2009, Arif and Egbu 2010, Quale *et al.* 2012) is the subdivision of offsite manufacturing based on product orientation i.e. generic types according to the geometric shape, assembly approach, extent of offsite operation, and state of completion of the product. This type of classification was first suggested by Gibb (1999) with four groups identified, namely: *whole building/modular, volumetric pre-assembly, non-volumetric pre-assembly and component manufacture & sub-assemblies* (Table 2). Although widely recognised and accepted, Gibb’s classification seems incomplete as other researchers (e.g., Abosoad et al., 2009; Hashemi and Hadjri, 2014) have identified similar product-oriented classification that incorporates panellised and hybrid systems products, which deviates from Gibb’s (1999) classification. Inconsistencies are noticed in the various classifications. For instance, pods is considered as an independent type from volumetric systems according to Hashemi and Hadjri (2014) and Steinhardt et al. (2014) but the type is well within Gibb’s definition for the volumetric sub-category as pods are three-dimensional volumetric building parts (Gibb, 2001). Perhaps, the type ‘modular’ is most confusing as Steinhardt et al. (2014) use the term ‘modular’ to refer to a level of prefabrication in a 6-level progressing continuum of a prefabricated house, from materials for a house (Level 1) to a complete house (Level 6) while other studies such as Arif and Egbu (2010), Gibb (1999), Mtech Group (2007) and Quale et al. (2012) consider ‘modular’ as a type of whole building offsite method. Also, Doran and Giannakis (2011) use the term ‘modular’ instead of offsite construction and sub-divide it according to (i) pure modular, (ii) hybrid modular, and (iii) onsite modular depending on the level and type of onsite activities. Their classification distinguishes onsite or offsite works involved in using a modular method with more attention to the design and construction approaches than the type of products or state of completion of a building. Furthermore, the location of production is used by Bari et al, (2012) and Mostafa et al. (2016) in their classification.

Mtech Group (2007) classified offsite according to the market sub-sectors including (i) complete structures (i.e., for permanent or reloadable volumetric units), (ii) structural elements and systems (i.e., for foundation, substructure, superstructure, building envelope or building services), (iii) civil engineering (i.e. for pre-assembled civil engineering structures) and (iv) special (i.e. for special structures or project specific offsite construction). Recognising the lack of common definitions and the arbitrary nature in classifying offsite construction, the suggested sub-sectors clearly follows the lineage of product-oriented classification such as Gibb's (1999) with slightly different groupings.

Table 2: OSM taxonomy according to literature

Group	Classification	Definition	Examples	Source
Product orientation	e. Whole building/modular	…make up the actual structure and fabric of the building. They enclose usable spaces and may be fully finished or partly finished	Retail outlets, office blocks and motels, concrete multi-storey modular units.	(Gibb 1999, Arif and Egbu 2010, Quale *et al.* 2012)
	f. Volumetric pre-assembly	Three-dimensional building parts that enclose a usable space. Installed onsite within independent structural frames and do not independently form the building itself.	Toilet pods, plant room units, kitchen spaces, stair shaft and building service risers and lifts, shower rooms etc.	
	g. Non-volumetric pre-assembly	Two-dimensional building components that do not enclose a usable space. May include several other sub-assemblies that constitute part of a building.	Pipework assembly, wall panels, structural sections such as slabs, beams, columns etc.	
	h. Component manufacture & sub-assemblies	Factory manufactured items that are manufactured offsite and will no way be considered for onsite production.	Bricks, tiles, window, lighting, door furniture etc.	
	f. Volumetric systems	Three-dimensional volumetric building units		(Abosoad *et al.* 2009)
	g. Panellised systems,	Two-dimensional building components	e.g. Slabs	
	h. Hybrid systems	A mix of two or more sub-categories and usually a combination of the volumetric and panelised sub-categories		
	i. Sub-assemblies and component systems	Small factory manufactured items	Bricks, tiles, window, lighting, door furniture etc.	
	j. Modular	Whole house building	Retail shops, whole residential houses	

	f. Panel systems (open & closed)	Two-dimensional building components		(Hashemi and Hadjri 2014), (Hashemi 2015)
	g. Volumetric systems	Three-dimensional volumetric building units	Kitchen, bath	
	h. Pods			
	i. Hybrid systems (semi-volumetric)	A mix of volumetric and panel systems sub-categories	Brick/block	
	j. Sub-assemblies and components	Small factory manufactured items		
	g. Construction materials	Standard building materials for construction	Timber or bricks	(Steinhardt *et al.* 2014)
	h. Components	Low level pre-cut or assembled components	Trusses, doors	
	i. Panels	Structural elements defining space	Walls	
	j. Pods	Volumetric units added to existing structure	Bathroom pods	
	k. Modular	Volumetric units, joined onsite to form house	Part-house	
	l. Complete	Whole houses including multiple rooms and fittings.	Whole house	
	g. Sub-assembly components	Factory-produced items not counted as full systems	Floor cassette, roof cassette	(Abanda *et al.* 2017)
	h. Volumetric	Factory-produced 3D units that enclose usable space	Bathroom pods, plant rooms, lift shafts	
	i. Panelised	Factory-produced flat panel units assembled onsite to produce the 3D structure.		
	j. Modular	Preassembled volumetric units that jointly form the whole building	Hotel modules	
	k. Site-based			
	l. Hybrid	A combination of volumetric and the panellised units	Tunnel form, aircrete	
	h. Frame system (pre-cast or steel)	Load bearing components	Precast concrete framing, prefabricated timber framing system and steel framing system	(Kamar et al., 2011)
	i. Panellised system	2D components		

	j. Onsite fabrication k. Sub-assembly and components l. Block work system m. Hybrid System n. Volumetric and modular system	A mix of two or more sub-categories 3D modules systems	Roof truss, balconies, staircases, toilets, lift chambers	
Modular type	d. Pure modular e. Hybrid modular f. Onsite modular	Do not accommodate changes, design is predetermined thus renders the client fully obliged to accepting the available design options Combination of onsite and offsite methods which allows customisation and it is associated with a higher requirement for coordination Pre-manufacture of modules onsite thus accommodating greater flexibility in terms of transportation		(Doran and Giannakis 2011)
Location of production	c. Offsite production d. Onsite production	Involves transferring building operations from site to factory Involve casting structural building elements at the site before erecting to its actual location		(Bari *et al.* 2012, Mostafa *et al.* 2016)
Market sub-sector	e. Complete structures (permanent or reloadable) f. Structural elements and systems g. Civil engineering h. Special		Relocatable volumetric units, Permanent volumetric units Foundation Substructure Superstructure Building envelope Building services Preassembled civil engineering structures Special structures	(Mtech Group 2007)

Production process	d. Static production e. Linear production f. Semi-automated linear production	Module is manufactured in one position, and materials, services, and personnel are brought to the module Manufacturing process is sequential, and is carried out in a discrete number of individual stages that is analogous to automotive production lines Based on the same principles of conventional linear production as non-automated lines, but tend to have more dedicated stages.		(Lawson *et al.* 2010)
	c. Factory production d. Workshop production	Features moving assembly lines with different stations Small open-plan buildings where products are moved between material and workers and modules are assembled without being moved		(Duncheva and Bradley 2016)
Geometry and configuration	d. Linear or skeleton e. Planar systems f. Box systems	Load bearing structures that transfer vertical and/or lateral load. Structures where load are distributed through large floor and wall panels Structures that do not support vertical loads itself	Beams and columns system, Panellised systems-slab, floors Three dimensional modules	(Warszawski 1999)
	d. Frame systems	Load bearing structures that transfer vertical and/or	Include beams and columns	(Badir *et al.* 2002)

	e. Panel systems f. Box systems	lateral load to the foundation. Refer to structures that carry load through slabs (i.e. floor) and wall panels Structures that do not support vertical loads itself but rather depends upon the panel systems to carry their load an also provide lateral stability.	Slabs (i.e. floor) and wall panels Kitchen and bathroom pods	
	d. Frame or post and beam system e. Panel system (2D structural elements) f. Box system (3D elements)	Structures that carry the loads through their beams and girders to columns and to the ground Structures where load are distributed through large floor and wall panels. Systems that employ three-dimensional modules for fabrication of habitable units, which are capable of withstand load from various directions due to their internal stability.		(Roy *et al.* 2007) (Thanoon *et al.* 2003)
	d. Frame e. Panel f. Cell	Load bearing components, 2D components ideal for façade application whether straight, curved or angled. 3D modules systems		Baghchesaraei et al. (2015)
Others	h. Frame system i. Panel system j. Onsite fabrication k. Sub-assembly and components l. Block work system m. Hybrid system n. Volumetric / Modular system			Musa *et al.*, (2015)

Another product aspect that has been used for classification is according to its geometry and configuration. For instance, researchers have come up with a classification for industrialised building systems (IBS) based on the geometry and configuration of framing components regardless of their enclosing materials. Warszawski (1999) gives IBS classification as (i) linear or skeleton (as in beams and columns) systems, (ii) planar systems (panellised systems) and

(iii) three dimensional or box systems. Similar classifications are used by Badir et al. (2002) for precast concrete IBS and Roy et al. (2007) for housing. There is, however, a major doubt about this type of classifications in terms of its completeness and practicality. According to Thanoon *et al.*, (2003), some new innovative systems could not be classified under this categorisation, such example is the interlocking load bearing blocks, which does not fall into any of the three categories. Additionally, Lawson et al. (2010) classified OSM according to various production processes as: static production, linear production and semi-automated linear production depending on the design of the production line while Duncheva and Bradley (2016) termed the processes as: factory and workshop production. Both classifications are similar in definitions but Lawson et al.'s (2010) classification gives room for a combination of both with their semi-automated linear production category.

The review reveals different perspective on OSM classification and a lack of consensus with regards to how OSM is to be classified, and what is deemed inclusive and what is not. The lack of a generic and standard classification has led to confusion and discrepancy especially when a classification system is needed in order to perform specific task (e.g. cost estimation). For instance, according to Kamar et al. (2011), the block work system sub-category is being separated from components and sub-assemblies even though most definitions of sub-assembles insinuates that block work is an example of this category. Also, Baghchesaraei et al. (2015) in their recent study argue that prefabrication should be divided according to criteria such as materials, methods, and structural configuration. However, their classification can only be grouped under structural/geometrical configuration. Similarly, Musa *et al.*, (2015) argue that the classification of IBS should be based on three criteria – materials, process and systems. However their classification does not reflect enough the categories they proposed.

4.2 Review and analysis of classification systems – based on UK construction industry standards systems

Apart from the attempts by researchers in previous studies to classify OSM, some standards classification systems have also been developed in the UK construction sector for classifying OSM for different purposes, e.g. for design and building information modelling such as (i) Uniclass 2015 classification system and (ii) Industry Foundation Classes respectively. These classifications systems are reviewed and compared to the existing taxonomies in literature materials.

(1) **Uniclass 2015** is a classification system used to represent all construction sector in the UK. The classification system is aimed at providing a structured library of materials and product model and project information (Afsari and Eastman 2016). It provides an information structure which is useful for categorising information for costing, briefing, preparation of specification documents and layering of CAD drawings (Delany 2015).

Table 3: Uniclass 2015 classification for prefabricated frames and walls (Source: NBS 2015)

Group	Element/Code	Systems/Codes

20	Frames (EF20_10)	Prefabricated framed and panelled structures (Ss_20_10_60)
		Prefabricated room systems (Ss_20_10_65)
		Composite pods (Ss_20_10_65_15)
		Concrete pods (Ss_20_10_65_17)
25	Walls (EF_25_10)	Prefabricated metal wall systems (Ss_25_12_85_60)
		Prefabricated glass block wall systems (Ss_25_13_33_64)

For off-site products, the top level of classification under Uniclass 2015 is 'Entity', which is a discrete unit such as a building, bridge or tunnel (Delany 2015). The information for these suite according to the Uniclass can be broken down further into Elements, Systems and Products according to the level of granularity. An element can be made up of a system or a collection of systems and a system is composed of individual products. For instance, the element 'wall' for a building can be composed of two systems, masonry wall systems and prefabricated metal wall systems. Masonry wall systems will typically include a collection of insulation, blockwork, brickwork, and wall finishes whereas prefabricated metal wall systems may include a collection of metal studs, metal joist, plasterboard, insulation and wall finishes. The products for the prefabricated metal wall systems may include aluminium, hardwood, light steel frames (LSF) etc. In Uniclass 2015, prefabricated systems and product are not independently classified, rather they are listed together across each element group thus making it difficult to extract a holistic product list if a fully prefabricated building is involved. As a result, efforts was made to identify instances of prefabricated systems in the element groups *Frames* (group 20) and *Walls* (group 25) as an example for the review (Table 3).

Based on the classification, panelled offsite structure and room systems are classified under the group element frames, which do not follow the trend and definitions previously examined in the literature (section 4.1). Review of literature materials describes frame offsite systems as load bearing structures that transfers vertical loads (Badir *et al.* 2002, Kamar *et al.* 2011), which in their case can be prefabricated columns or beams. Thus, a prefabricated room or pod system (i.e. volumetric) does not qualify under the frames group element. Also, a wall being a two-dimensional system is normally classified as a panelised system of OSM whereas it is classified differently from panels in Uniclass 2015. If classifications are a means of grouping things with similar characteristics, then a prefabricated metal-framed wall system is more likely a branch of panellised elements. Also, there is no classification for whole house offsite systems, which is a typical product category different from a room unit volumetric system (Gibb 1999) as reviewed earlier. To conclude, it is difficult to consistently evaluate OSM options with the use Uniclass 2015's classification.

(2) **Industry Foundation Classes (IFC)** was first developed to serve as a standard format for data exchange in the AEC industry. It is a high-level object-oriented data model for all types of AEC projects that gives a hierarchical structure of different aspects ranging from building,

geometry properties, materials properties, organisations and many more (Froese 2003). IFC classification is used to arrange the objects of common characteristics or purposes (buildingSMART 2016). IFC classifies object models and allows different classification systems to be referenced (Grani 2016) in a situation where there is need to adopt a specific classification system or where IFC does not include enough information of properties and attributes of an object (Grani 2016). The latest standard is IFC4 Addendum 2, which was published in 2016 (buildingSMART 2016). IFC classifies building element as *IfcElementType* when populating values for export (*IfcExportAs)* between different applications and systems. The group *ifcSharedBuildingElements* (Table 4) represents the high level categories of building elements used to represent the architectural design of a building according to IFC4.

IFC4 group element however does not include provisions for prefabricated systems such as volumetric units (e.g. pods, room units) and whole building systems, also prefabricated panel systems are not specifically categorised. This is perhaps because the data exchange format (i.e. IFC) has been mainly driven by the need of designers who are traditionally not trained to design with the use of OSM. Thus, the data structure in IFC emulates the traditional approach to element classification and attribute assertions. This is a major concern to use IFC as a basis for sharing information of prefabricated elements as it may result in a lot of inconsistency and incompleteness regarding the information created and shared.

Table 4: IFC4 Add2 building element classification (Source: buildingSMART 2016)

Group	Type
IFC Shared Building Elements	IfcBeamTypeEnum
	IfcBuildingElementProxyTypeEnum
	IfcBuildingSystemTypeEnum
	IfcChimneyTypeEnum
	IfcColumnTypeEnum
	IfcConnectionTypeEnum
	IfcCoveringTypeEnum
	IfcCurtainWallTypeEnum
	IfcDoorTypeEnum
	IfcDoorTypeOperationEnum
	IfcMemberTypeEnum
	IfcPlateTypeEnum
	IfcRailingTypeEnum
	IfcRampFlightTypeEnum
	IfcRampTypeEnum
	IfcRoofTypeEnum
	IfcShadingDeviceTypeEnum
	IfcSlabTypeEnum
	IfcStairFlightTypeEnum
	IfcStairTypeEnum
	IfcWallTypeEnum
	IfcWindowTypeEnum
	IfcWindowTypePartitioningEnum

5. Discussion

5.1 Classification system for OSM

The review from the previous sections reveals the differences in classifications of OSM. By synthesizing the data retrieved from previous studies for the purpose of comparing evidence to generate new construct, it is established that various factors influences how OSM is classified, this includes: materials type, production methods, products types and sizes, and structural configuration. These various factors can however be grouped under three high-level concepts which are (i) based on product (ii) based on process (iii) based on people (Figure 4). This classification system in Figure 4 summarises the different approaches previously reviewed and should help achieve consistency in terms of the use of agreed vocabularies and also enhance communication. The use of OSM related keywords in the definitions and classifications is due to the rationale behind the development of structured knowledge. The aim is to use a set of approved vocabularies by the experts in the field in order to aid communication.
One major advantage of classifying in this approach is the ability to make the classification robust enough and suitable for different purposes. For instance, the knowledge of OSM may be needed for various purposes such as costing, risk management, scheduling, production sequence planning and many other tasks. A further explanation of these are outlined in sections 5.1.1, 5.1.2 and 5.1.3.

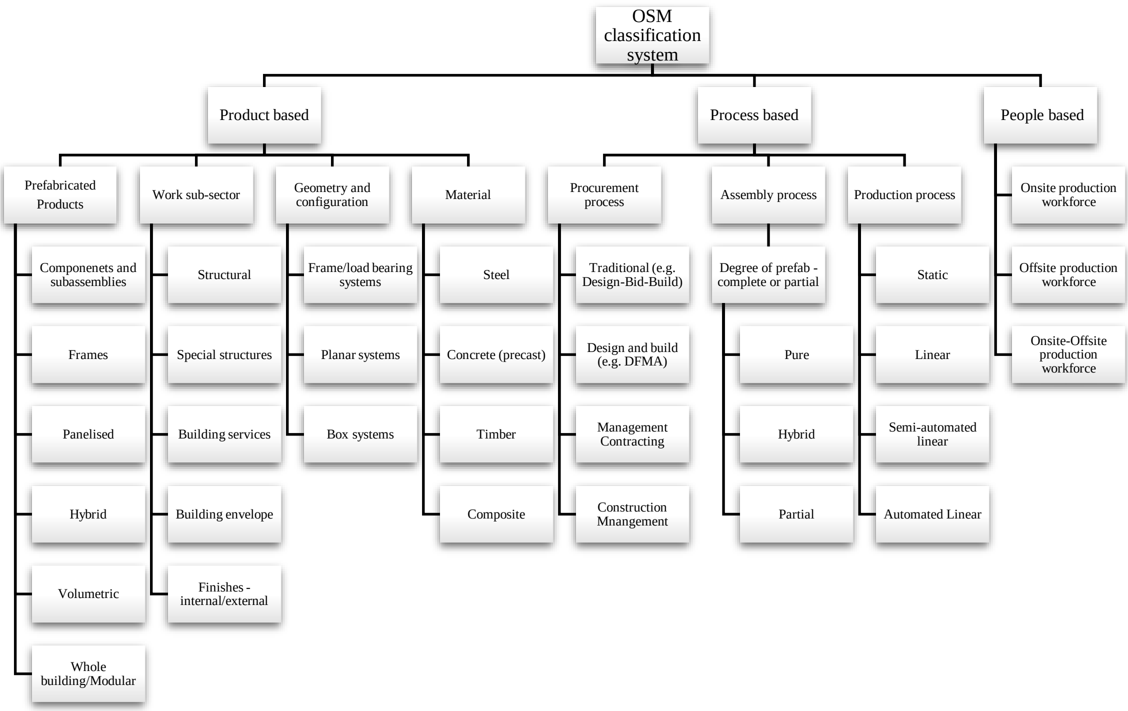


Figure 4: OSM Classification

5.1.1 Product-based classification

The product-based classification for OSM is according to the characteristics and types of the end/finished product of an offsite manufacturing process, which include: the types of prefabricated elements, component materials, geometry and sector of work for a product (Table 5). This classification is useful for identifying types of offsite manufactured products and grouping them for specific purposes. For instance, the product-based classification will be useful for elemental costing purposes to attribute properties to each offsite elements or components. As an example, a prefabricated product typically has a material type, geometry and also fall under a specific work sub-sector (e.g. a panelised offsite product made from timber has a plane geometry, and can either be grouped as a structural element – e.g. load-bearing wall, or building envelope – e.g. curtain walls). Accordingly, the knowledge of offsite products is enriched through defining the relationships between the various properties and the influence on the final cost of such element.

Table 5: Definition of concepts in the product-based classification

Class	Subclass	Instances	Description
Prefabricated Products	Components and sub-assemblies	Bricks, tiles, window, lighting, door furniture etc.	Factory manufactured items that are produced offsite and certainly not considered for onsite production.
	Frames	Beams, columns, bracings etc.	Load bearing structures that transfer vertical and/or lateral load to the foundation.
	Panelised	Wall panels, floors panels etc.	Two-dimensional building components that do not enclose a usable space and may include several other sub-assemblies that constitute part of a building.
	Hybrid	Roofs	A mix of two or more sub-categories and usually a combination of the volumetric and panelised sub-categories.
	Volumetric	Toilet pods, plant room units, kitchen spaces, stair shaft and building service risers and lifts, shower rooms etc.	Three-dimensional building parts that enclose a usable space but do not independently form a building itself.
	Whole building	Retail outlets (shops and stores), office blocks and motels	They enclose usable spaces and make up the actual structure and fabric of the building. Usually a low rise complete building which may be fully finished or partly finished
Work sub-sector	Structural	Columns, beams, foundations, walls etc.	Primary physical parts of a building
	Building services	Pods, Lifts, plant room etc.	Systems installed in buildings to enhance functionality
	Building envelope	Façade systems, roof systems	The exterior of a building which serves as physical separator between the interior and exterior of a building
	Finishes	Plaster, paints etc.	The final surface of a building element
	Special structures	Unique structures e.g. stadia	Structures that require engineering creativity and specialist design, analysis and construction
Geometry and configuration	Frame system	Beams and columns	Load-bearing structures
	Planar system	Slab, floors, wall panels etc.	Two-dimensional components that may be straight, curved or angled
	Box system	Kitchen and bathroom pods etc.	Three-dimensional modules that do not support vertical loads itself.
Materials	Steel	Lightweight steel etc.	A metal part containing iron as a primary material
	Concrete (precast)	Self-compacting concrete, lightweight concrete etc.	Comprising of a mixture of cement, aggregate and water where components are manufactured in a central plant and

			later brought to the building site for assembly.
	Timber	Bamboo, Oak, plywood, soft wood etc.	Wood suitable for engineering purposes.
	Composite	Fibre-reinforced polymer (FRP), PVC polyester etc.	Comprising two or more constituent materials with significantly different physical or chemical properties

5.1.2 Process-based classification

OSM can also be classified based on its processes including the procurement process (i.e. the sequence of design to production and whether the design approach attempts to integrate the ease of manufacture and efficiency of assembly or to address conventional construction design concerns), the assembly process (i.e. the extent in which manufactured components are complete for assembly) or production process (i.e. the methods employed in producing the manufactured components such as the use of innovative technologies and amount of skilled/unskilled labour required) (Table 6). For instance, an OSM project can be procured via a traditional design-bid-build approach where the subcontractor or specialist contractor undertakes production in a way similar to the onsite approach (i.e. static production method). Alternatively, a production can be carried out sequentially on a line with the use of robotics stationed at strategic points to hasten the process (i.e. an automated linear production). In a situation where the advantages of modularisation is more desirable, all components can be factory manufactured with only assembly done onsite (i.e. pure prefab). Describing OSM in this manner is advantageous for purposes such as planning and scheduling of the production and assembly processes.

Table 6: Definition of terms in the process-based classification

Class	Instances	Description
Procurement process	Traditional – design-bid-build	Where the client appoints consultants to design the development and then a contractor to construct the works, the contractor has little or no influence on the design.
	Design and build - DFMA	A single contractor to design and build the work and the contractor has a say in the design process. The contactors has little or no influence on the design.
	Management Contracting	A management contractor contracts and manages the work to other work contractors to construct the work.
	Construction Management	A construction manager to serve as a representative of the client in coordinating all work contracts and other trade contractors
Production process	Static	A process where prefabricated elements are manufactured in one position, and materials, services, and personnel are brought to the fabrication point.
	Linear	Production process is sequential and carried out in a discrete number of individual stages.
	Semi-automated linear	Based on the same principles of conventional linear production as non-automated lines, but tend to have more dedicated stages
	Automated linear	Linear production with sequential stages that are automated

Assembly process	Pure prefab	All activities carried out in a controlled environment (either offsite or onsite) with only assembly and installation done onsite.
	Hybrid prefab	Comprising of both onsite and offsite prefabricated components assembled together. For instance, an onsite factory produced element joined together with an offsite purchased structural element to make a complete structure.
	Partial prefab	A mix of offsite factory produced components and onsite cast insitu components.

5.1.3 People-based classification

This category gives information on the degree of prefabrication and category of workforce required for an offsite product manufacture i.e. whether products are manufactured/assembled using onsite or offsite labour, or a combination of both (Table 7). The choice of production/assembly process influences the type/characteristics of workforce required. If a higher degree of prefabrication is sought, the amount of work that needs to be finished off in the factory will be higher and thus, required more onsite activities and workforce, and a few workforce onsite for just assembly. This classification system may be used in carrying out tasks such as risk assessment or health and safety analysis both onsite and offsite, as well as generating onsite/offsite labour cost for offsite manufactured products.

Table 7: Definition of terms in the people-based classification

Class	Instances	Description
Organisation	Offsite	Involves transferring building operations from site to factory using factory located personnel.
	Onsite	Involves the production of building elements at the site before erecting to its actual location using site based personnel.
	Onsite-offsite	Involves a mix of both offsite and onsite production and assembly team.

6. Conclusion and future work

6.1 Conclusion

Offsite manufacturing (OSM) as a domain is reviewed to identify issues with its definitions and classification systems. Finding from the review suggest that there is a great level of misconceptions about its definition and taxonomies. This paper proposes a definition and classification approach which combines the essential elements of existing classifications. The following conclusion has been drawn from the review:

- Although OSM is defined differently by most researchers in the field, most existing definitions covers mostly the essential aspect that distinguishes OSM concept from the conventional approach. However, elements of the benefits of modularisation and standardisation are largely missing from most of the definitions.
- There is a significant lack of consensus on OSM classification approach thus leading to misunderstanding on what should be regarded as part of OSM and what is not.

Researchers tend to classify OSM based on the particular theme of their study or the purpose for which the classification is needed.

- Existing classification system in the UK such as Uniclass and IFC are limited in terms of providing a detailed level classification for OSM compared to traditional approach. These classification systems needs to be consistent in describing major OSM classes and their sub-classes, and also should be extended to cover missing elements and serve as a basis for a unified approach for classifying OSM.

Although attempt has been made in this study to develop a generic definition and classification system for OSM. This is only based on high-level concepts and essentially to identify common traits and include all aspects from previous classification systems. The generic classification for OSM will need to be extended in order to provide a more robust system fit for different purposes. The authors believe that to fully benefit from the classification system, there is a need to adopt both top-down and bottom-up approaches. The attempt to review previous works on classifications in this study to develop the high-level OSM classification is an example of a top-down approach to integrate the existing ideas and concepts. Efforts will need to be spent on developing the classification further using a bottom-up approach as well, i.e. through capturing knowledge from individual cases of offsite (e.g. steel, timber or concrete offsite systems), as OSM knowledge is likely highly specialised and can involve a lot of localised properties that is not necessarily possible to be generalised without learning from actual cases.

6.2 Future work

This research has highlighted areas of opportunities with regards to OSM classification. Based on the classification system developed, there are several areas of research arising from the study which will need to be pursued. There is need to consider the application of more scientific approaches recognised for knowledge development in a specific domain. An example is the use of ontology knowledge modelling approach for the formalisation of offsite vocabularies to enable knowledge extraction and facilitate communication. This would benefit from the bottom-up approach through the use of case studies to determine finite level classes, subclasses and properties and their corresponding relationships so as to facilitate automated retrieval on information for various purposes (e.g. cost estimation). The formalisation of offsite knowledge through an ontology development gives transparency and the ease of communication for professionals, and the potential to automate advices using software applications.

References

AAQS, 2016. *Guide to Elemental Cost Estimating & Analysis for Building Works 2016*. Second.

Abanda, F.H., Tah, J.H.M., and Cheung, F.K.T., 2017. BIM in off-site manufacturing for buildings. *Journal of Building Engineering*, 14 (September), 89–102.

Abanda, F.H., Taj, J.H.M., Pettang, C., and Manjia, M.B., 2011. An ontology-driven building construction labour cost estimation in Cameroon. *Journal of Information Technology in*

Construction (ITcon), 16, 617–634.

Abdullah, M.. and Egbu, C.., 2010. Selection criteria frameword for choosing industrialized building systems for housing projects. *In*: C. Egbu, ed. *Procs 26th Annual ARCOM Conference, 6-8 September 2010*. Leeds: Association of Researchers in Construction Management.

Abdullah, M.R. and Egbu, C.O., 2009. *Industrialised building system in Malaysia: Issues for research in a changing financial and property market*. Proceedings of the BUHU 9th International Post Graduate Research Conference.

Abdulmalek, F.A. and Rajgopal, J., 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of Production Economics*, 107 (1), 223–236.

Abosoad, H., Underwood, J., and Boreny, S., 2009. Towards an Information System Representation of off Site Manufacturing (OSM) in Facilitating the Virtual Prototyping of Housing Design. *In*: *9th International Postgraduate Research Conference (IPGRC)', University of Salford, Salford, UK*. 509–520.

Adamides, E.D. and Karacapilidis, N., 2006. A knowledge centred framework for collaborative business process modelling. *Business Process Management Journal*, 12 (5), 557–575.

Adeli, H. and Wu, M., 1998. Regularization neural network for construction cost estimation. *Journal of Construction Engineering and Management*, 124 (1), 18–23.

Afsari, K. and Eastman, C.M., 2016. A Comparison of Construction Classification Systems Used for Classifying Building Product Models. *In*: *52nd ASC Annual International Conference Proceedings*. Associated Schools of Construction.

Aguilar-Savén, R.S., 2004. Business process modelling: Review and framework. *International Journal of Production Economics*, 90 (2), 129–149.

Ahmed, V., Opoku, A., and Aziz, Z., 2016. *Research Methodology in the Built Environment: A selection of case studies*. New York: Routledge.

Akasah, Z.A., Amirudin, R., and Alias, M., 2010. Maintenance management process model for school buildings: An application of IDEF 0 modelling methodology . *Australian Journal of Civil Engineering*, 8 (1), 1–12.

Akintoye, A. and Fitzgerald, E., 2000. A survey of current cost estimating practices in the UK A. *Construction Management & Economics*, 18, 161–172.

Akyol, D.E., Tuncel, G., and Bayhan, G.M., 2007. An Analysis of Activity-Based Costing in a Manufacturing System. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, 1 (11), 1040–1043.

Aldridge, G., Pasquire, C., Gibb, A., and Blismas, N., 2001. Methods for Measuring the "Unmeasurable": Evaluating the Benefits of Pre-Assembly and Standardization in Construction. *In*: *17th Annual ARCOM Conference, 5-7 September 2001, University of Salford. Association of Researchers in Construction Management*. 311–9.

Almeida, A. and Cunha, J., 2017. The implementation of an Activity-Based Costing (ABC) system in a manufacturing company. *Procedia Manufacturing*, 13, 932–939.

Alonso, R., Borras, M., Koppelaar, R.H.E.M., Lodigiani, A., Loscos, E., and Yöntem, E., 2019.

SPHERE: BIM Digital Twin Platform. *Proceedings*, 20 (1), 9.

Arafa, M. and Alqedra, M., 2011. Early Stage Cost Estimation of Building Construction Projects using Artificial Neural Networks. *Journal of Artificial Intelligence*, 4 (1), 63–75.

Arbizzani, E. and Civiero, P., 2013. Technical solutions and industrialised construction systems for advanced sustainable buildings. *In*: *PORTUGAL SB13 - CONTRIBUTION OF SUSTAINABLE BUILDING TO MEET EU 20-20-20 TARGETS*. 371–378.

Arditi, D. and Mochtar, K., 2000. Trends in productivity improvement in the US construction industry. *Construction Management & Economics*, 18 (1), 15–27.

Arif, M. and Egbu, C., 2010. Making a case for offsite construction in Making a case for offsite construction in China. *Engineering Construction & Architectural Management*, 17 (6), 536–548.

Assaf, S.A. and Al-Hejji, S., 2006. Causes of delay in large construction projects. *International Journal of Project Management*, 24, 349–357.

Awuzie, B. and McDermott, P., 2017. An abductive approach to qualitative built environment research: A viable system methodological exposé. *Qualitative Research Journal*, 17 (4), 356–372.

Ayachit, A.C., Attarde, P.M., and Kulkarni, S., 2014. Activity Based Costing in Construction. *International Journal of Advanced Engineering Research and Studies*, 4 (1), 9–14.

Ayinla, K.O., Cheung, F., and Tawil, A.R., 2019. Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system. *Construction Innovation*, 20 (2), 223–246.

Badir, Y.F., Kadir, M.R.A., and Hashim, A.H., 2002. Industrialized Building Systems Construction in Malaysia. *Journal of Architectural Engineering*, 8 (1).

Baghchesaraei, A., Kaptan, M.V., and Baghchesaraei, O.R., 2015. Using prefabrication systems in building construction. *International Journal of Applied Engineering Research*, 10 (24), 44258–44262.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., and Wong, I., 2006. Designing out waste in high-rise residential buildings : analysis of precasting and methods and traditional construction. *In*: *The International Conference on Asia-European Sustainable Urban Development*. Chongqing, China.

Baloi, D., 2003. Sustainable construction: Challenges And Opportunities. *In*: *19th Annual ARCOM Conference*. 289–97.

Barber, K.D., Dewhurst, F.W., Burns, R.L.D.H., and Rogers, J.B.B., 2003. Business-process modelling and simulation for manufacturing management: A practical way forward. *Business Process Management Journal*, 9 (4), 527–542.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertran, N., and Brown, S.V., 2017. *Reinventing construction through a productivity revolution*.

Bari, N.A.A., Abdullah, N.A., Yusuff, R., Ismail, N., and Jaapar, A., 2012. Environmental Awareness and Benefits of Industrialized Building Systems (IBS). *Procedia - Social and Behavioral Sciences*, 50 (July), 392–404.

Baxter, P. and Jack, S., 1990. Qualitative case study methodology: study design and implementation for novice researchers. *The Qualitative Report*, 13 (4), 544–559.

Baxter, P. and Jack, S., 2008. Qualitative Case Study Methodology : Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13 (4), 544–559.

Ben-Arieh, D. and Qian, L., 2003. Activity-based cost management for design and development stage. *International Journal of Production Economics*, 83 (2), 169–183.

Bertelsen, S., 2005. Modularization – a third approach to making construction lean? *In*: *13th annual conference in the International Group for Lean Construction*. Sydney, Australia, 1–11.

Blismas, N., Pasquire, C., and Gibb, A., 2006a. Bene t evaluation for o ff-site production in construction. *Construction Management & Economics*, 24 (2), 121–130.

Blismas, N., Pasquire, C., and Gibb, A., 2006b. Benefit evaluation for off - site production in construction. *Construction Management and Economics*, 24 (2), 121–130.

Blismas, N. and Wakefield, R., 2007. Drivers constraints and the future of off-site manufacture in Australia. *Construction Innovation Special Edition*.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114 (January), 103179.

Bottom, D., Gann, D., Groak, S., and Meikle, J., 1996. *Innovation in Japanese Prefabricated House-Building Industries: Department of Trade and Industry Overseas Science and Technology Expert Mission Visit Report*. Construction Industry Research and Information Association.

Brockmans, S., Haase, P., Hitzler, P., and Studer, R., 2006. A Metamodel and UML Profile for Rule-extended OWL DL Ontologies. *In*: Y. Sure and J. Domingue, eds. *ESWC 2006*. Berlin Heidelberg: Springer-Verlag, 303–316.

Bryman, A., 2012. *Social Research Methods*. 4th editio. New York: Oxford University Press.

buildingSMART, 2016. IFC4 Add2 - Addendum 2 [online]. *buildingSMART International Ltd.* Available from: http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/ [Accessed 2 Jan 2019].

Cabinet Office, 2011. *Government Construction Strategy*. London.

Caputo, A.C. and Pelagagge, P.M., 2005. Parametric and Neural Methods for Cost Estimation Of Process Vessels. *In*: *18th International Congress of Mechanical Engineering*.

Carli, G. and Canavari, M., 2013. Introducing Direct Costing and Activity based Costing in a Farm Management System: A Conceptual Model. *Procedia Technology*, 8 (Haicta), 397–405.

Carr, R.I., 1989. Cost - Estimating Principles. *Journal of Construction Engineering and Management*.

Chan, C.W. and Johnstonb, M., 1996. Knowledge modelling for constructing an expert system to support reforestation decisions. *Knowledge-Based Systems*, 9, 41–59.

Chan, E.H.W. and Tse, R.Y.C., 2003. Cultural Considerations in Cultural Considerations in International Construction Contracts. *Journal of Construction Engineering and*

Management, 129 (4), 375–381.

Chau, K.W., 1995. The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs : empirical evidence from Hong Kong. *Construction Management and Economics*, 13 (1), 15–21.

Chau, K.W. and Anson, M., 2002. A Knowledge-Based System for Constr uction Site Level Facilities Layout, 2358, 393–402.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010a. Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction*, 19 (2), 235–244.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010b. Automation in Construction Decision support for construction method selection in concrete buildings : Prefabrication adoption and optimization. *Automation in Construction*, 19, 665–667.

Cheng-Leong, A., Pheng, K.L., and Leng, G.R.K., 1999. IDEF: A comprehensive modelling methodology for the development of manufacturing enterprise systems. *International Journal of Production Research*, 37 (17), 3839–3858.

Cheung, F.K.T., Kurul, E., and Oti, A.H., 2016. A case study of hybrid strategies to create value for a contracting business in the education sector in England and Wales. *Construction Management and Economics*, 34 (4–5), 335–352.

Chevallier, Z., Finance, B., and Boulakia, B.C., 2020. A reference architecture for smart building digital twin. *CEUR Workshop Proceedings*, 2615, 1–12.

Chiang, Y.H., Hon-Wan Chan, E., and Ka-Leung Lok, L., 2006. Prefabrication and barriers to entry-a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, 30 (3), 482–499.

Chou, J.-S., Yang, I.-T., and Chong, W.K., 2009. Probabilistic simulation for developing likelihood distribution of engineering project cost. *Automation in Construction*, 18 (August), 570–577.

Chou, J.S., 2011. Cost simulation in an item-based project involving construction engineering and management. *International Journal of Project Management*, 29 (6), 706–717.

Corcho, O., Fernandez-Lopez, M., and Gomez-Perez, A., 2003. Methodologies , tools and languages for building ontologies . Where is their meeting point ? *Data & Knowledge Engineering*, 46, 41–64.

Corcho, O. and Gómez-Pérez, A., 2000a. Evaluating Knowledge Representation and Reasoning Capabilities of Ontology Specification Languages. *In*: *Applications of Ontologies and Problem Solving Methods 14th European Conference on Artificial Intelligence (ECAI'00)*. 3.1 – 3.9.

Corcho, O. and Gómez-Pérez, A., 2000b. A roadmap to ontology specification languages. *In*: R. Dieng and O. Corby, eds. *EKAW*. Berlin Heidelberg: Springer-Verlag Berlin, 80–96.

Cox, R.F., Issa, R.R.A., Asce, M., and Ahrens, D., 2003. Management ' s Perception of Key Performance Indicators for Construction. *Journal of Construction Engineering & Management*, 129 (2), 142–151.

Creswell, J.W., 2009. *Research Design_ Qualitative, Quantitative, and Mixed Methods*

Approaches. Third edit. London: SAGE Publications.

Cutting-Decelle, A.-F., Young, B.I., Das, B.P., Case, K., Rahimifard, S., Anumba, C.J., and Bouchlaghem, D.M., 2007. A Review of Approaches to Supply Chain Communications: From Manufacturing to Construction. *ITcon*, 12, 73–102.

Datta, P.P. and Roy, R., 2009. Cost Modelling Techniques for Availability Type Service Support Contracts : a Literature Review and Empirical Study. *In*: *Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2)*. 216.

Dave, B., Koskela, L., and Kiviniemi, A., 2013. *Implementing Lean in construction: Lean construction and BIM*. CIRIA Guide C725 - Construction Industry Research and Information Association. London: CIRIA.

Delany, S., 2015. Classification [online]. *National Building Specification (NBS) BIM Toolkit*. Available from: https://toolkit.thenbs.com/articles/classification#classificationtables [Accessed 4 Feb 2019].

Denzin, N.K. and Lincoln, Y.S., 2000. *Handbook of Qualitative Research*. Second. London: SAGE Publications.

Djurić, D., Gašević, D., and Devedžić, V., 2005. Ontology modeling and MDA. *Journal of Object Technology*, 4 (1), 109–128.

Doomun, R. and Jungum, N.V., 2008. Business process modelling, simulation and reengineering: Call centres. *Business Process Management Journal*, 14 (6), 838–848.

Doran, D. and Giannakis, M., 2011. An examination of a modular supply chain : a construction sector perspective. *An International Journal of Supply Chain Management*, 16 (4), 260–270.

Dubois, A. and Gadde, L.-E., 1999. Case studies in business market research: An abductive approach. *In*: M. Damien and C. Horan, eds. *Proceedings of the 15th Annual IMP Conference*. Dublin, 1–20.

Duncheva, T. and Bradley, F.F., 2016. A comparison between Volumetric Timber Manufacturing Strategies in the UK and mainland Europe. *In*: *2016 Modular and Offsite Construction (MOC) Summit*. Edmonton, Alberta, Canada, 10–17.

Durdyev, S. and Mbachu, J., 2011. On-site Labour Productivity of New Zealand Construction Industry : Key Constraints and Improvement Measures. *Australasian Journal of Construction Economics and Building*, 11 (3), 18–33.

Duverlie, P. and Castelain, J.M., 1999. Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method. *The International Journal of Advanced Manufacturing Technology*, 15, 895–906.

Eastman, C.M. and Sacks, R., 2008. Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134 (7), 517–526.

Egan, J., 1998. *Rethinking Construction*. The Report of the Construction Task Force.

El-Diraby, T.A., Lima, C., and Feis, B., 2005. Domain Taxonomy for Construction Concepts : Toward a Formal Ontology for Construction Knowledge. *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, 19 (4), 394–406.

El-Gohary, N.M. and El-Diraby, T.E., 2015. Domain Ontology for Processes in Infrastructure and Construction. *Journal of Construction Engineering and Management ASCE*, (January).

Elhag, T.M.S. and Boussabaine, A.H., 1998. An Artificial Neural System for Cost Estimation Of Construction Projects. *In*: *14th Annual ARCOM Conference*. 219–226.

Elnaas, E., 2014. The Decision To Use Off-Site Manufacturing (OSM) Systems for House Building Projects in the UK. University of Brighton. UK.

Elo, S. and Kyngäs, H., 2008. The qualitative content analysis process. *Journal of Advanced Nursing*, 62 (1), 107–115.

Enshassi, A., Mohamed, S., and Abushaban, S., 2009. Factors affecting the performance of construction projects in the Gaza strip. *Journal of Civil Engineering and Management*, 15 (2), 269–280.

Farmer, M., 2016. *Modernise or die: The Framer Review of the UK construction labour market*. The Farmer Review of the UK Construction Labour Model.

Fellows, R.F. and Liu, A.M.M., 2015. *Research Methods for Construction*. Fourth Edi. West Sussex: John Wiley & Sons Ltd.

Fensel, D., 2000. Relating Ontology Languages and Web Standards Ontology Languages.

Fernández-solís, J.L., 2009. How the Construction Industry does differ from manufacturing ? *In*: *Associated Schools of Construction International Proceedings of the 45th Annual Conference*. Gainesville.

Fernández, L.M., 1999. Overview Of Methodologies For Building Ontologies. *Proceedings of the IJCAI99 Workshop on Ontologies and ProblemSolving Methods Lessons Learned and Future Trends CEUR Publications*, 1999 (2), 1–13.

Fernandez, M., Gomez-Perez, A., and Juristo, N., 1997. *METHONTOLOGY : From Ontological Art Towards Ontological Engineering*.

Finnimore, B., 1989. *Houses from the Factory: System Building and the Welfare State*. California: Rivers Oram Press.

Flick, U., 2007. *Designing Qualitative Research*. London: SAGE Publications.

Flick, U., 2014. *The SAGE Handbook of Qualitative Data Analysis*. London: SAGE Publications.

Formoso, C.T., 1991. A Knowledge-based Framework for Planning House Building Projects. University of Salford.

Forsberg, A. and Saukkoriipi, L., 2007. Measurement of waste and productivity in relation to lean thinking. *In*: *Lean Construction: A New Paradigm for Managing Capital Projects - 15th IGLC Conference*. 67–76.

Fortineau, V., Paviot, T., Louis-Sidney, L., and Lamouri, S., 2012. SWRL as a rule language for ontology-based models in power plant design. *IFIP Advances in Information and Communication Technology*, 388 AICT, 588–597.

Froese, T., 2003. FUTURE DIRECTIONS FOR IFC-BASED INTEROPERABILITY. *ITcon*, 8 (December 2002), 231–246.

Future Focus, 2017. *Offsite and Modular Building Market Research*.

Gann, D.M., 1996. Construction as a manufacturing process ? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics*, 14 (5), 437–450.

Gbadamosi, A.Q., Mahamadu, A.M., Oyedele, L.O., Akinade, O.O., Manu, P., Mahdjoubi, L., and Aigbavboa, C., 2019. Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, 215, 1180–1190.

Giacobbi, P.R., Poczwardowski, A., and Hager, P., 2005. A pragmatic research philosophy for applied sport psychology. *Sport Psychologist*, 19 (1), 18–31.

Gibb, A.G.F., 1999. *Off-site fabrication: Prefabrication, Pre-assembly and Modularisation*. New York: John Wiley & Sons.

Gibb, A.G.F., 2001. Standardization and pre-assembly – distinguishing myth from reality using case study research. *Construction Management and Economics*, 19, 307–315.

Gibb, A.G.F. and Isack, F., 2003. Re-engineering through pre-assembly : client expectations and drivers. *Building Research & Information*, 31 (2), 146–160.

Girmscheid, G. and Scheublin, F., 2010. New perspective in industrialisation in construction - a state of the art report. *International Council For Research And Innovation In Building And Construction (CIB)*, (May).

Golbreich, C., 2004. Combining Rule and Ontology Reasoner for the Semantic Web. *In*: Grigoris Antoniou and H. Boley, eds. *Third International Workshop, RuleML 2004*. Berlin: Springer, ??? ????

Gómez-Pérez, A. and Corcho, O., 2002. Ontology languages for the semantic web. *IEEE Intelligent Systems and Their Applications*, 17 (1), 54–60.

Goodier, C. and Gibb, A., 2005. *The value of the UK market for offsite*. London.

Gorgolewski, M.T., 2005. The Potential for Prefabrication in UK Housing to Improve Sustainability. *In*: J. Yang, P.S. Brandon, and A.C. Sidwell, eds. *Smart & Sustainable Built Environments*. Oxford, UK.: Blackwell Publishing Ltd, 1–8.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012a. Offsite Construction : Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1, 62–73.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012b. Offsite Construction: Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1 (1), 62–73.

Goulding, J.S., Pour Rahimian, F., Arif, M., and Sharp, M.D., 2015. New offsite production and business models in construction: priorities for the future research agenda. *Architectural Engineering and Design Management*, 11 (3), 163–184.

GOV.UK, 2020. Live tables on house building [online]. *Ministry of Housing, Communities & Local Government*. Available from: https://www.gov.uk/government/statistical-data-sets/live-tables-on-house-building [Accessed 1 Feb 2020].

Grani, H.K., 2016. BIM Classification - Giving your Model some Class [online]. *Areo blog - Lifecycle BIM and smart FM*.

Griffith, M. and Jefferys, P., 2013. *Solutions for the housing shortage: How to build the*

250.000 homes we need each year. London.

Gruber, T.R., 1995. Toward principles for the design of ontologies used in knowledge sharing. *International Journal of Human Computer Studies*, 43, 907–928.

Gu, N. and London, K., 2010. Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, 19 (8), 988–999.

Guba, E.G. and Lincoln, Y.S., 1994. Competing Paradigms in Qualitative Research. *In*: N.K. Denzin and Y.S. Lincoln, eds. *Handbook of qualitative research*. 105–117.

Guizzardi, G., 2007. On Ontology, ontologies, Conceptualizations, Modeling Languages, and (Meta)Models. *In*: O. Vasilecas et al., ed. *Databases and Information Systems IV*. IOS Press.

Gunasekaran, A. and Kobu, B., 2002. Modelling and analysis of business process reengineering. *International Journal of Production Research*, 40 (11), 2521–2546.

Gunasekaran, A. and Sarhadi, M., 1998. Implementation of activity-based costing in manufacturing. *Intern. Journal of Production Economics*, 56–57 (1998), 231–242.

Gunaydın, H.M. and Dogan, S.Z., 2004. A neural network approach for early cost estimation of structural systems of buildings. *International Journal of Project Management*, 22 (2004), 595–602.

Gunduz, M., Ugur, L.O., and Ozturk, E., 2011. Parametric cost estimation system for light rail transit and metro trackworks. *Expert Systems with Applications*, 38 (3), 2873–2877.

Gurcanli, G.E., Bilir, S., and Sevim, M., 2015. Activity based risk assessment and safety cost estimation for residential building construction projects. *Safety Science*, 80 (112), 1–12.

Hairstans, R. and Smith, R.E., 2018. Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK. *Architectural Engineering and Design Management*, 14 (1–2), 60–77.

Haron, N.A., Abdul-Rahman, H., Wang, C., and Wood, L.C., 2015. Quality function deployment modelling to enhance industrialised building system adoption in housing projects. *Total Quality Management and Business Excellence*, 26 (7–8), 703–718.

Hashemi, A., 2015. Offsite Manufacturing: A Survey on the Current Status and Risks of Offsite Construction in Iran, 9, 141–152.

Hashemi, A. and Hadjri, K., 2014. Offsite Construction, a Potential Answer to the Iranian Housing Shortages. *In*: *Construction Technology and Management CTM 2014 International Scientific Conference*. 189–199.

Hause, M., 2006. The SysML Modelling Language. *In*: *Fifteenth European Systems Engineering Conference*. 12.

HM Government, 2013. *Construction 2025. Industrial Strategy: Government and industry in partnership*.

Holten, M. and Ferdinand, G., 2020. BOT : the Building Topology Ontology of the W3C Linked Building Data Group. *Semantic Web*, 12 (1), 143–161.

Höök, M. and Stehn, L., 2008. Lean principles in industrialized housing production : the need for a cultural change Lean culture. *Lean Construction Journal 2008*, (April), 20–33.

Horrocks, I., 2002. DAML+OIL: a Description Logic for the Semantic Web. *Bulletin of the Technical Committee on Data Engineering*, 25 (1).

Horrocks, I. and Sattler, U., 2001. Ontology reasoning in the SHOQ(D) description logic. *IJCAI International Joint Conference on Artificial Intelligence*, 199–204.

Howell, G. and Ballard, G., 1998. Implimenting construction: understanding and action. *Proceedings International Group for Lean Construction*, 0, 9.

Howell, G.A., 1999. What is Lean Construction. *In*: I.D. Tommelein, ed. *IGLC 2012 - 20th Conference of the International Group for Lean Construction*. UNIVERSITY OF CALIFORNIA BERKELEY, CALIFORNIA, USA.

Hueber, C., Horejsi, K., and Schledjewski, R., 2016. Review of cost estimation: methods and models for aerospace composite manufacturing. *Advanced Manufacturing: Polymer and Composites Science*, 2 (1), 1–13.

Hyde, K.F., 2000. Recognising deductive processes in qualitative research. *Qualitative Market Research: An International Journal*, 3 (2), 82–90.

Ijomah, W.L. and Childe, S.J., 2007. A model of the operations concerned in remanufacture. *International Journal of Production Research*, 45 (24), 5857–5880.

Jabar, I. laili, Ismail, F., and Mustafa, A.A., 2013. Issues in Managing Construction Phase of IBS Projects. *Procedia - Social and Behavioral Sciences*, 101, 81–89.

Jaillon, L. and Poon, C.S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment : a Hong Kong case study. *Construction Management and Economics*, 26 (9), 953–966.

Jaillon, L. and Poon, C.S., 2009. The evolution of prefabricated residential building systems in Hong Kong : A review of the public and the private sector. *Automation in Construction*, 18 (3), 239–248.

Jaillon, L., Poon, C.S., and Chiang, Y.H., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management*, 29 (1), 309–320.

Jarkas, A.M. and Bitar, C.G., 2012. Factors Affecting Construction Labor Productivity in Kuwait. *Journal of Construction Engineering and Management*, 138 (7), 811–820.

Ji, S., Park, M., and Lee, H., 2011. Cost estimation model for building projects using case-based reasoning. *Canadian Journal of Civil Engineering*, 38, 570–581.

Jones, D., Bench-capon, T., and Visser, P., 1998. Methodologies for Ontology Development. *In*: *Proc. IT&KNOWS Conference of the 15th IFIP World Computer Congress*. Budapest.

Jonsson, H. and Rudberg, M., 2014. Classification of production systems for industrialized building : a production strategy perspective. *Construction Management and Economics*, 32 (1–2), 53–69.

Jung, J., 2002. Manufacturing cost estimation for machined parts based on manufacturing features. *Journal of Intelligent Manufacturing*, 13, 227–238.

Kalemi, E.V., Cheung, F., Tawil, A., Patlakas, P., and Alyania, K., 2020. ifcOWL-DfMA a new ontology for the offsite construc- tion domain. *In*: *Proceedings of the7578th Linked Data in Architecture and Construction Workshop - LDAC2020 ifcOWL-DfMA*. 105–117.

Kamar, K.A., Abd Hamid, Z., Azman, M.N.A., and Ahamad, M.S.S., 2011. Industrialized Building System (IBS): Revisiting Issues of Definition and Classification. *International Journal of Emerging. Sciences*, 1 (2), 120–132.

Karhu, V., 2000. Formal Languages for Construction Process Modelling. *Construction Information Technology 2000, Taking the construction industry into the 21st century, CIB W78.*, 525–534.

Kenley, R., 2014. Productivity improvement in the construction process Productivity improvement in the construction process. *Construction Management and Economics*, 32 (6), 489–494.

Kenley, R., Kanjanabootra, S., Ouyang, C., and Wynn, M., 2012. Procuring OSM: base-line models of off-site manufacture business processes in Australia. *In*: *16th Pacific Association of Quantity Surveyors Congress-Innovation and Sustaining: Challenges and Opportunities*. 1–10.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., and Holmstrom, J., 2019. Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7, 147406–147419.

Khosrowshahi, F. and Kaka, A.P., 1996. Estimation of Project Total Cost and Duration for Housing Projects in the U.K. *Building and Environment*, 31 (4), 373–383.

Kifer, M., 2008. Rule Interchange Format: The Framework. *In*: N. Bassiliades, G. Governatori, and A. Paschke, eds. *International Symposium, RuleML 2008*. Berlin: Springer-Verlag.

Kim, C.H., Weston, R.H., Hodgson, A., and Lee, K.H., 2003. The complementary use of IDEF and UML modelling approaches. *Computers in Industry*, 50 (1), 35–56.

Kim, S. and Shim, J.H., 2014. Combining case-based reasoning with genetic algorithm optimization for preliminary cost estimation in construction industry. *Canadian Journal of Civil Engineering*, 41 (November 2013), 65–73.

Kim, Y.-W., 2017. *Activity Based Costing for Construction Companies*. First Edit. West Sussex: John Wiley & Sons Ltd.

Kim, Y. and Ballard, G., 2001. Activity-based costing and its application to lean construction. *International Group for Lean Construction*, (January), 1–13.

Kim, Y. and Ballard, G., 2002. Case Study - overhead costs analysis. *In*: *Proceedings IGLC-10*. Gramado, Brazil, 1–13.

Kolo, S.J., Rahimian, F.P., and Goulding, J.S., 2014. Housing delivery in Nigeria and the opportunity for offsite manufacturing. *In*: *Creative Construction Conference*. 85–90.

Koskela, L., 1992. *Application of the new production philosophy to construction*. Stanford, CA.

KPMG, 2016. *Smart construction - How offsite manufacturing can transform our industry*.

Lang, R., Goodier, C., and Glass, J., 2016. Are housebuilders' production strategies a barrier to offsite construction uptake in the UK? *Proceedings of the 32nd Annual ARCOM Conference, ARCOM 2016*, 1245–1253.

Larsson, J. and Simonsson, P., 2012. Barriers and drivers for increased use of off-site bridge construction in Sweden. *In*: *28th Annual ARCOM Conference*. Edinburgh, UK:

Association of Researchers in Construction Management, 751–761.

Latham, M., 1994. *Constructing the Team*. Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry.

Lawson, M., Ogden, R., and Goodier, C., 2010. *Design in Modular Construction*. Taylor & Francis Group.

Lee, S., Kim, K., and Yu, J., 2014. Automation in Construction BIM and ontology-based approach for building cost estimation. *Automation in Construction*, 41, 96–105.

Leishman, C. and Warren, F., 2006. Private housing design customization through house type substitution. *Construction Management and Economics*, 24, 149–158.

Lemaignan, S., Siadat, A., Dantan, J.-Y., and Semenenko, A., 2006. MASON : A proposal for an ontology of manufacturing domain. *In*: *Proceedings of the IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications (DIS'06) 0-7695-2589-X/06*.

Lere, J.C., 2000. Activity-based costing: A powerful tool for pricing. *Journal of Business and Industrial Marketing*, 15 (1), 23–33.

Lessing, J., Stehn, L., and Ekholm, A., 2015. Industrialised house-building – development and conceptual orientation of the field. *Construction Innovation*, 15 (3), 378–399.

Li, Z.C., Hong, J., Xue, F., Shen, G.Q., Xu, X., and Luo, L., 2016. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. *Habitat International*, 57, 74–87.

Liao, S., 2004. Expert system methodologies and applications - a decade review from 1995 to 2004. *Expert Systems with Applications*, 1–11.

Lim, E.C. and Alum, J., 1995. Construction productivity: Issues encountered by contractors in Singapore. *International Journal of Project Management*, 13 (1), 51–58.

Lin, Y.C., Wang, L.C., and Tserng, H.P., 2006. Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan. *Automation in Construction*, 15 (6), 693–705.

Liu, H., Lu, M., and Al-hussein, M., 2016. Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry. *Advanced Engineering Informatics*, 30 (2), 190–207.

Liu, X., Li, Z., and Jiang, S., 2016. Ontology-Based Representation and Reasoning in Building Construction Cost Estimation in China. *Future Internet*, 8 (39).

Liu, Z., Osmani, M., Demian, P., and Baldwin, A.N., 2011. The potential use of BIM to aid construction waste minimalisation. *In*: –Sophia Antipolis, ed. *Proceedings of the CIB W78-W102 2011*. France.

Lou, Y.-I., Wang, H.C., and Lan, J.-S., 2017. Design and Implement the Activity-Based Costing in Taiwan Firm. *IOSR Journal of Business and Management*, 19 (01), 41–46.

Lovett, P.J., Ingram, A., and Bancroft, C.N., 2000. Knowledge-based engineering for SMEs - a methodology. *Journal of Materials Processing Technology*, 107, 384–389.

Lu, Q., Xie, X., Heaton, J., Parlikad, A.K., and Schooling, J., 2020. From BIM towards digital twin: Strategy and future development for smart asset management. *Studies in Computational Intelligence*, 853, 392–404.

Lucko, G. and Rojas, E.M., 2010. Research Validation: Challenges and Opportunities in the Construction Domain. *Journal of Construction Engineering and Management*, 136 (1).

Luo, L., Mao, C., Shen, L., and Li, Z., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system. *Engineering, Construction and Architectural Management*, 22 (6), 622–643.

Ma, Z.M. and Wang, X., 2012. Rule interchange in the semantic web. *Journal of Information Science and Engineering*, 28 (2), 393–406.

Mao, C., Shen, Q., Shen, L., and Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods : Two case studies of residential projects. *Energy & Buildings*, 66, 165–176.

McKay, L.J., 2010. The effect of offsite construction on occupational health and safety. *A Doctoral Thesis Submitted In Partial Fulfilment Of The Requirements For The Award Of Doctor Of Philosophy*. Loughborough University.

Meiling, J., Backlund, F., and Johnsson, H., 2012a. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Meiling, J., Backlund, F., and Johnsson, H., 2012b. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Melão, N. and Pidd, M., 2000. A conceptual framework for understanding business processes and business process modelling. *Information Systems Journal*, 10 (2), 105–129.

Melton, T., 2005. The benefits of lean manufacturing: What lean thinking has to offer the process industries. *Chemical Engineering Research and Design*, 83 (6 A), 662–673.

Miah, S.J. and Genemo, H., 2016. A Design Science Research Methodology for Expert Systems Development. *Australasian Journal of Information Systems*, 20, 1–29.

Miles, J. and Whitehouse, N., 2013. *Offsite Housing Review*. London.

Milton, N., 2008. *Knowledge Technologies*. Italy: Polimetrica ®.

Mizoguchi, R. and Ikeda, M., 1998. Towards ontology engineering. *Journal-Japanese Society for Artificial Intelligence*, 13 (1), 259–266.

Montali, J., Overend, M., Pelken, P.M., and Sauchelli, M., 2018. Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends. *Architectural Engineering and Design Management*, 14 (1–2), 78–94.

Morgan, D.L., 2007. Paradigms Lost and Pragmatism Regained: Qualitative and Quantitative Methods. *Journal of Mixed Methods Research*, 1 (48), 48–76.

Mossman, A., 2009. Creating value: A sufficient way to eliminate waste in lean design and lean production. *Lean Construction Journal*, 2009, 13–23.

Mostafa, S., Chileshe, N., and Abdelhamid, T., 2016. Lean and agile integration within offsite construction using discrete event simulation. *Construction Innovation*, 16 (4), 483–525.

Motawa, I. and Almarshad, A., 2013. A knowledge-based BIM system for building maintenance. *Automation in Construction*, 29, 173–182.

Mtech Group, 2007. *Offsite Construction Industry Survey 2006*. BuildOffsite. London.

Murtaza, M.B., Fisher, D.J., and Skibniewski, M.J., 1993. Knowledge-Based Approach to Modular Construction Decision Support. *Journal of Construction Engineering and Management*, 119, 115–130.

Murugaiah, U., Benjamin, S.J., and Marathamuthu, M.S., 2010. Scrap loss reduction using the 5-whys analysis. *International Journal of Quality & Reliability Management*, 27 (5), 527–540.

Musa, M.F., Mohammad, M.F., Yusof, M.R., and Mahbub, R., 2015. The Way Forward for Industrialised Building System (IBS) in Malaysia. *In*: *InCIEC 2014*. Singapore: Springer, pp 163-175.

Nadim, W. and Goulding, J.S., 2011. Offsite production : a model for building down barriers. *Engineering, Construction and Architectural Management*, 18 (1), 82–101.

Nahmens, I. and Ikuma, L.H., 2012. Effects of Lean Construction on Sustainability of Modular Homebuilding. *Journal of Architectural Engineering*, 18 (2), 155–163.

Nasereddin, M., Mullens, M.A., and Cope, D., 2007. Automated simulator development : A strategy for modeling modular housing production. *Automation in Construction*, 16, 212–223.

Naufal, A., Jaffar, A., Yusoff, N., and Hayati, N., 2012. Development of kanban system at local manufacturing company in Malaysia-Case study. *Procedia Engineering*, 41 (Iris), 1721–1726.

Nawari, N.O., 2012. BIM Standard in Off-Site Construction. *Journal of Architectural Engineering*, 18 (2).

NBS, 2015. Uniclass 2015 [online]. *National Building Specification (NBS)*. Available from: https://www.thenbs.com/our-tools/uniclass-2015 [Accessed 2 Jan 2019].

Nepal, M.P., Staub-French, S., Pottinger, R., and Zhang, J., 2013. Ontology- based feature modeling for construction information extraction from a build- ing information model. *Journal of Computing in Civil Engineering*, 27 (5), 555–569.

Neuman, L.W., 2014. *Social Research Methods: Qualitativr and Quantitative Approaches*. Seventh Ed. Essex, England: Pearson Education Limited.

Niazi, A. and Dai, J.S., 2006. Product Cost Estimation : Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, 128 (May).

Nicholls, D., 2017. Qualitative research. Part 2: Methodologies. *International Journal of Therapy and Rehabilitation*, 24 (2), 71–77.

Nikakhtar, A., Hosseini, A.A., Wong, K.Y., and Zavichi, A., 2015. Application of lean construction principles to reduce construction process waste using computer simulation: A case study. *International Journal of Services and Operations Management*, 20 (4), 461–480.

Nurcan, S., Etien, A., Kaabi, R., Zoukar, I., and Rolland, C., 2005. A strategy driven business process modelling approach. *Business Process Management Journal*, 11 (6), 628–649.

O'Connor, M., Knublauch, H., Tu, S., Grosof, B., Dean, M., Grosso, W., and Musen, M., 2005. Supporting rule system interoperability on the semantic Web with SWRL. *In*: Y. Gil et al., ed. *ISWC 2005*. Berlin: Springer-Verlag, 974–986.

Ochieng, E.G. and Price, A.D.F., 2009. Managing cross-cultural communication in multicultural construction project teams : The case of Kenya and UK. *International Journal of Project Management ·*, (July).

Ofori, G., 2000. Challenges of Construction Industries in Developing Countries : Lessons from Various Countries. *In*: *2nd International Conference on Construction in Developing Countries: Challenges Facing the Construction Industry in Developing Countries*. Gabarone, 1–13.

Ogunlana, S.O., 1989. Accuracy in design cost estimating.

Ong, N.S., 1995. Manufacturing cost estimation for PCB assembly : An activity-based approach. *International Journal of Production Economics*, 38, 159–172.

Ormerod, R.J., 2010. Rational inference: Deductive, inductive and probabilistic thinking. *Journal of the Operational Research Society*, 61 (8), 1207–1223.

Ou-Yang, C. and Lin, T.S., 1997. Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. *International Journal of Advanced Manufacturing Technology*, 13, 618–629.

Ozaki, R., 2003. Customer-focused approaches to innovation in housebuilding. *Construction Management and Economics*, 21, 557–564.

Ozbayrak, M., Akgun, M., and Turker, A.K., 2004. Activity-based cost estimation in a push / pull advanced manufacturing system. *International Journal of Production Economics*, 87, 49–65.

Pan, W., Dainty, A.R.J., and Gibb, A.G.F., 2012. Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, 138 (11), 1239–1250.

Pan, W., Gibb, A.G.F., and Dainty, A.R.J., 2008. *Leading UK housebuilders' utilisation of offsite modern methods of construction*. Building Research & Information.

Pan, W. and Goodier, C., 2012. House-Building Business Models and Off-Site Construction Take-Up. *Journal of Architectural Engineering*, 18 (2), 84–93.

Pan, W. and Sidwell, R., 2011. Demystifying the cost barriers to offsite construction in the UK. *Construction Management & Economics*, 29, 1081–1099.

Pasquire, C., Gibb, A., and Blismas, N., 2005. What should you really measure if you want to compare prefabrication with traditional construction? *In*: *Proceedings IGLC*. Sydney, Australia, 481–491.

Pasquire, C.L. and Connolly, G.E., 2002. Leaner construction through off-site manufacturing. *In*: *Proceedings 10th of the Internationa Group of Lean Construction Conference, Gramado, Brazil*. 1–13.

Pauwels, P. and Terkaj, W., 2016. EXPRESS to OWL for construction industry : Towards a recommendable and usable ifcOWL ontology. *Automation in Construction*, 63, 100–133.

Pearce, A., Pons, D., and Neitzert, T., 2018. Implementing lean—Outcomes from SME case studies. *Operations Research Perspectives*, 5, 94–104.

Persson, S., Malmgren, L., and Johnsson, H., 2009. Information management in industrial housing design and manufacture. *Electronic Journal of Information Technology in Construction*, 14 (June), 110–122.

Pheng, L.S. and Leong, C.H.Y., 2000. Cross-Cultural project management for international construction in China. *International Journal of Project Management*, 18 (5), 307–316.

Post, 2003. *Modern methods of house building*. Parliamentary Office of Science and Technology. London.

Pulido, J.R.G., Ruiz, M.A.G., Herrera, R., Cabello, E., Legrand, S., and Elliman, D., 2006. Ontology languages for the semantic web: A never completely updated review. *Knowledge-Based Systems*, 19 (7), 489–497.

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., and Zimmerman, J.B., 2012. Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*, 16 (2), 243–254.

Rahani, A. and Muhammad, A.-A., 2012. Production Flow Analysis through Value Stream Mapping : A Lean Manufacturing Process Case Study. *Procedia Engineering - International Symposium on Robotics and Intelligent Sensors*, 41 (Iris), 1727–1734.

Rahman, N.A.A., Sharif, S.M., and Esa, M.M., 2013. Lean Manufacturing Case Study with Kanban System Implementation. *Procedia Economics and Finance*, 7 (Icebr), 174–180.

Rahman, S., Perera, S., Odeyinka, H., and Bi, Y., 2008. A Conceptual Knowledge-Based Cost Model for Optimizing the Selection of Materials and Technology for Building Design. *24th Annual ARCOM Conference*, (September), 217–225.

Raz, T. and Elnathan, D., 1999. Activity based costing for projects. *International Journal of Project Management*, 17 (1), 61–67.

Rezgui, Y., Hopfe, C.J., and Vorakulpipat, C., 2010. Generations of knowledge management in the architecture , engineering and construction industry : An evolutionary perspective. *Advanced Engineering Informatics*, 24 (2), 219–228.

Richard, R.B., 2005. Industrialised building systems: Reproduction before automation and robotics. *Automation in Construction*, 14 (4), 442–451.

RICS, 2012a. *NRM1: Order of Cost Estimating and Cost Planning for Capital Building Works*. 2nd Editio. Coventry UK: Royal Institution of Chartered Surveyors (RICS).

RICS, 2012b. *NRM 2: Detailed Measurement for Building Works*. 1st Editio. Coventry: Royal Institution of Chartered Surveyors (RICS).

La Rocca, G., 2012. Knowledge based engineering : Between AI and CAD . Review of a language based technology to support engineering design. *Advanced Engineering Informatics*, 26 (2), 159–179.

Roy, A.U.K., Roy, M., and Saha, P.S., 2007. Mass-Industrialized Housing to Combat Consistent Housing Shortage in Developing Countries : Towards an Appropriate System for India. *In*: *World Congress on Housing National Housing Programmes- New Visions November 03-07, Kolkota, India*. Kolkata, India, 1–7.

Roy, R., Souchoroukov, P., and Shehab, E., 2011. Detailed cost estimating in the automotive industry : Data and information requirements. *Intern. Journal of Production Economics*, 133 (2), 694–707.

Rožanec, J.M., Jinzhi, L., Košmerlj, A., Kenda, K., Dimitris, K., Jovanoski, V., Rupnik, J., Karlovčec, M., and Fortuna, B., 2020. Towards actionable cognitive digital twins for manufacturing. *CEUR Workshop Proceedings*, 2615, 1–12.

Rundora, R., Ziemerink, T., and Oberholzer, M., 2013. Activity-based costing in small manufacturing firms: South African study. *Journal of Applied Business Research*, 29 (2), 485–498.

Saad, A. and Shaharin, S., 2016. The Methodology for Ontology Development in Lesson Plan Domain. *International Journal of Advanced Computer Science and Applications (IJACSA)*, 7 (4), 557–562.

Sabol, L., 2008. *Challenges in Cost Estimating with Building Information Modeling*. Washington, DC.

Sarvimaki, M., 2017. *Case Study Strategies for Architects and Designers : Integrative Data Research Methods: Integrative Data Research Methods*. London: Taylor & Francis Group.

Saunders, M., Lewis, P., and Thornhill, A., 2009. *Research Methods for Business Students*. New York: Pearson.

Schell, C., 1992. *The Value of the Case Study as a Research Strategy*.

Schreiber, A.T., Akkermans, J.M., Anjewierden, A.A., de Hoog, R., Shadbolt, N.R., Velde, W. Van de, and Wielinga, B.J., 2001. *Knowledge Engineering and Management - The CommonKADS Methodology*. Cambridge,Massachusetts: MIT Press.

Schuh, K.L. and Barab, S.A., 2008. Philosophical Perspectives. *In*: J. David, S.J. Michael, D. Marcy, M. David, and M. Jeroen, eds. *Handbook of Research on Educational Communications*. New York: Taylor & Francis, 67–82.

Schwitter, R., 2010. Controlled natural languages for knowledge representation. *In*: *Coling 2010 - 23rd International Conference on Computational Linguistics, Proceedings of the Conference*. Beijing, 1113–1121.

Secretary of State for Communities and Local Government, 2017. *Fixing our broken housing market*. Department for Communities and Local Government. London: Crown.

Shadbolt, N. and Milton, N., 1999. From Knowledge Engineering to Knowledge Management. *British Journal of Management*, 10, 309–322.

Shamsuddin, S.M., Zakaria, R., and Mohamed, S.F., 2013. Economic Attributes in Industrialised Building System in Malaysia. *Procedia - Social and Behavioral Sciences*, 105, 75–84.

Shang, G. and Sui Pheng, L., 2014. Barriers to lean implementation in the construction industry in China. *Journal of Technology Management in China*, 9 (2), 155–173.

Shi, J.J., Lee, D.E., and Kuruku, E., 2008. Task-based modeling method for construction business process modeling and automation. *Automation in Construction*, 17 (5), 633–640.

Shostak, L. and Houghton, J., 2008. The credit crunch and the housing shortage - Time for a radical new approach to building affordable homes. *Local Economy*, 23 (3), 121–126.

Sivakumar, R. and Arivoli, P.V., 2011. Ontology Visualization Protégé Tools - A Review. *International Journal of Advanced Information Technology*, 1 (4), 39–39.

Smith, A.E. and Mason, A.K., 1996. Cost Estimation Predictive Modeling : Regression versus Neural Network. *The Engineering Economist*.

Sobh, R. and Perry, C., 2006. Research design and data analysis in realism research. *European Journal of Markerting*, 40 (11), 1194–1209.

Sodikov, J., 2005. COST ESTIMATION OF HIGHWAY PROJECTS IN DEVELOPING COUNTRIES : ARTIFICIAL NEURAL NETWORK APPROACH. *Journal of the Eastern Asia Society for Transportation Studies*, 6, 1036–1047.

Soiferman, L.K., 2010. Compare and Contrast Inductive and Deductive Research Approaches. *Inductive and Deductive Research Approaches*, (April), 1–23.

Song, J., Fagerlund, W.R., Haas, C.T., Tatum, C.B., and Vanegas, J.A., 2005. Considering Prework on Industrial Projects. *Journal of Construction Engineering and Management*, 131 (6), 723–733.

Spens, K.M. and Kovács, G., 2006. A content analysis of research approaches in logistics research. *International Journal of Physical Distribution and Logistics Management*, 36 (5), 374–390.

Spyns, P., Meersman, R., and Jarrar, M., 2002. Data modelling versus ontology engineering. *ACM SIGMOD Record*, 31 (4), 12–17.

Staub-french, S., Fischer, M., Kunz, J., Paulson, B., and Ishii, K., 2002. *A Feature Ontology to Support Construction Cost Estimating*.

Steinhardt, D., Manley, K., and Miller, W.F., 2014. Reshaping housing using prefabricated systems. *Proceedings of World Sustainable Building Conference (SB14)*.

Studer, R., Benjamins, V.R., and Fensel, D., 1998. Knowledge Engineering : Principles and methods. *Data & Knowledge Engineering*, 25, 161–197.

Sundar, R., Balaji, A.N., and Satheesh Kumar, R.M., 2014. A review on lean manufacturing implementation techniques. *Procedia Engineering*, 97, 1875–1885.

Szuba, J.S., Grabska, E.G., and Borkowski, A., 1999. Graph Visualization in ArchiCAD. *In*: *Proceedings of the International Workshop on Applications of Graph Transformations with Industrial Relevance*. 241–246.

Tam, V.W.Y., Tam, C.M., Zeng, S.X., and Ng, W.C.Y., 2007. Towards adoption of prefabrication in construction. *Building and Environment*.

Tang, J., Zhang, M., Tang, H., and Chen, Y., 2015. Research on Cost Management of Construction Project based on Activity-based Costing. *In*: *International Conference on Civil, Materials and Environmental Sciences (CMES 2015)*. 51–54.

Taylor, S., 2009. *Offsite Production in the UK Construction Industry, abrief overview*. HSE.

Tennant, S., McCarney, M., Tong, M.K., and Tennant, G., 2012. Re-Engineering the Construction Supply Chain: Transferring on-Site Activity, Off- Site. *In*: *Procs 28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 3–5.

Terkaj, W. and Urgo, M., 2014. Ontology-based modeling of production systems for design and performance evaluation. *Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014*, 748–753.

Thanoon, W.A., Peng, L.W., AbdulKadir, M.R., Jaafar, M.S., and Salit, M.S., 2003. The Essential Characteristics of Industrialised Building System. *In*: *International Conference on Industrialised Building Systems*. 10–11.

Thomas, G., 2011. Qualitative Inquiry A Typology for the Case Study in Social Science Following a Review of Definition , Discourse , and Structure. *Qualitative Inquiry*, 17 (6), 511 –521.

Tran, V. and Tookey, J., 2007. Labour Productivity in the New Zealand Construction Industry : A Thorough Investigation. *Australasian Journal of Construction Economics and Building*, 11 (1), 41–60.

Trehan, V., Chapman, C., and Raju, P., 2015. Informal and formal modelling of engineering processes for design automation using knowledge based engineering. *Journal of Zhejiang University: Science A*, 16 (9), 706–723.

Tsai, W.H., Yang, C.H., Chang, J.C., and Lee, H.L., 2014. An Activity-Based Costing decision model for life cycle assessment in green building projects. *European Journal of Operational Research*, 238 (2), 607–619.

Vakaj, E., F., C., H., T.A.-R., Pauwels, P., and Patlakas, P., 2021. Semanic representation of DfMA offsite housing.

Venables, T., Barlow, J., and Gann, D., 2004. *Manufacturing Excellence - UK Offsite Capacity in Off-Site Manufacturing*. Constructing Excellence.

Verhagen, W., Bermell-Garcia, P., Mariot, P., Cotton, J.-P., Ruiz, D., Redon, R., and Curran, R., 2010. (Costing) Knowledge-Based Cost Modelling of Composite Wing Structures. *International Journal of Computer Integrated Manufacturing*, pp.1.

Vernikos, V.K., Nelson, R., Goodier, C.I., and Robery, P.C., 2013. Implementing an offsite construction strategy: a UK contracting organisation case study. *In*: *Proceedings of the 29th Annual ARCOM Conference*. Reading, UK, 667–677.

Vibaek, K.S., 2014. *Architectural System and Structures - Integrating design complexity in industralised construction*. London: Routledge.

Volk, R., Stengel, J., and Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, 38 (October 2017), 109–127.

Voss, E., Jin, Q., and Overend, M., 2013. A BPMN-based process map for the design and construction of façades. *Journal of Facade Design and Engineering*, 1 (1–2), 17–29.

Wagner, A. and Uwe, R., 2019. BPO : The Building Product Ontology for Assembled Products. *In*: *Proceedings of the 7th Linked Data in Architecture and Construction Workshop - LDAC2019*. 106–119.

Wahab, A.N.A., Mukhtar, M., and Sulaiman, R., 2013. A Conceptual Model of Lean Manufacturing Dimensions. *Procedia Technology*, 11 (Iceei), 1292–1298.

Waissi, G.R., Demir, M., Humble, J.E., and Lev, B., 2015. Automation of strategy using IDEF0

- A proof of concept. *Operations Research Perspectives*, 2, 106–113.

Warszawski, A., 1999. *Industrialised and automated building systems*. First edit. London: E & FN Spon.

Willis, J.W., 2007. *World Views, Paradigms, and the Practice of Social Science Research*. London: Sage.

Wilson, L., 2010. *How to Implement Lean Manufacturing*. New York: McGrawHill.

Wong, R., Hao, J., and Ho, C., 2003. Prefabricated building construction systems adopted in Hong Kong. *In*: *Proc. of the International Association for Housing Science on Word Congress of Housing: Process and Product*. Canada.

Wu, S., Wood, G., Ginige, K., and Jong, S.W., 2014. A technical review of bim based cost estimating in UK quantity surveying practice, standards and tools. *Journal of Information Technology in Construction*, 19 (March), 535–563.

Xu, Y., Elgh, F., Erkoyuncu, J.A., Bankole, O., Goh, Y., Cheung, W.M., Baguley, P., Wang, Q., Arundachawat, P., Shehab, E., Newnes, L., and Roy, R., 2011. Cost engineering for manufacturing : current and future research. *International Journal of Computer Intergrated Manufacturing*, 25 (4–5), 300–314.

Xu, Z., Abualdenien, J., Liu, H., and Kang, R., 2020. An IDM-Based Approach for Information Requirement in Prefabricated Construction. *Advances in Civil Engineering*, 2020, 21.

Yaman, H. and Tas, E., 2007. A building cost estimation model based on functional elements. *ITU Journal of Faculty of Architecture*, 4 (1), 73–87.

Yang, H., Yeung, J.F.Y., Chan, A.P.C., Chiang, Y.H., and Chan, D.W.M., 2010. A critical review of performance measurement in construction. *Journal of Facilities Management*, 8 (4), 269–284.

Yi, W. and Chan, A.P.C., 2014. Critical Review of Labor Productivity Research in Construction Journals. *Journal of Management in Engineering*, 30 (2), 214–225.

Yin, R.K., 1994. *Case Study Research: Design and Methods*. Second. Bervely Hills: Sage Publishing.

Yin, R.K., 2009. *Case Study Reserach: Design and methods*. Fourth. London: SAGE Publications.

Yin, R.K., 2016. *Qualitative Research from Start to Finish*. Second Edi. London: Guilford Publications.

Yitmen, I., 2007. The challenge of change for innovation in construction : A North Cyprus perspective. *Building and Environment*, 42, 1319–1328.

Young, B., Harty, C., Lu, S., and Davies, R., 2015. Developing Temporary Manufacturing Facilities for Residential Building : a Case of the Modern Flying Factory. *Procs 31st Annual ARCOM Conference, 7-9 September 2015,* (September), 1033–1042.

Yunus, R. and Yang, J., 2012. Critical Sustainability Factors in Industrialised Building Systems Abstract. *Construction Innovation*, 12 (4), 447–463.

Zainal, Z., 2007. Case study as a research method. *Jurnal Kemanusiaan*, 9.

Zakaria, S.A., Gajendran, T., Rose, T., and Brewer, G., 2018. Contextual, structural and behavioural factors influencing the adoption of industrialised building systems: a review. *Architectural Engineering and Design Management*, 14 (1–2), 3–26.

Zhai, X., Reed, R., and Mills, A., 2014. Addressing sustainable challenges in China. *Smart and Sustainable Built Environment*, 3 (3), 261–274.

Zhang, S., Boukamp, F., and Teizer, J., 2015. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, 52, 29–41.

Zhang, X. and Skitmore, M., 2012. Industrialized housing in China: a coin with two sides. *International Journal of Strategic Property Management*, 16 (2), 143–157.

Zhang, Y., Fan, G., Lei, Z., Han, S., Raimondi, C., Al-Hussein, M., and Bouferguene, A., 2016. Lean-based diagnosis and improvement for offsite construction factory manufacturing facilities. *In*: *ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction*. 1090–1098.

Zhang, Y., Lei, Z., Han, S., Bouferguene, A., and Al-Hussein, M., 2020. Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance. *Journal of Construction Engineering and Management*, 146 (9).

Zhong, B.T., Ding, L.Y., Love, P.E.D., and Luo, H.B., 2015. An ontological approach for technical plan definition and verification in construction. *Automation in Construction*, 55, 47–57.

Zhuang, C., Miao, T., Liu, J., and Xiong, H., 2021. The connotation of digital twin, and the construction and application method of shop-floor digital twin. *Robotics and Computer-Integrated Manufacturing*, 68 (September 2020), 102075.

A Semantic Offsite Construction Digital Twin- Offsite Manufacturing Production Workflow (OPW) Ontology

Kudirat Ayinla[1], Edlira Vakaj[2], Franco Cheung[2], and Abdel-Rahman H. Tawil[2]

[1] London South Bank University, Department of Built Environment and Architecture, London, UK. {ayinlak@lsbu.ac.uk}

[2] Birmingham City University, Faculty of Computing, Engineering and Build Environment, Birmingham, UK

{edlira.vakaj, francho.cheung, abdel-Rahman.Tawil}@bcu.ac.uk

Abstract. Offsite Manufacturing (OSM) is a modern and innovative method of construction with the potential to adopt advanced factory production system through a more structured workflow, standardised products, and the use of robotics for automation. However, there have been challenges in quantifying improvements from the conventional method, which leads to the low uptake. The concept of a digital twin (DT) is useful for OSM, which enables production to be represented virtually and visually including all activities associated with it, resources, and workflow involved. Thus, essential information in the product development process such as cost, time, waste, and environmental impacts can be assessed. However, the data required to have accurate results and better-informed decision-making come from heterogeneous data formats (i.e. spreadsheets and BIM models) and across different domains. The inclusion of semantic web technologies such as Linked Data (LD) and Web Ontology Language (OWL) models has proven to better address these challenges especially in terms of interoperability and unambiguous knowledge systematisation. Through an extensive systematic literature review followed up by a case study, an ontology knowledge structure representing the production workflow for OSM is developed. A real-life use case of a semi-automated production line of wall panel production is used to test and demonstrate the benefits of the semantic digital twin in obtaining cost and time data of the manufacturing for assessment. Results demonstrated the potential capability and power of capturing knowledge for an ontology to assess production workflow in terms of cost, time, carbon footprint thereby enabling more informed decision making for continuous improvements.

Keywords: Offsite Manufacturing. Production Workflow · Digital Twins · Ontologies. Process Modelling.

1 Introduction

OSM is an aspect of design for manufacturing and assembly (DfMA) that moves most of the construction processes to a factory environment where components are assembled to form modules and then transported to a final point for assembly, usually the construction site

(Meiling *et al.* 2012b, Pan and Goodier 2012, Quale *et al.* 2012). The benefits of this method have been widely studied, e.g. reductions in construction time, increased quality, low health and safety risks, low environmental impact, reduced whole-life cost, and a consequent increase in predictability, productivity, whole-life performance, and profitability (Blismas *et al.* 2006a, Pan *et al.* 2008, Pan and Goodier 2012). While most benefits are claimed to be the outcome of the process improvements due to the workflow in a factory environment (Pasquire and Connolly 2002), quantitative assessment of the benefits is not evident. Unlike operations onsite that focus predominately on the organization of labour and materials, the planning of OSM is more complex involving the organisation of various production line workflows, design configurations of different workstation arrangements, different automation processes, and various levels of human intervention.

The use of DTs have the benefits of simulating processes and is capable of allowing powerful data collection to enhance efficiency in the value chain (Boje *et al.* 2020). Previous development of DTs has been mainly on the use of immersive technology such as augmented reality (AR) and application of DTs with Building Information Modelling (BIM) (Boje *et al.* 2020). However, these applications have been mostly focused on the design and construction, and/or operational aspects of assets with little application on the manufacturing or production stage of a building (Zhuang *et al.* 2021).

This study proposes an ontology-based digital twin for assessment of the performance of OSM. Disregarding the challenges of semantic DT application, such as the need to handle high-volume streaming of data in a semantic context, provide integration of semantic models with analytical solutions, semantically link simulations to specific use-cases, and learn semantic models over time, the use of semantic web technologies or ontologies is known for being efficient in knowledge capture and sharing, and are capable of giving intelligent real-time and context-specific data, which would be useful for design development in the OSM domain. This paper explains how the modelling of OSM workflow can be supported by automated quantitative assessment from an OSM ontology developed.

2 Literature Review

2.1 Semantic Web Technologies for Construction Digital Twins

A DT is a virtual model of the real product (Rožanec *et al.* 2020), consistent with its corresponding physical entity capable of simulating and mirroring the behavior and performance of the physical entity (Zhuang *et al.* 2021). For OSM, a DT is a virtual digital replica of a building's physical components and production methods that collects real-world information about the physical and production line workflow via sensors and other wireless technology. The "twin" is continuously updated with data collected from multiple heterogeneous sources across different construction domains and provides valuable insights about the performance, operation, or profitability using advanced analytics, machine-learning algorithms and artificial intelligence (AI). As such, a DT can serve as the backbone for OSM and as a more significant means for improving offsite construction efficiency.

A DT for the modelling of OSM production workflow needs to consider several aspects ranging from physical components (e.g. Buildings machine tools, part types to be produced, etc.) to production methods (e.g. process plans, production logics, etc.), from production workflow (e.g. placement of production resources in the factory layout) to organizational management (e.g. roles of the involved actors), from costs (e.g. labour, nominal power consumption of a machine tool) to dynamics (e.g. evolution of the states of a resource) with data generated and captured across the entire product lifecycle. Thus, the effectiveness of a DT relies on the robust construction of intelligent services and framework to be put in place (e.g., simulation, prediction, forecasting) to support the various heterogeneous systems and technologies involved in construction (Terkaj and Urgo 2014).

Emerging Building Information Modelling (BIM) tools and technologies have changed the way information about the built environment is created, stored, and exchanged between involved stakeholders (Szuba *et al.* 1999). When completed, the computer-generated BIM model contains precise geometry and relevant data needed to support the construction, fabrication, and procurement activities needed to realize the building (Alonso *et al.* 2019), and even more data on the time schedule, cost estimation, and maintenance management (Khajavi *et al.* 2019). The use of BIM models has not benefited from real-time data inputs of the object data from OSM, as the focus in practice has been on improving the design collaboration, construction activities such as logistic management as well as operational and management of an asset. However, BIM lacks semantic completeness in areas outside the scope of the components and systems of a building. Thus, the need for an all-inclusive, sustainable approach that considers dynamic data at different levels (Boje *et al.* 2020). In order to enable and encourage this exchange, a common schema has been developed, which is specifically referred to as Industry Foundation Classes (IFC). Since the advent of the IFC, more integrated methods to share construction data have emerged and have since become adopted industry-wide. At the same time, digital technologies across the board are advancing at an ever-increasing pace, taking advantage of the Internet of Things (IoT) and Artificial Intelligence (AI) agents (data analytics, machine learning, deep learning, etc.). The success of a DT relies on the various processes and data layers that are intended to support construction intelligent services and applications assuming a robust framework is in place to support the various heterogeneous systems and technologies involved.

The evolution of BIM should be carefully framed within a paradigm that factors people, processes, and other emerging technologies in an increasingly inter-connected world through the application of sensor networks (Khajavi *et al.* 2019). Building/infrastructure-related information can be directly or indirectly integrated within available digital technologies in a BIM-enabled environment, a broad list of related research work is detailed in (Lu *et al.* 2020).

The use of semantic models (ontologies) as demonstrated by IFC for openBIM is particularly useful as it links data of many contexts. The DT paradigm aims to enhance existing construction processes and BIM models, with their underpinning semantics (e.g., IFC, COBie) within the context of a cyber-physical synchronicity, where the digital models are a reflection of the construction physical assets at any given moment in time [13]. The current limitation is that the data shared from IFC is only based on the geometry of a building while COBie data is operational. There has been little focus on modelling the knowledge of the manufacturing and production aspects with regards to the use of OSM. This sort of data is not captured in a BIM model thus limiting the potential interventions in terms of optimizing processes and increasing efficiency during the manufacturing stage of building assets. Given that a DT continuously receives data from different sources, there is a need to develop proper ontologies for data representation and formalization.

2.2 Semantic Digital Twin Representation through Ontologies

Ontologies are a well-established approach for leveraging data and information sources with semantics, thus providing a shared, machine-understandable vocabulary for information exchange among dispersed agents (e.g. humans and different machines) interacting and communicating in a heterogeneous distributed intelligent system (Zhong *et al.* 2015). There have been previous studies on the application of domain ontologies for supporting data capturing in DT. Chevallier et al. (Chevallier *et al.* 2020) propose to build a Smart Building Digital Twins reference architecture that is based on various domain ontologies such as ifcOWL for the infrastructure, SSN (Semantic Sensor Network), and SOSA (Sensor, Observation, Sample, and Actuator) for IoT description and Vakaj et al. (Vakaj, E. *et al.* 2021) developed the Offsite Housing Ontology to support offsite housing design evaluation. DTs are independent of tools and servers where each IoT is associated (linked) to its physical counter object. Using ontologies, all the information produced by sensors, which reflect the state of a Smart Building over time could be associated with their physical ifcOWL counterparts.

The review of existing literature in the OSM domain was conducted to reuse terminologies and existing knowledge classification. The review also considered the possibility of extending some of the existing ontologies relevant to the research problem. Ontologies such as ifcOWL ontology generated from the IFC standards (Pauwels and Terkaj 2016), Building Topology Ontology (BOT) (Holten and Ferdinand 2020) describing the topology of buildings, and Building Product Ontology (BPO) (Wagner and Uwe 2019) for describing building products, are very useful for modelling the AEC domain information in a Linked Building Data format. However, BOT and BPO ontologies were purposely implemented as lightweight ontologies to promote reuse and do not include specific DfMA concepts for offsite manufacturing which is a challenge. Similarly, while MASON (Lemaignan *et al.* 2006) provides the core concepts of manufacturing, extending it to include the complexities and depth of analysis of buildings, and, more so, offsite buildings, creates a substantial challenge with redundancy and complexity. It is necessary that any extension of an ontology leads to a result that is lightweight, efficient, and conceptually coherent, in order to support adoption and implementation. As argued by Kalemi et al. (Kalemi *et al.* 2020), ontologies in complex domains that attempt to be all-inclusive often are not optimal for purpose: a prominent example in construction is the development of BOT as a way of addressing ifcOWL’s complexity.

Hence, the study further complements these ontologies by modelling low-level concepts relating to the production stage of an OSM building workflow. The semantic DT approach proposed in this study provides a viable way of crossing from a BIM worldview with its existing ifcOWL knowledge domain, towards a holistic view which promises greater possibilities by the intersection of production knowledge through descriptive and formal domain models using ontological inferences in real-world situations. Given that a DT continuously receives data from different sources, there is a need to develop proper ontologies for data representation and formalization, and it will be beneficial for the DT to also incorporate data on production workflow for monitoring factory shop floor efficiency as illustrated in Figure 1.

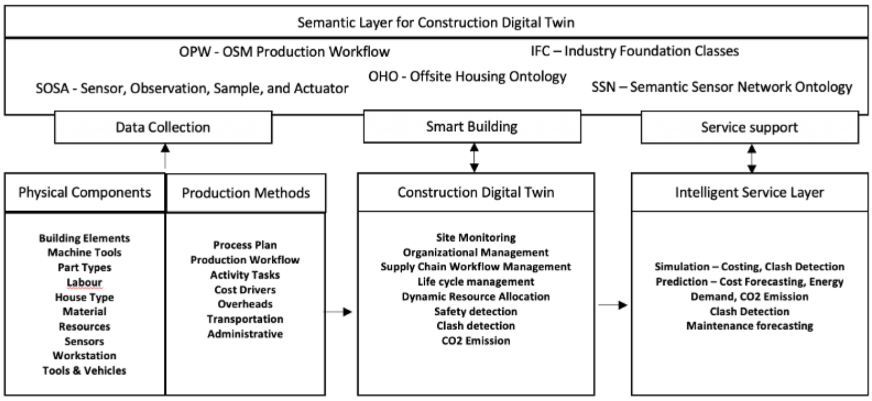


Fig. 1. Digital Twin Semantics for Smart OSM Construction Services

3 OSM Production Workflow (OPW) Ontology

The OSM production workflow (OPW) ontology aims to model the knowledge of the production process of a factory-manufactured building from the point of material delivery to the transportation of the finished manufactured products to the site. The data gathering process is based on the case study of OSM house production involving various units of analysis (i.e. the cases of two production methods, static production and semi-automated linear production methods of factory house building). The multidisciplinary knowledge required to define the main concepts and their relationships is collected from different sources as illustrated in Figure 2.

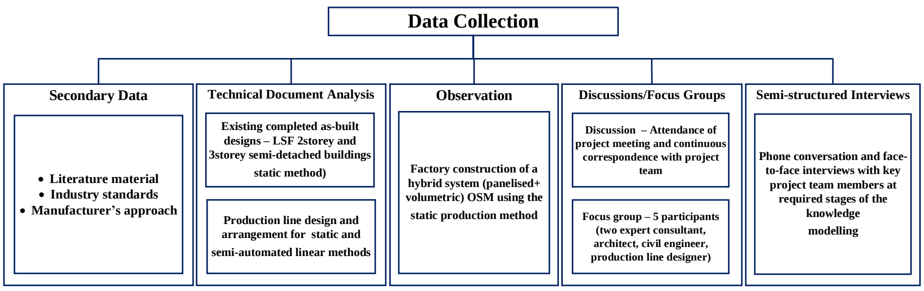


Fig. 2. Knowledge collection strategy

The data collection is followed by the ontology development exercise. The OPW ontology design and development is guided by the Meth-ontology methodology, which is considered one of the most mature methods for ontology development (Fernandez *et al.* 1997, Corcho *et al.* 2003). Four stages were followed comprising:

- Specification: identifying the purpose of ontology and defining some competency questions.
- Conceptualization: capturing domain knowledge via various sources of information such as literature review and case studies, and informal representation of knowledge gathered.
- Formalisation: knowledge representation in semi-formal languages ready for implementation.
- Implementation: formal representation of the knowledge in an ontology using a machine-readable language (OWL).

A set of competency questions are defined and used to guide the knowledge modeled in the ontology. Relevant knowledge and data to answer those queries in the ontology are semantically modeled using the OWL. For the proposed OPW ontology, the set of competency questions include:

- What activities are involved in manufacturing a house using various systems of OSM (i.e. panelised, volumetric or hybrid methods) and what resources are involved in each process? (See Experiment 1);
- What is the hierarchy of events and process flow based on the factory layout, and which activities fall in each workstation and production methods? (See Experiment 1);
- What are the time and cost spent on each activity and ultimately workstations involved in producing a house using the OSM method? (See Experiment 2);
- What is the proportion of waste generated from activities involved in the production process of different methods? (See Experiment 3).

3.1 Classification and Relations in the OPW Ontology

For the OPW ontology, there are 8 major classes (Level 1) required to formalise the production process knowledge which relates to all offsite methods (Figure 3). These include concepts such as (i) OSMFactoryProductionMethod – for classifying all types of production systems (ii) Production Process – for classifying the processes involved in each method, (iii) WorkStation – for capturing the categories of activities in each station (iv) ProcessType – relating to the workflow of events in the production process, (v) Activity – for classifying the major tasks performed on the factory shop floor, (vi) Resources – relating to resources consumed in the processes (vii) Product – relating to the final product from the production line and (viii) Building – for classifying the final product at the destination point, which is onsite.

The subclasses of the major classes are represented (Level 2) with the *isA* relationship to denote a parent-child relationship.

Finally, some relationships between the various classes are represented. The key attributes/properties needed to include semantics in the ontology include data properties such as Cost, Time, Distance, Length, Width, etc., and object properties such as *hasComponentPart*, *consumes*, *isComposedOf*, *hasOutput* etc.

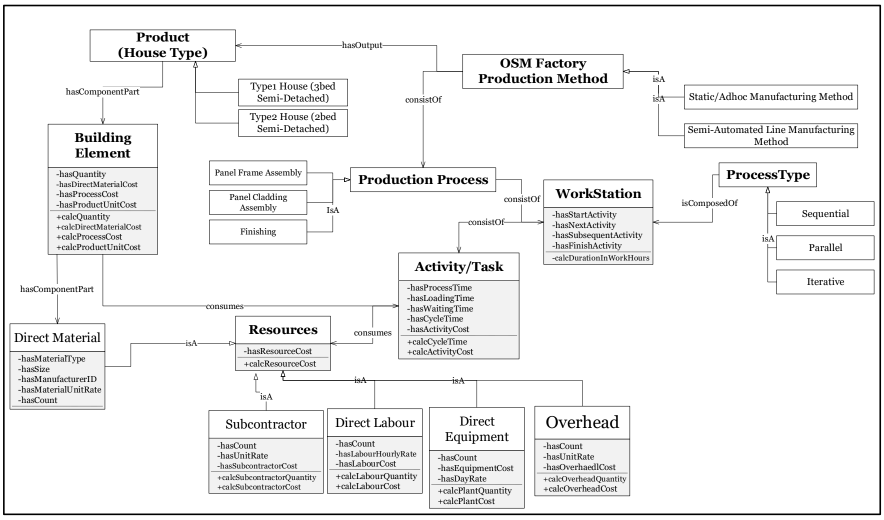


Fig. 3. Classes, subclasses, and properties of the OPW ontology

As an example, an OSM production method (OSMProductionMethod) '*consistOf*' production processes (ProductionProcess), and each production process (ProductionProcess) '*consistOf*' various work station (WorkStations). There are different sequences of events in each workstation (ProcessTypes) which could be parallel, sequential, or iterative in nature. Also, each work station (WorkStation) '*consistOf*' activities (Activities), and activities (Activity) '*consume*' resources (Resources) which can be labour, plant/equipment, materials, or overhead. Finally, the production methods (OSMProductionMethod) have the products as outputs (Product). These classes, attributes, and relationships will enable retrieval of data on the instances in the ontology to support analysis of the production workflow for design making and continuous improvement. The OPW ontology developed is published on the web for sharing, and reuse of the production knowledge relating to OSM.[2]

4 Use Case of a Static and Semi-automated Linear Methods of OSM Production

Having finalised the knowledge modelling in the ontology, a use case of a type of OSM production process was selected to enable the population of the ontology with instances and retrieval of data, i.e. a semi-automated linear method of factory house building. The data used for the workflow and activity modelling are based on an actual project using the static method and the design and simulation of a semi-automated production process by a partner production engineering company.

The workflow of the static and semi-automated linear method used in the use case is illustrated in Figures 4 and 5 respectively. The static method involves an ad-hoc manual production sequence predominantly dependent on labor resources while the semi-automated method features a structured workflow where production is done on an assembly line with dedicated stages/stations. The production of a wall panel is composed of three stages, the first being frame assembly and another for cladding assembly. The third stage involving finishing is to be done manually for both methods. The semi-automated consists of automated machines such as various robotic arms, and some human interventions and tasks embedded in the workflow. The third stage involving applying finishes is to be done manually. The completed units are moved on a conveyor system and are picked up by fork-lift or trolleys to be loaded on transport vehicles. The batch manufacturing method is used instead of a singular house build method where the tool is set up for a particular batch type of frame at a time. Finished batches of wall panels are moved to a temporary storage area in the factory and later transported to site. The use-case selected for testing the ontology is a case of a 3BED Semi-detached house type (hereafter House-Type 1). House-Type 1 is made of Light Steel Framed (LSF) material using

[2] The OPW ontology can be accessed from: https://edlirak.github.io/oho-pro/index-en.html

the panelised system of OSM. For the factory production, the external frame of the house is divided into a total of 32 panels which are the output from the production process. This consists of 20 external clad panels and 12 internal panels for the party walls.

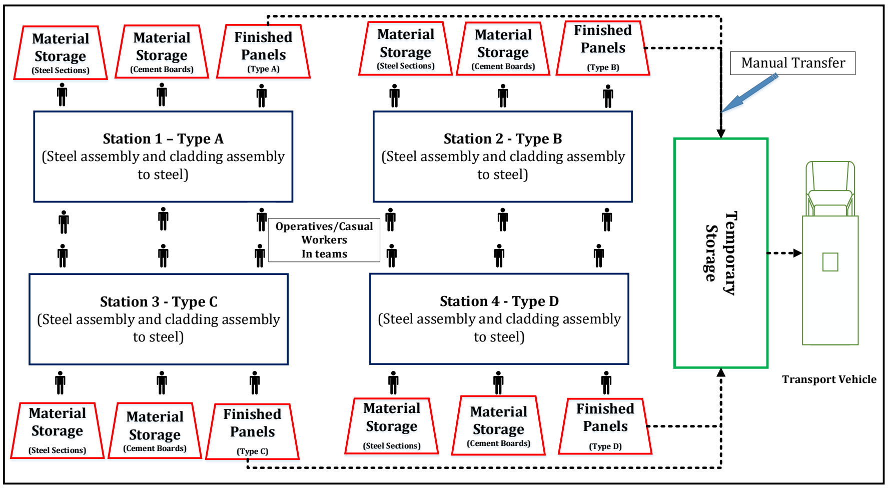


Fig. 4. Static production arrangement

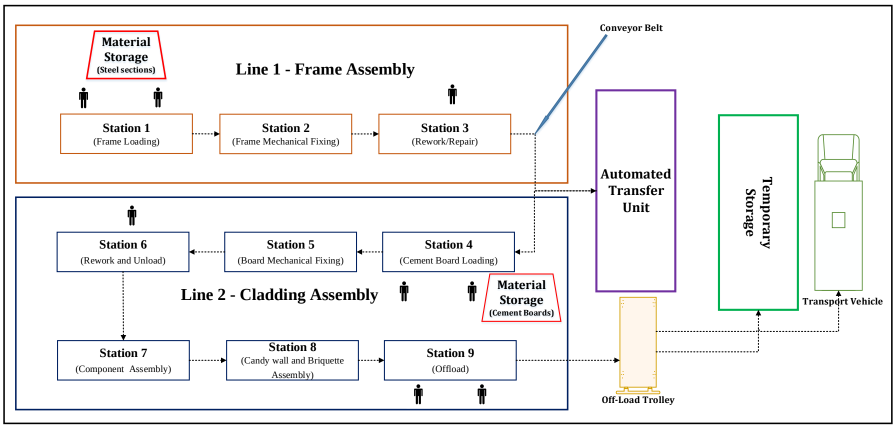


Fig. 5. Semi-automated linear production arrangement

Experiment 1: Querying the Ontology for Retrieving General Information Relating to the Production Line

The first experiment demonstrates the various types of data that can be retrieved from the semantic model regarding the production process of a building element. In this test, the semantic model is queried to generate data on the activities involved in the production of an instance of a wall panel (i.e. *3BED-GF-Front-LSF-01*) and the resources consumed in the process (Figure 6). The query returns data about the production process that can enable understanding of the processes and the consumption of resources. This information can potentially compare various methods of production for the same building type in terms of workflow, chain of events, and performance.

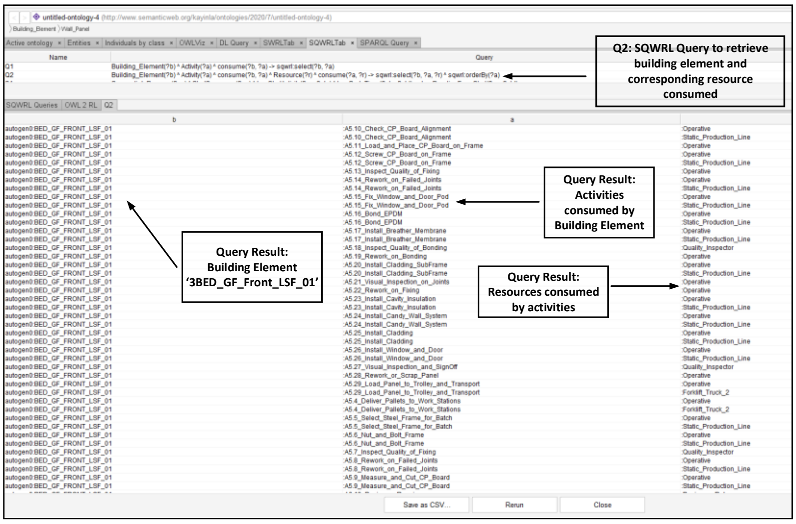


Fig. 6. SQWRL Query Result - Process Information for an instance of wall panel

Experiment 2: Retrieving and Analyzing Cost Information of Products

The second competency question relates to retrieving information on the cost of activities involved in an OSM production process and linking these with the various building elements that consume the activities.

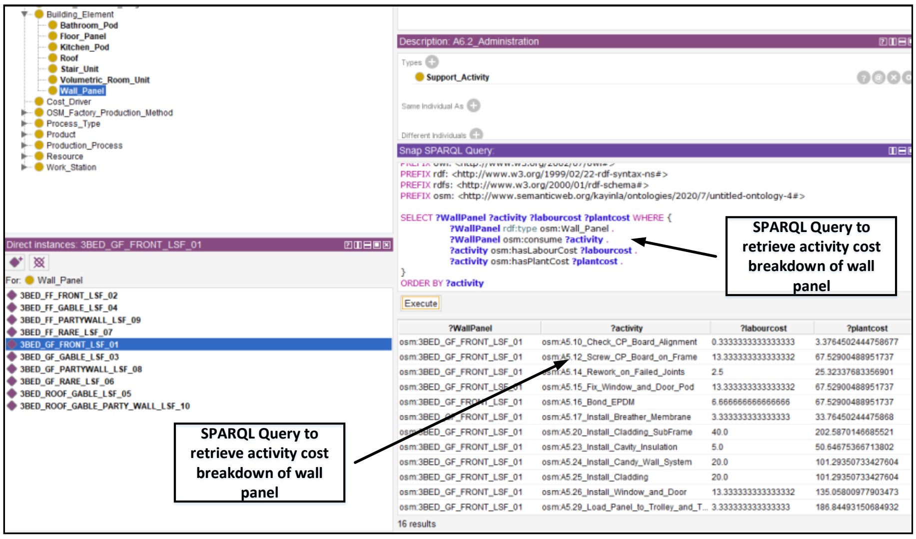


Fig. 7. SPARQL Query Result - Activities cost of an instance of wall panel with the static production method

The building elements are in turn related to a specific house type through the object property '*hasComponentPart*' thus allowing for the cost of each product to be computed. The data property relating to this is the '*hasActivityCost*' which is computed by summing up the cost of resources consumed by activity through the properties '*hasLabourCost*', '*hasPlantCost*', and '*hasOverheadCost*' depending on the resources applicable to each activity. The activity costs in turn form the process cost in producing any product from the OSM method. The data properties ('*hasLabourCost'*, '*hasPlantCost*', and '*hasOverheadCost*') are computed with the help of SWRL rules and are then fed back into the knowledge base as inferred properties. To test the ontology, a query was developed to retrieve information on the breakdown of the cost of activities involved in the production of a type of wall panel with both methods of production, using the instance of '*3BED-GF-Front-LSF-01*'. The query result returned data on the cost of each activity based on the labour and plant consumed in the production of the wall panel instance (Figure 7). This information can be useful for the manufacturer in analyzing the process cost of any building element while reviewing which activities consumes the most resources and why based on two alternative approaches.

Experiment 3: Analysing Cost and Time Spent on Processes in Various Production Methods

The third selected test case allows the analysis of the time spent on the various categories of activities between two methods of OSM production, the static and semi-automated methods, and analyzing value-adding in terms of time and cost. The aim is to compare the process information for each production method.

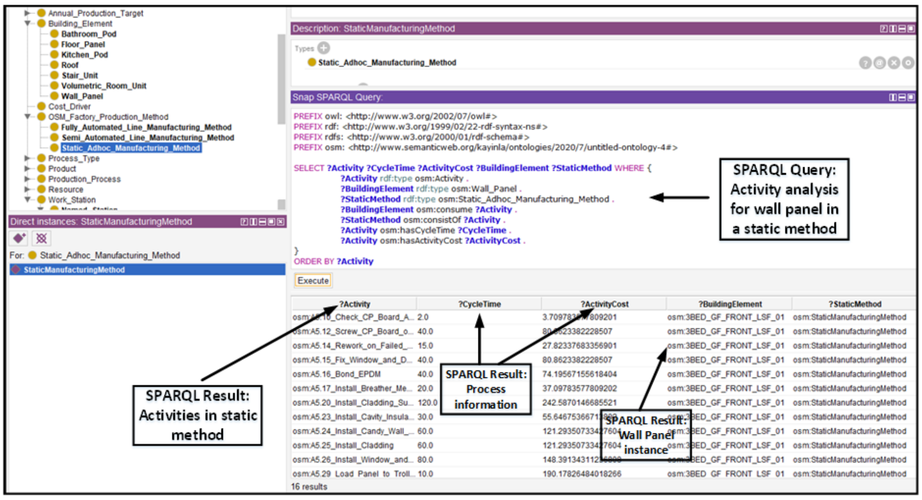


Fig. 8. SPARQL Query Result - Activities cost of an instance of wall panel with the static production method

As the ontology already contains knowledge on the two methods and the sort of activities involved, this will allow the manufacturer to analyse both options in aspects such as the time spent on various activities in a product development process and the cost incurred. Potentially also, to determine where intervention is needed for continuous improvement.

A SPARQL query was written to retrieve information on the cost and time spent in the production of the wall panel instance *'3BED-GF-Front-LSF-01'* for both methods of OSM production. Figure 8 shows the result for the static method while Figure 9 shows the results for the semi-automated linear method of OSM production.

The query result returned data on the cost and time of each activity consumed in the production of the wall panel. This information can be useful for the manufacturer in analyzing the efficiency of the various methods of production and in determining the output/productivity that can be attained.

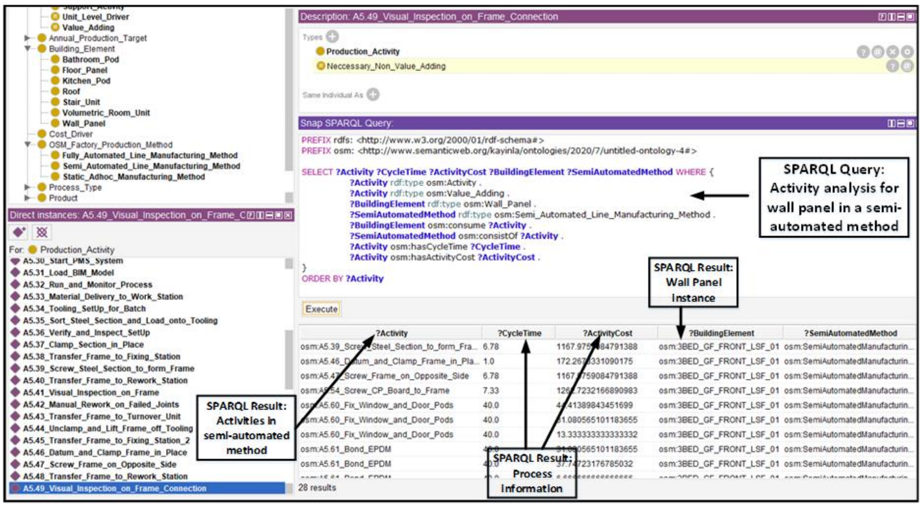


Fig. 9. SPARQL Query Result – Activities cost of an instance of wall panel with the semi-automated production method

5 Conclusions

This paper shows a newly developed OSM Production Workflow (OPW) Ontology and how it is applied to obtain knowledge from the ontology to evaluate processes. It demonstrates how semantic technologies can be applied to link production data to offsite building components. OPW can complement widely adopted data exchange schema such as IFC as the latter focuses on geometric data exchange by adding another dimension of knowledge relating to production workflow.

The linkage between production data and building elements is a novel development of semantic DT, addressing the manufacturing aspect of the building life cycle that has not been widely explored. The implication is significant as the use of ontology enables multiple usages of a single data source. OSM production can be queried, monitored, and improved continuously over time. This will allow the development of a variety of applications to be used in relation to production, e.g. measuring efficiency or optimising modular product and processes, and so on.

Acknowledgments

This research was supported by UKRI COVID-19 Extension Grant "DfMA house Part 2". The authors would like to thank the participating industrial partners of the research project, particularly Hadley Group, Walsall Housing Group, and QM Systems for their contribution to this study

References

AAQS, 2016. *Guide to Elemental Cost Estimating & Analysis for Building Works 2016*. Second.

Abanda, F.H., Tah, J.H.M., and Cheung, F.K.T., 2017. BIM in off-site manufacturing for buildings. *Journal of Building Engineering*, 14 (September), 89–102.

Abanda, F.H., Taj, J.H.M., Pettang, C., and Manjia, M.B., 2011. An ontology-driven building construction labour cost estimation in Cameroon. *Journal of Information Technology in Construction (ITcon)*, 16, 617–634.

Abdullah, M.. and Egbu, C.., 2010. Selection criteria frameword for choosing industrialized building systems for housing projects. *In*: C. Egbu, ed. *Procs 26th Annual ARCOM Conference, 6-8 September 2010*. Leeds: Association of Researchers in Construction Management.

Abdullah, M.R. and Egbu, C.O., 2009. *Industrialised building system in Malaysia: Issues for research in a changing financial and property market*. Proceedings of the BUHU 9th International Post Graduate Research Conference.

Abdulmalek, F.A. and Rajgopal, J., 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of Production Economics*, 107 (1), 223–236.

Abosoad, H., Underwood, J., and Boreny, S., 2009. Towards an Information System Representation of off Site Manufacturing (OSM) in Facilitating the Virtual Prototyping of Housing Design. *In*: *9th International Postgraduate Research Conference (IPGRC)', University of Salford, Salford, UK*. 509–520.

Adamides, E.D. and Karacapilidis, N., 2006. A knowledge centred framework for collaborative business process modelling. *Business Process Management Journal*, 12 (5), 557–575.

Adeli, H. and Wu, M., 1998. Regularization neural network for construction cost estimation. *Journal of Construction Engineering and Management*, 124 (1), 18–23.

Afsari, K. and Eastman, C.M., 2016. A Comparison of Construction Classification Systems Used for Classifying Building Product Models. *In*: *52nd ASC Annual International Conference Proceedings*. Associated Schools of Construction.

Aguilar-Savén, R.S., 2004. Business process modelling: Review and framework. *International Journal of Production Economics*, 90 (2), 129–149.

Ahmed, V., Opoku, A., and Aziz, Z., 2016. *Research Methodology in the Built Environment: A selection of case studies*. New York: Routledge.

Akasah, Z.A., Amirudin, R., and Alias, M., 2010. Maintenance management process model for school buildings: An application of IDEF 0 modelling methodology . *Australian Journal of Civil Engineering*, 8 (1), 1–12.

Akintoye, A. and Fitzgerald, E., 2000. A survey of current cost estimating practices in the UK A. *Construction Management & Economics*, 18, 161–172.

Akyol, D.E., Tuncel, G., and Bayhan, G.M., 2007. An Analysis of Activity-Based Costing in a Manufacturing System. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, 1 (11), 1040–1043.

Aldridge, G., Pasquire, C., Gibb, A., and Blismas, N., 2001. Methods for Measuring the "Unmeasurable": Evaluating the Benefits of Pre-Assembly and Standardization in Construction. *In*: *17th Annual ARCOM Conference, 5-7 September 2001, University of Salford. Association of Researchers in Construction Management*. 311–9.

Almeida, A. and Cunha, J., 2017. The implementation of an Activity-Based Costing (ABC) system in a manufacturing company. *Procedia Manufacturing*, 13, 932–939.

Alonso, R., Borras, M., Koppelaar, R.H.E.M., Lodigiani, A., Loscos, E., and Yöntem, E., 2019. SPHERE: BIM Digital Twin Platform. *Proceedings*, 20 (1), 9.

Arafa, M. and Alqedra, M., 2011. Early Stage Cost Estimation of Building Construction Projects using Artificial Neural Networks. *Journal of Artificial Intelligence*, 4 (1), 63–75.

Arbizzani, E. and Civiero, P., 2013. Technical solutions and industrialised construction systems for advanced sustainable buildings. *In*: *PORTUGAL SB13 - CONTRIBUTION OF SUSTAINABLE BUILDING TO MEET EU 20-20-20 TARGETS*. 371–378.

Arditi, D. and Mochtar, K., 2000. Trends in productivity improvement in the US construction industry. *Construction Management & Economics*, 18 (1), 15–27.

Arif, M. and Egbu, C., 2010. Making a case for offsite construction in Making a case for offsite construction in China. *Engineering Construction & Architectural Management*, 17 (6), 536–548.

Assaf, S.A. and Al-Hejji, S., 2006. Causes of delay in large construction projects. *International Journal of Project Management*, 24, 349–357.

Awuzie, B. and McDermott, P., 2017. An abductive approach to qualitative built environment research: A viable system methodological exposé. *Qualitative Research Journal*, 17 (4), 356–372.

Ayachit, A.C., Attarde, P.M., and Kulkarni, S., 2014. Activity Based Costing in Construction. *International Journal of Advanced Engineering Research and Studies*, 4 (1), 9–14.

Ayinla, K.O., Cheung, F., and Tawil, A.R., 2019. Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system. *Construction Innovation*, 20 (2), 223–246.

Badir, Y.F., Kadir, M.R.A., and Hashim, A.H., 2002. Industrialized Building Systems Construction in Malaysia. *Journal of Architectural Engineering*, 8 (1).

Baghchesaraei, A., Kaptan, M.V., and Baghchesaraei, O.R., 2015. Using prefabrication systems in building construction. *International Journal of Applied Engineering Research*, 10 (24), 44258–44262.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., and Wong, I., 2006. Designing out waste in high-rise residential buildings : analysis of precasting and methods and traditional construction. *In*: *The International Conference on Asia-European Sustainable Urban Development*. Chongqing, China.

Baloi, D., 2003. Sustainable construction: Challenges And Opportunities. *In*: *19th Annual ARCOM Conference*. 289–97.

Barber, K.D., Dewhurst, F.W., Burns, R.L.D.H., and Rogers, J.B.B., 2003. Business-process modelling and simulation for manufacturing management: A practical way forward.

Business Process Management Journal, 9 (4), 527–542.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertran, N., and Brown, S.V., 2017. *Reinventing construction through a productivity revolution*.

Bari, N.A.A., Abdullah, N.A., Yusuff, R., Ismail, N., and Jaapar, A., 2012. Environmental Awareness and Benefits of Industrialized Building Systems (IBS). *Procedia - Social and Behavioral Sciences*, 50 (July), 392–404.

Baxter, P. and Jack, S., 1990. Qualitative case study methodology: study design and implementation for novice researchers. *The Qualitative Report*, 13 (4), 544–559.

Baxter, P. and Jack, S., 2008. Qualitative Case Study Methodology : Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13 (4), 544–559.

Ben-Arieh, D. and Qian, L., 2003. Activity-based cost management for design and development stage. *International Journal of Production Economics*, 83 (2), 169–183.

Bertelsen, S., 2005. Modularization – a third approach to making construction lean? *In*: *13th annual conference in the International Group for Lean Construction*. Sydney, Australia, 1–11.

Blismas, N., Pasquire, C., and Gibb, A., 2006a. Bene t evaluation for o ff-site production in construction. *Construction Management & Economics*, 24 (2), 121–130.

Blismas, N., Pasquire, C., and Gibb, A., 2006b. Benefit evaluation for off - site production in construction. *Construction Management and Economics*, 24 (2), 121–130.

Blismas, N. and Wakefield, R., 2007. Drivers constraints and the future of off-site manufacture in Australia. *Construction Innovation Special Edition*.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114 (January), 103179.

Bottom, D., Gann, D., Groak, S., and Meikle, J., 1996. *Innovation in Japanese Prefabricated House-Building Industries: Department of Trade and Industry Overseas Science and Technology Expert Mission Visit Report*. Construction Industry Research and Information Association.

Brockmans, S., Haase, P., Hitzler, P., and Studer, R., 2006. A Metamodel and UML Profile for Rule-extended OWL DL Ontologies. *In*: Y. Sure and J. Domingue, eds. *ESWC 2006*.

Berlin Heidelberg: Springer-Verlag, 303–316.

Bryman, A., 2012. *Social Research Methods*. 4th editio. New York: Oxford University Press.

buildingSMART, 2016. IFC4 Add2 - Addendum 2 [online]. *buildingSMART International Ltd*. Available from: http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/ [Accessed 2 Jan 2019].

Cabinet Office, 2011. *Government Construction Strategy*. London.

Caputo, A.C. and Pelagagge, P.M., 2005. Parametric and Neural Methods for Cost Estimation Of Process Vessels. *In*: *18th International Congress of Mechanical Engineering*.

Carli, G. and Canavari, M., 2013. Introducing Direct Costing and Activity based Costing in a Farm Management System: A Conceptual Model. *Procedia Technology*, 8 (Haicta), 397–405.

Carr, R.I., 1989. Cost - Estimating Principles. *Journal of Construction Engineering and Management*.

Chan, C.W. and Johnstonb, M., 1996. Knowledge modelling for constructing an expert system to support reforestation decisions. *Knowledge-Based Systems*, 9, 41–59.

Chan, E.H.W. and Tse, R.Y.C., 2003. Cultural Considerations in Cultural Considerations in International Construction Contracts. *Journal of Construction Engineering and Management*, 129 (4), 375–381.

Chau, K.W., 1995. The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs : empirical evidence from Hong Kong. *Construction Management and Economics*, 13 (1), 15–21.

Chau, K.W. and Anson, M., 2002. A Knowledge-Based System for Constr uction Site Level Facilities Layout, 2358, 393–402.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010a. Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction*, 19 (2), 235–244.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010b. Automation in Construction Decision support for construction method selection in concrete buildings : Prefabrication adoption and optimization. *Automation in Construction*, 19, 665–667.

Cheng-Leong, A., Pheng, K.L., and Leng, G.R.K., 1999. IDEF: A comprehensive modelling methodology for the development of manufacturing enterprise systems. *International Journal of Production Research*, 37 (17), 3839–3858.

Cheung, F.K.T., Kurul, E., and Oti, A.H., 2016. A case study of hybrid strategies to create value for a contracting business in the education sector in England and Wales. *Construction Management and Economics,* 34 (4–5), 335–352.

Chevallier, Z., Finance, B., and Boulakia, B.C., 2020. A reference architecture for smart building digital twin. *CEUR Workshop Proceedings*, 2615, 1–12.

Chiang, Y.H., Hon-Wan Chan, E., and Ka-Leung Lok, L., 2006. Prefabrication and barriers to entry-a case study of public housing and institutional buildings in Hong Kong. *Habitat International,* 30 (3), 482–499.

Chou, J.-S., Yang, I.-T., and Chong, W.K., 2009. Probabilistic simulation for developing likelihood distribution of engineering project cost. *Automation in Construction*, 18 (August), 570–577.

Chou, J.S., 2011. Cost simulation in an item-based project involving construction engineering and management. *International Journal of Project Management*, 29 (6), 706–717.

Corcho, O., Fernandez-Lopez, M., and Gomez-Perez, A., 2003. Methodologies , tools and languages for building ontologies . Where is their meeting point ? *Data & Knowledge Engineering*, 46, 41–64.

Corcho, O. and Gómez-Pérez, A., 2000a. Evaluating Knowledge Representation and Reasoning Capabilities of Ontology Specification Languages. *In*: *Applications of Ontologies and Problem Solving Methods 14th European Conference on Artificial Intelligence (ECAI'00)*. 3.1 – 3.9.

Corcho, O. and Gómez-Pérez, A., 2000b. A roadmap to ontology specification languages. *In*: R. Dieng and O. Corby, eds. *EKAW*. Berlin Heidelberg: Springer-Verlag Berlin, 80–96.

Cox, R.F., Issa, R.R.A., Asce, M., and Ahrens, D., 2003. Management ' s Perception of Key Performance Indicators for Construction. *Journal of Construction Engineering & Management*, 129 (2), 142–151.

Creswell, J.W., 2009. *Research Design_ Qualitative, Quantitative, and Mixed Methods Approaches*. Third edit. London: SAGE Publications.

Cutting-Decelle, A.-F., Young, B.I., Das, B.P., Case, K., Rahimifard, S., Anumba, C.J., and

Bouchlaghem, D.M., 2007. A Review of Approaches to Supply Chain Communications: From Manufacturing to Construction. *ITcon*, 12, 73–102.

Datta, P.P. and Roy, R., 2009. Cost Modelling Techniques for Availability Type Service Support Contracts : a Literature Review and Empirical Study. *In*: *Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2)*. 216.

Dave, B., Koskela, L., and Kiviniemi, A., 2013. *Implementing Lean in construction: Lean construction and BIM*. CIRIA Guide C725 - Construction Industry Research and Information Association. London: CIRIA.

Delany, S., 2015. Classification [online]. *National Building Specification (NBS) BIM Toolkit*. Available from: https://toolkit.thenbs.com/articles/classification#classificationtables [Accessed 4 Feb 2019].

Denzin, N.K. and Lincoln, Y.S., 2000. *Handbook of Qualitative Research*. Second. London: SAGE Publications.

Djurić, D., Gašević, D., and Devedžić, V., 2005. Ontology modeling and MDA. *Journal of Object Technology*, 4 (1), 109–128.

Doomun, R. and Jungum, N.V., 2008. Business process modelling, simulation and reengineering: Call centres. *Business Process Management Journal*, 14 (6), 838–848.

Doran, D. and Giannakis, M., 2011. An examination of a modular supply chain : a construction sector perspective. *An International Journal of Supply Chain Management*, 16 (4), 260–270.

Dubois, A. and Gadde, L.-E., 1999. Case studies in business market research: An abductive approach. *In*: M. Damien and C. Horan, eds. *Proceedings of the 15th Annual IMP Conference*. Dublin, 1–20.

Duncheva, T. and Bradley, F.F., 2016. A comparison between Volumetric Timber Manufacturing Strategies in the UK and mainland Europe. *In*: *2016 Modular and Offsite Construction (MOC) Summit*. Edmonton, Alberta, Canada, 10–17.

Durdyev, S. and Mbachu, J., 2011. On-site Labour Productivity of New Zealand Construction Industry : Key Constraints and Improvement Measures. *Australasian Journal of Construction Economics and Building*, 11 (3), 18–33.

Duverlie, P. and Castelain, J.M., 1999. Cost Estimation During Design Step: Parametric

Method versus Case Based Reasoning Method. *The International Journal of Advanced Manufacturing Technology*, 15, 895–906.

Eastman, C.M. and Sacks, R., 2008. Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134 (7), 517–526.

Egan, J., 1998. *Rethinking Construction*. The Report of the Construction Task Force.

El-Diraby, T.A., Lima, C., and Feis, B., 2005. Domain Taxonomy for Construction Concepts : Toward a Formal Ontology for Construction Knowledge. *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, 19 (4), 394–406.

El-Gohary, N.M. and El-Diraby, T.E., 2015. Domain Ontology for Processes in Infrastructure and Construction. *Journal of Construction Engineering and Management ASCE*, (January).

Elhag, T.M.S. and Boussabaine, A.H., 1998. An Artificial Neural System for Cost Estimation Of Construction Projects. *In*: *14th Annual ARCOM Conference*. 219–226.

Elnaas, E., 2014. The Decision To Use Off-Site Manufacturing (OSM) Systems for House Building Projects in the UK. University of Brighton. UK.

Elo, S. and Kyngäs, H., 2008. The qualitative content analysis process. *Journal of Advanced Nursing*, 62 (1), 107–115.

Enshassi, A., Mohamed, S., and Abushaban, S., 2009. Factors affecting the performance of construction projects in the Gaza strip. *Journal of Civil Engineering and Management*, 15 (2), 269–280.

Farmer, M., 2016. *Modernise or die: The Framer Review of the UK construction labour market*. The Farmer Review of the UK Construction Labour Model.

Fellows, R.F. and Liu, A.M.M., 2015. *Research Methods for Construction*. Fourth Edi. West Sussex: John Wiley & Sons Ltd.

Fensel, D., 2000. Relating Ontology Languages and Web Standards Ontology Languages.

Fernández-solís, J.L., 2009. How the Construction Industry does differ from manufacturing ? *In*: *Associated Schools of Construction International Proceedings of the 45th Annual Conference*. Gainesville.

Fernández, L.M., 1999. Overview Of Methodologies For Building Ontologies. *Proceedings of* *the IJCAI99 Workshop on Ontologies and ProblemSolving Methods Lessons Learned and Future Trends CEUR Publications*, 1999 (2), 1–13.

Fernandez, M., Gomez-Perez, A., and Juristo, N., 1997. *METHONTOLOGY : From Ontological Art Towards Ontological Engineering*.

Finnimore, B., 1989. *Houses from the Factory: System Building and the Welfare State*. California: Rivers Oram Press.

Flick, U., 2007. *Designing Qualitative Research*. London: SAGE Publications.

Flick, U., 2014. *The SAGE Handbook of Qualitative Data Analysis*. London: SAGE Publications.

Formoso, C.T., 1991. A Knowledge-based Framework for Planning House Building Projects. University of Salford.

Forsberg, A. and Saukkoriipi, L., 2007. Measurement of waste and productivity in relation to lean thinking. *In*: *Lean Construction: A New Paradigm for Managing Capital Projects - 15th IGLC Conference*. 67–76.

Fortineau, V., Paviot, T., Louis-Sidney, L., and Lamouri, S., 2012. SWRL as a rule language for ontology-based models in power plant design. *IFIP Advances in Information and Communication Technology*, 388 AICT, 588–597.

Froese, T., 2003. FUTURE DIRECTIONS FOR IFC-BASED INTEROPERABILITY. *ITcon*, 8 (December 2002), 231–246.

Future Focus, 2017. *Offsite and Modular Building Market Research*.

Gann, D.M., 1996. Construction as a manufacturing process ? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics*, 14 (5), 437–450.

Gbadamosi, A.Q., Mahamadu, A.M., Oyedele, L.O., Akinade, O.O., Manu, P., Mahdjoubi, L., and Aigbavboa, C., 2019. Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, 215, 1180–1190.

Giacobbi, P.R., Poczwardowski, A., and Hager, P., 2005. A pragmatic research philosophy for applied sport psychology. *Sport Psychologist*, 19 (1), 18–31.

Gibb, A.G.F., 1999. *Off-site fabrication: Prefabrication, Pre-assembly and Modularisation*. New York: John Wiley & Sons.

Gibb, A.G.F., 2001. Standardization and pre-assembly – distinguishing myth from reality using case study research. *Construction Management and Economics*, 19, 307–315.

Gibb, A.G.F. and Isack, F., 2003. Re-engineering through pre-assembly : client expectations and drivers. *Building Research & Information*, 31 (2), 146–160.

Girmscheid, G. and Scheublin, F., 2010. New perspective in industrialisation in construction - a state of the art report. *International Council For Research And Innovation In Building And Construction (CIB)*, (May).

Golbreich, C., 2004. Combining Rule and Ontology Reasoner for the Semantic Web. *In*: Grigoris Antoniou and H. Boley, eds. *Third International Workshop, RuleML 2004*. Berlin: Springer, ??? ????

Gómez-Pérez, A. and Corcho, O., 2002. Ontology languages for the semantic web. *IEEE Intelligent Systems and Their Applications*, 17 (1), 54–60.

Goodier, C. and Gibb, A., 2005. *The value of the UK market for offsite*. London.

Gorgolewski, M.T., 2005. The Potential for Prefabrication in UK Housing to Improve Sustainability. *In*: J. Yang, P.S. Brandon, and A.C. Sidwell, eds. *Smart & Sustainable Built Environments*. Oxford, UK.: Blackwell Publishing Ltd, 1–8.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012a. Offsite Construction : Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1, 62–73.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012b. Offsite Construction: Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1 (1), 62–73.

Goulding, J.S., Pour Rahimian, F., Arif, M., and Sharp, M.D., 2015. New offsite production and business models in construction: priorities for the future research agenda. *Architectural Engineering and Design Management*, 11 (3), 163–184.

GOV.UK, 2020. Live tables on house building [online]. *Ministry of Housing, Communities & Local Government*. Available from: https://www.gov.uk/government/statistical-data-sets/live-tables-on-house-building [Accessed 1 Feb 2020].

Grani, H.K., 2016. BIM Classification - Giving your Model some Class [online]. *Areo blog - Lifecycle BIM and smart FM*.

Griffith, M. and Jefferys, P., 2013. *Solutions for the housing shortage: How to build the 250.000 homes we need each year*. London.

Gruber, T.R., 1995. Toward principles for the design of ontologies used in knowledge sharing. *International Journal of Human Computer Studies*, 43, 907–928.

Gu, N. and London, K., 2010. Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, 19 (8), 988–999.

Guba, E.G. and Lincoln, Y.S., 1994. Competing Paradigms in Qualitative Research. *In*: N.K. Denzin and Y.S. Lincoln, eds. *Handbook of qualitative research*. 105–117.

Guizzardi, G., 2007. On Ontology, ontologies, Conceptualizations, Modeling Languages, and (Meta)Models. *In*: O. Vasilecas et al., ed. *Databases and Information Systems IV*. IOS Press.

Gunasekaran, A. and Kobu, B., 2002. Modelling and analysis of business process reengineering. *International Journal of Production Research*, 40 (11), 2521–2546.

Gunasekaran, A. and Sarhadi, M., 1998. Implementation of activity-based costing in manufacturing. *Intern. Journal of Production Economics*, 56–57 (1998), 231–242.

Gunaydın, H.M. and Dogan, S.Z., 2004. A neural network approach for early cost estimation of structural systems of buildings. *International Journal of Project Management*, 22 (2004), 595–602.

Gunduz, M., Ugur, L.O., and Ozturk, E., 2011. Parametric cost estimation system for light rail transit and metro trackworks. *Expert Systems with Applications*, 38 (3), 2873–2877.

Gurcanli, G.E., Bilir, S., and Sevim, M., 2015. Activity based risk assessment and safety cost estimation for residential building construction projects. *Safety Science*, 80 (112), 1–12.

Hairstans, R. and Smith, R.E., 2018. Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK. *Architectural Engineering and Design Management*, 14 (1–2), 60–77.

Haron, N.A., Abdul-Rahman, H., Wang, C., and Wood, L.C., 2015. Quality function deployment modelling to enhance industrialised building system adoption in housing projects. *Total Quality Management and Business Excellence*, 26 (7–8), 703–718.

Hashemi, A., 2015. Offsite Manufacturing: A Survey on the Current Status and Risks of Offsite Construction in Iran, 9, 141–152.

Hashemi, A. and Hadjri, K., 2014. Offsite Construction, a Potential Answer to the Iranian Housing Shortages. *In*: *Construction Technology and Management CTM 2014*

International Scientific Conference. 189–199.

Hause, M., 2006. The SysML Modelling Language. *In*: *Fifteenth European Systems Engineering Conference*. 12.

HM Government, 2013. *Construction 2025. Industrial Strategy: Government and industry in partnership*.

Holten, M. and Ferdinand, G., 2020. BOT : the Building Topology Ontology of the W3C Linked Building Data Group. *Semantic Web*, 12 (1), 143–161.

Höök, M. and Stehn, L., 2008. Lean principles in industrialized housing production : the need for a cultural change Lean culture. *Lean Construction Journal 2008*, (April), 20–33.

Horrocks, I., 2002. DAML+OIL: a Description Logic for the Semantic Web. *Bulletin of the Technical Committee on Data Engineering*, 25 (1).

Horrocks, I. and Sattler, U., 2001. Ontology reasoning in the SHOQ(D) description logic. *IJCAI International Joint Conference on Artificial Intelligence*, 199–204.

Howell, G. and Ballard, G., 1998. Implimenting construction: understanding and action. *Proceedings International Group for Lean Construction*, 0, 9.

Howell, G.A., 1999. What is Lean Construction. *In*: I.D. Tommelein, ed. *IGLC 2012 - 20th Conference of the International Group for Lean Construction*. UNIVERSITY OF CALIFORNIA BERKELEY, CALIFORNIA, USA.

Hueber, C., Horejsi, K., and Schledjewski, R., 2016. Review of cost estimation: methods and models for aerospace composite manufacturing. *Advanced Manufacturing: Polymer and Composites Science*, 2 (1), 1–13.

Hyde, K.F., 2000. Recognising deductive processes in qualitative research. *Qualitative Market Research: An International Journal*, 3 (2), 82–90.

Ijomah, W.L. and Childe, S.J., 2007. A model of the operations concerned in remanufacture. *International Journal of Production Research*, 45 (24), 5857–5880.

Jabar, I. laili, Ismail, F., and Mustafa, A.A., 2013. Issues in Managing Construction Phase of IBS Projects. *Procedia - Social and Behavioral Sciences*, 101, 81–89.

Jaillon, L. and Poon, C.S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment : a Hong Kong case study. *Construction Management and Economics*, 26 (9), 953–966.

Jaillon, L. and Poon, C.S., 2009. The evolution of prefabricated residential building systems in Hong Kong : A review of the public and the private sector. *Automation in Construction*, 18 (3), 239–248.

Jaillon, L., Poon, C.S., and Chiang, Y.H., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management*, 29 (1), 309–320.

Jarkas, A.M. and Bitar, C.G., 2012. Factors Affecting Construction Labor Productivity in Kuwait. *Journal of Construction Engineering and Management*, 138 (7), 811–820.

Ji, S., Park, M., and Lee, H., 2011. Cost estimation model for building projects using case-based reasoning. *Canadian Journal of Civil Engineering*, 38, 570–581.

Jones, D., Bench-capon, T., and Visser, P., 1998. Methodologies for Ontology Development. *In*: *Proc. IT&KNOWS Conference of the 15th IFIP World Computer Congress*. Budapest.

Jonsson, H. and Rudberg, M., 2014. Classification of production systems for industrialized building : a production strategy perspective. *Construction Management and Economics*, 32 (1–2), 53–69.

Jung, J., 2002. Manufacturing cost estimation for machined parts based on manufacturing features. *Journal of Intelligent Manufacturing*, 13, 227–238.

Kalemi, E.V., Cheung, F., Tawil, A., Patlakas, P., and Alyania, K., 2020. ifcOWL-DfMA a new ontology for the offsite construc- tion domain. *In*: *Proceedings of the7578th Linked Data in Architecture and Construction Workshop - LDAC2020 ifcOWL-DfMA*. 105–117.

Kamar, K.A., Abd Hamid, Z., Azman, M.N.A., and Ahamad, M.S.S., 2011. Industrialized Building System (IBS): Revisiting Issues of Definition and Classification. *International Journal of Emerging. Sciences*, 1 (2), 120–132.

Karhu, V., 2000. Formal Languages for Construction Process Modelling. *Construction Information Technology 2000, Taking the construction industry into the 21st century, CIB W78.*, 525–534.

Kenley, R., 2014. Productivity improvement in the construction process Productivity improvement in the construction process. *Construction Management and Economics*, 32 (6), 489–494.

Kenley, R., Kanjanabootra, S., Ouyang, C., and Wynn, M., 2012. Procuring OSM: base-line models of off-site manufacture business processes in Australia. *In*: *16th Pacific Association of Quantity Surveyors Congress-Innovation and Sustaining: Challenges and Opportunities*. 1–10.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., and Holmstrom, J., 2019. Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7, 147406–147419.

Khosrowshahi, F. and Kaka, A.P., 1996. Estimation of Project Total Cost and Duration for Housing Projects in the U.K. *Building and Environment*, 31 (4), 373–383.

Kifer, M., 2008. Rule Interchange Format: The Framework. *In*: N. Bassiliades, G. Governatori, and A. Paschke, eds. *International Symposium, RuleML 2008*. Berlin: Springer-Verlag.

Kim, C.H., Weston, R.H., Hodgson, A., and Lee, K.H., 2003. The complementary use of IDEF and UML modelling approaches. *Computers in Industry*, 50 (1), 35–56.

Kim, S. and Shim, J.H., 2014. Combining case-based reasoning with genetic algorithm optimization for preliminary cost estimation in construction industry. *Canadian Journal of Civil Engineering*, 41 (November 2013), 65–73.

Kim, Y.-W., 2017. *Activity Based Costing for Construction Companies*. First Edit. West Sussex: John Wiley & Sons Ltd.

Kim, Y. and Ballard, G., 2001. Activity-based costing and its application to lean construction. *International Group for Lean Construction*, (January), 1–13.

Kim, Y. and Ballard, G., 2002. Case Study - overhead costs analysis. *In*: *Proceedings IGLC-10*. Gramado, Brazil, 1–13.

Kolo, S.J., Rahimian, F.P., and Goulding, J.S., 2014. Housing delivery in Nigeria and the opportunity for offsite manufacturing. *In*: *Creative Construction Conference*. 85–90.

Koskela, L., 1992. *Application of the new production philosophy to construction*. Stanford, CA.

KPMG, 2016. *Smart construction - How offsite manufacturing can transform our industry*.

Lang, R., Goodier, C., and Glass, J., 2016. Are housebuilders’ production strategies a barrier to offsite construction uptake in the UK? *Proceedings of the 32nd Annual ARCOM Conference, ARCOM 2016*, 1245–1253.

Larsson, J. and Simonsson, P., 2012. Barriers and drivers for increased use of off-site bridge construction in Sweden. *In*: *28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 751–761.

Latham, M., 1994. *Constructing the Team*. Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry.

Lawson, M., Ogden, R., and Goodier, C., 2010. *Design in Modular Construction*. Taylor & Francis Group.

Lee, S., Kim, K., and Yu, J., 2014. Automation in Construction BIM and ontology-based approach for building cost estimation. *Automation in Construction*, 41, 96–105.

Leishman, C. and Warren, F., 2006. Private housing design customization through house type substitution. *Construction Management and Economics*, 24, 149–158.

Lemaignan, S., Siadat, A., Dantan, J.-Y., and Semenenko, A., 2006. MASON : A proposal for an ontology of manufacturing domain. *In*: *Proceedings of the IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications (DIS'06) 0-7695-2589-X/06*.

Lere, J.C., 2000. Activity-based costing: A powerful tool for pricing. *Journal of Business and Industrial Marketing*, 15 (1), 23–33.

Lessing, J., Stehn, L., and Ekholm, A., 2015. Industrialised house-building – development and conceptual orientation of the field. *Construction Innovation*, 15 (3), 378–399.

Li, Z.C., Hong, J., Xue, F., Shen, G.Q., Xu, X., and Luo, L., 2016. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. *Habitat International*, 57, 74–87.

Liao, S., 2004. Expert system methodologies and applications - a decade review from 1995 to 2004. *Expert Systems with Applications*, 1–11.

Lim, E.C. and Alum, J., 1995. Construction productivity: Issues encountered by contractors in Singapore. *International Journal of Project Management*, 13 (1), 51–58.

Lin, Y.C., Wang, L.C., and Tserng, H.P., 2006. Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan. *Automation in Construction*, 15 (6), 693–705.

Liu, H., Lu, M., and Al-hussein, M., 2016. Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry.

Advanced Engineering Informatics, 30 (2), 190–207.

Liu, X., Li, Z., and Jiang, S., 2016. Ontology-Based Representation and Reasoning in Building Construction Cost Estimation in China. *Future Internet*, 8 (39).

Liu, Z., Osmani, M., Demian, P., and Baldwin, A.N., 2011. The potential use of BIM to aid construction waste minimalisation. *In*: –Sophia Antipolis, ed. *Proceedings of the CIB W78-W102 2011*. France.

Lou, Y.-I., Wang, H.C., and Lan, J.-S., 2017. Design and Implement the Activity-Based Costing in Taiwan Firm. *IOSR Journal of Business and Management*, 19 (01), 41–46.

Lovett, P.J., Ingram, A., and Bancroft, C.N., 2000. Knowledge-based engineering for SMEs - a methodology. *Journal of Materials Processing Technology*, 107, 384–389.

Lu, Q., Xie, X., Heaton, J., Parlikad, A.K., and Schooling, J., 2020. From BIM towards digital twin: Strategy and future development for smart asset management. *Studies in Computational Intelligence*, 853, 392–404.

Lucko, G. and Rojas, E.M., 2010. Research Validation: Challenges and Opportunities in the Construction Domain. *Journal of Construction Engineering and Management*, 136 (1).

Luo, L., Mao, C., Shen, L., and Li, Z., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system. *Engineering, Construction and Architectural Management*, 22 (6), 622–643.

Ma, Z.M. and Wang, X., 2012. Rule interchange in the semantic web. *Journal of Information Science and Engineering*, 28 (2), 393–406.

Mao, C., Shen, Q., Shen, L., and Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods : Two case studies of residential projects. *Energy & Buildings*, 66, 165–176.

McKay, L.J., 2010. The effect of offsite construction on occupational health and safety. *A Doctoral Thesis Submitted In Partial Fulfilment Of The Requirements For The Award Of Doctor Of Philosophy*. Loughborough University.

Meiling, J., Backlund, F., and Johnsson, H., 2012a. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Meiling, J., Backlund, F., and Johnsson, H., 2012b. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Melão, N. and Pidd, M., 2000. A conceptual framework for understanding business processes and business process modelling. *Information Systems Journal*, 10 (2), 105–129.

Melton, T., 2005. The benefits of lean manufacturing: What lean thinking has to offer the process industries. *Chemical Engineering Research and Design*, 83 (6 A), 662–673.

Miah, S.J. and Genemo, H., 2016. A Design Science Research Methodology for Expert Systems Development. *Australasian Journal of Information Systems*, 20, 1–29.

Miles, J. and Whitehouse, N., 2013. *Offsite Housing Review*. London.

Milton, N., 2008. *Knowledge Technologies*. Italy: Polimetrica ®.

Mizoguchi, R. and Ikeda, M., 1998. Towards ontology engineering. *Journal-Japanese Society for Artificial Intelligence*, 13 (1), 259–266.

Montali, J., Overend, M., Pelken, P.M., and Sauchelli, M., 2018. Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends. *Architectural Engineering and Design Management*, 14 (1–2), 78–94.

Morgan, D.L., 2007. Paradigms Lost and Pragmatism Regained: Qualitative and Quantitative Methods. *Journal of Mixed Methods Research*, 1 (48), 48–76.

Mossman, A., 2009. Creating value: A sufficient way to eliminate waste in lean design and lean production. *Lean Construction Journal*, 2009, 13–23.

Mostafa, S., Chileshe, N., and Abdelhamid, T., 2016. Lean and agile integration within offsite construction using discrete event simulation. *Construction Innovation*, 16 (4), 483–525.

Motawa, I. and Almarshad, A., 2013. A knowledge-based BIM system for building maintenance. *Automation in Construction*, 29, 173–182.

Mtech Group, 2007. *Offsite Construction Industry Survey 2006*. BuildOffsite. London.

Murtaza, M.B., Fisher, D.J., and Skibniewski, M.J., 1993. Knowledge-Based Approach to Modular Construction Decision Support. *Journal of Construction Engineering and Management*, 119, 115–130.

Murugaiah, U., Benjamin, S.J., and Marathamuthu, M.S., 2010. Scrap loss reduction using the 5-whys analysis. *International Journal of Quality & Reliability Management*, 27 (5), 527–

540.

Musa, M.F., Mohammad, M.F., Yusof, M.R., and Mahbub, R., 2015. The Way Forward for Industrialised Building System (IBS) in Malaysia. *In*: *InCIEC 2014*. Singapore: Springer, pp 163-175.

Nadim, W. and Goulding, J.S., 2011. Offsite production : a model for building down barriers. *Engineering, Construction and Architectural Management*, 18 (1), 82–101.

Nahmens, I. and Ikuma, L.H., 2012. Effects of Lean Construction on Sustainability of Modular Homebuilding. *Journal of Architectural Engineering*, 18 (2), 155–163.

Nasereddin, M., Mullens, M.A., and Cope, D., 2007. Automated simulator development : A strategy for modeling modular housing production. *Automation in Construction*, 16, 212–223.

Naufal, A., Jaffar, A., Yusoff, N., and Hayati, N., 2012. Development of kanban system at local manufacturing company in Malaysia-Case study. *Procedia Engineering*, 41 (Iris), 1721–1726.

Nawari, N.O., 2012. BIM Standard in Off-Site Construction. *Journal of Architectural Engineering*, 18 (2).

NBS, 2015. Uniclass 2015 [online]. *National Building Specification (NBS)*. Available from: https://www.thenbs.com/our-tools/uniclass-2015 [Accessed 2 Jan 2019].

Nepal, M.P., Staub-French, S., Pottinger, R., and Zhang, J., 2013. Ontology- based feature modeling for construction information extraction from a build- ing information model. *Journal of Computing in Civil Engineering*, 27 (5), 555–569.

Neuman, L.W., 2014. *Social Research Methods: Qualitativr and Quantitative Approaches*. Seventh Ed. Essex, England: Pearson Education Limited.

Niazi, A. and Dai, J.S., 2006. Product Cost Estimation : Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, 128 (May).

Nicholls, D., 2017. Qualitative research. Part 2: Methodologies. *International Journal of Therapy and Rehabilitation*, 24 (2), 71–77.

Nikakhtar, A., Hosseini, A.A., Wong, K.Y., and Zavichi, A., 2015. Application of lean construction principles to reduce construction process waste using computer simulation: A case study. *International Journal of Services and Operations Management*, 20 (4), 461–

480.

Nurcan, S., Etien, A., Kaabi, R., Zoukar, I., and Rolland, C., 2005. A strategy driven business process modelling approach. *Business Process Management Journal*, 11 (6), 628–649.

O'Connor, M., Knublauch, H., Tu, S., Grosof, B., Dean, M., Grosso, W., and Musen, M., 2005. Supporting rule system interoperability on the semantic Web with SWRL. *In*: Y. Gil et al., ed. *ISWC 2005*. Berlin: Springer-Verlag, 974–986.

Ochieng, E.G. and Price, A.D.F., 2009. Managing cross-cultural communication in multicultural construction project teams : The case of Kenya and UK. *International Journal of Project Management ·*, (July).

Ofori, G., 2000. Challenges of Construction Industries in Developing Countries : Lessons from Various Countries. *In*: *2nd International Conference on Construction in Developing Countries: Challenges Facing the Construction Industry in Developing Countries*. Gabarone, 1–13.

Ogunlana, S.O., 1989. Accuracy in design cost estimating.

Ong, N.S., 1995. Manufacturing cost estimation for PCB assembly : An activity-based approach. *International Journal of Production Economics*, 38, 159–172.

Ormerod, R.J., 2010. Rational inference: Deductive, inductive and probabilistic thinking. *Journal of the Operational Research Society*, 61 (8), 1207–1223.

Ou-Yang, C. and Lin, T.S., 1997. Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. *International Journal of Advanced Manufacturing Technology*, 13, 618–629.

Ozaki, R., 2003. Customer-focused approaches to innovation in housebuilding. *Construction Management and Economics*, 21, 557–564.

Ozbayrak, M., Akgun, M., and Turker, A.K., 2004. Activity-based cost estimation in a push / pull advanced manufacturing system. *International Journal of Production Economics*, 87, 49–65.

Pan, W., Dainty, A.R.J., and Gibb, A.G.F., 2012. Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, 138 (11), 1239–1250.

Pan, W., Gibb, A.G.F., and Dainty, A.R.J., 2008. *Leading UK housebuilders' utilisation of* *offsite modern methods of construction*. Building Research & Information.

Pan, W. and Goodier, C., 2012. House-Building Business Models and Off-Site Construction Take-Up. *Journal of Architectural Engineering*, 18 (2), 84–93.

Pan, W. and Sidwell, R., 2011. Demystifying the cost barriers to offsite construction in the UK. *Construction Management & Economics*, 29, 1081–1099.

Pasquire, C., Gibb, A., and Blismas, N., 2005. What should you really measure if you want to compare prefabrication with traditional construction? *In*: *Proceedings IGLC*. Sydney, Australia, 481–491.

Pasquire, C.L. and Connolly, G.E., 2002. Leaner construction through off-site manufacturing. *In*: *Proceedings 10th of the Internationa Group of Lean Construction Conference, Gramado, Brazil*. 1–13.

Pauwels, P. and Terkaj, W., 2016. EXPRESS to OWL for construction industry : Towards a recommendable and usable ifcOWL ontology. *Automation in Construction*, 63, 100–133.

Pearce, A., Pons, D., and Neitzert, T., 2018. Implementing lean—Outcomes from SME case studies. *Operations Research Perspectives,* 5, 94–104.

Persson, S., Malmgren, L., and Johnsson, H., 2009. Information management in industrial housing design and manufacture. *Electronic Journal of Information Technology in Construction*, 14 (June), 110–122.

Pheng, L.S. and Leong, C.H.Y., 2000. Cross-Cultural project management for international construction in China. *International Journal of Project Management*, 18 (5), 307–316.

Post, 2003. *Modern methods of house building*. Parliamentary Office of Science and Technology. London.

Pulido, J.R.G., Ruiz, M.A.G., Herrera, R., Cabello, E., Legrand, S., and Elliman, D., 2006. Ontology languages for the semantic web: A never completely updated review. *Knowledge-Based Systems,* 19 (7), 489–497.

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., and Zimmerman, J.B., 2012. Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*, 16 (2), 243–254.

Rahani, A. and Muhammad, A.-A., 2012. Production Flow Analysis through Value Stream Mapping : A Lean Manufacturing Process Case Study. *Procedia Engineering* -

International Symposium on Robotics and Intelligent Sensors, 41 (Iris), 1727–1734.

Rahman, N.A.A., Sharif, S.M., and Esa, M.M., 2013. Lean Manufacturing Case Study with Kanban System Implementation. *Procedia Economics and Finance*, 7 (Icebr), 174–180.

Rahman, S., Perera, S., Odeyinka, H., and Bi, Y., 2008. A Conceptual Knowledge-Based Cost Model for Optimizing the Selection of Materials and Technology for Building Design. *24th Annual ARCOM Conference*, (September), 217–225.

Raz, T. and Elnathan, D., 1999. Activity based costing for projects. *International Journal of Project Management*, 17 (1), 61–67.

Rezgui, Y., Hopfe, C.J., and Vorakulpipat, C., 2010. Generations of knowledge management in the architecture , engineering and construction industry : An evolutionary perspective. *Advanced Engineering Informatics*, 24 (2), 219–228.

Richard, R.B., 2005. Industrialised building systems: Reproduction before automation and robotics. *Automation in Construction*, 14 (4), 442–451.

RICS, 2012a. *NRM1: Order of Cost Estimating and Cost Planning for Capital Building Works*. 2nd Editio. Coventry UK: Royal Institution of Chartered Surveyors (RICS).

RICS, 2012b. *NRM 2: Detailed Measurement for Building Works*. 1st Editio. Coventry: Royal Institution of Chartered Surveyors (RICS).

La Rocca, G., 2012. Knowledge based engineering : Between AI and CAD . Review of a language based technology to support engineering design. *Advanced Engineering Informatics*, 26 (2), 159–179.

Roy, A.U.K., Roy, M., and Saha, P.S., 2007. Mass-Industrialized Housing to Combat Consistent Housing Shortage in Developing Countries : Towards an Appropriate System for India. *In*: *World Congress on Housing National Housing Programmes- New Visions November 03-07, Kolkota, India*. Kolkata, India, 1–7.

Roy, R., Souchoroukov, P., and Shehab, E., 2011. Detailed cost estimating in the automotive industry : Data and information requirements. *Intern. Journal of Production Economics*, 133 (2), 694–707.

Rožanec, J.M., Jinzhi, L., Košmerlj, A., Kenda, K., Dimitris, K., Jovanoski, V., Rupnik, J., Karlovčec, M., and Fortuna, B., 2020. Towards actionable cognitive digital twins for manufacturing. *CEUR Workshop Proceedings*, 2615, 1–12.

Rundora, R., Ziemerink, T., and Oberholzer, M., 2013. Activity-based costing in small manufacturing firms: South African study. *Journal of Applied Business Research*, 29 (2), 485–498.

Saad, A. and Shaharin, S., 2016. The Methodology for Ontology Development in Lesson Plan Domain. *International Journal of Advanced Computer Science and Applications (IJACSA)*, 7 (4), 557–562.

Sabol, L., 2008. *Challenges in Cost Estimating with Building Information Modeling*. Washington, DC.

Sarvimaki, M., 2017. *Case Study Strategies for Architects and Designers : Integrative Data Research Methods: Integrative Data Research Methods*. London: Taylor & Francis Group.

Saunders, M., Lewis, P., and Thornhill, A., 2009. *Research Methods for Business Students*. New York: Pearson.

Schell, C., 1992. *The Value of the Case Study as a Research Strategy*.

Schreiber, A.T., Akkermans, J.M., Anjewierden, A.A., de Hoog, R., Shadbolt, N.R., Velde, W. Van de, and Wielinga, B.J., 2001. *Knowledge Engineering and Management - The CommonKADS Methodology*. Cambridge,Massachusetts: MIT Press.

Schuh, K.L. and Barab, S.A., 2008. Philosophical Perspectives. *In*: J. David, S.J. Michael, D. Marcy, M. David, and M. Jeroen, eds. *Handbook of Research on Educational Communications*. New York: Taylor & Francis, 67–82.

Schwitter, R., 2010. Controlled natural languages for knowledge representation. *In*: *Coling 2010 - 23rd International Conference on Computational Linguistics, Proceedings of the Conference*. Beijing, 1113–1121.

Secretary of State for Communities and Local Government, 2017. *Fixing our broken housing market*. Department for Communities and Local Government. London: Crown.

Shadbolt, N. and Milton, N., 1999. From Knowledge Engineering to Knowledge Management. *British Journal of Management*, 10, 309–322.

Shamsuddin, S.M., Zakaria, R., and Mohamed, S.F., 2013. Economic Attributes in Industrialised Building System in Malaysia. *Procedia - Social and Behavioral Sciences*, 105, 75–84.

Shang, G. and Sui Pheng, L., 2014. Barriers to lean implementation in the construction industry in China. *Journal of Technology Management in China*, 9 (2), 155–173.

Shi, J.J., Lee, D.E., and Kuruku, E., 2008. Task-based modeling method for construction business process modeling and automation. *Automation in Construction*, 17 (5), 633–640.

Shostak, L. and Houghton, J., 2008. The credit crunch and the housing shortage - Time for a radical new approach to building affordable homes. *Local Economy*, 23 (3), 121–126.

Sivakumar, R. and Arivoli, P.V., 2011. Ontology Visualization Protégé Tools - A Review. *International Journal of Advanced Information Technology*, 1 (4), 39–39.

Smith, A.E. and Mason, A.K., 1996. Cost Estimation Predictive Modeling : Regression versus Neural Network. *The Engineering Economist*.

Sobh, R. and Perry, C., 2006. Research design and data analysis in realism research. *European Journal of Markerting*, 40 (11), 1194–1209.

Sodikov, J., 2005. COST ESTIMATION OF HIGHWAY PROJECTS IN DEVELOPING COUNTRIES : ARTIFICIAL NEURAL NETWORK APPROACH. *Journal of the Eastern Asia Society for Transportation Studies*, 6, 1036–1047.

Soiferman, L.K., 2010. Compare and Contrast Inductive and Deductive Research Approaches. *Inductive and Deductive Research Approaches*, (April), 1–23.

Song, J., Fagerlund, W.R., Haas, C.T., Tatum, C.B., and Vanegas, J.A., 2005. Considering Prework on Industrial Projects. *Journal of Construction Engineering and Management*, 131 (6), 723–733.

Spens, K.M. and Kovács, G., 2006. A content analysis of research approaches in logistics research. *International Journal of Physical Distribution and Logistics Management*, 36 (5), 374–390.

Spyns, P., Meersman, R., and Jarrar, M., 2002. Data modelling versus ontology engineering. *ACM SIGMOD Record*, 31 (4), 12–17.

Staub-french, S., Fischer, M., Kunz, J., Paulson, B., and Ishii, K., 2002. *A Feature Ontology to Support Construction Cost Estimating*.

Steinhardt, D., Manley, K., and Miller, W.F., 2014. Reshaping housing using prefabricated systems. *Proceedings of World Sustainable Building Conference (SB14)*.

Studer, R., Benjamins, V.R., and Fensel, D., 1998. Knowledge Engineering : Principles and methods. *Data & Knowledge Engineering*, 25, 161–197.

Sundar, R., Balaji, A.N., and Satheesh Kumar, R.M., 2014. A review on lean manufacturing implementation techniques. *Procedia Engineering*, 97, 1875–1885.

Szuba, J.S., Grabska, E.G., and Borkowski, A., 1999. Graph Visualization in ArchiCAD. *In*: *Proceedings of the International Workshop on Applications of Graph Transformations with Industrial Relevance*. 241–246.

Tam, V.W.Y., Tam, C.M., Zeng, S.X., and Ng, W.C.Y., 2007. Towards adoption of prefabrication in construction. *Building and Environment*.

Tang, J., Zhang, M., Tang, H., and Chen, Y., 2015. Research on Cost Management of Construction Project based on Activity-based Costing. *In*: *International Conference on Civil, Materials and Environmental Sciences (CMES 2015)*. 51–54.

Taylor, S., 2009. *Offsite Production in the UK Construction Industry, abrief overview*. HSE.

Tennant, S., McCarney, M., Tong, M.K., and Tennant, G., 2012. Re-Engineering the Construction Supply Chain: Transferring on-Site Activity, Off- Site. *In*: *Procs 28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 3–5.

Terkaj, W. and Urgo, M., 2014. Ontology-based modeling of production systems for design and performance evaluation. *Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014*, 748–753.

Thanoon, W.A., Peng, L.W., AbdulKadir, M.R., Jaafar, M.S., and Salit, M.S., 2003. The Essential Characteristics of Industrialised Building System. *In*: *International Conference on Industrialised Building Systems*. 10–11.

Thomas, G., 2011. Qualitative Inquiry A Typology for the Case Study in Social Science Following a Review of Definition , Discourse , and Structure. *Qualitative Inquiry*, 17 (6), 511 –521.

Tran, V. and Tookey, J., 2007. Labour Productivity in the New Zealand Construction Industry : A Thorough Investigation. *Australasian Journal of Construction Economics and Building*, 11 (1), 41–60.

Trehan, V., Chapman, C., and Raju, P., 2015. Informal and formal modelling of engineering processes for design automation using knowledge based engineering. *Journal of Zhejiang*

University: Science A, 16 (9), 706–723.

Tsai, W.H., Yang, C.H., Chang, J.C., and Lee, H.L., 2014. An Activity-Based Costing decision model for life cycle assessment in green building projects. *European Journal of Operational Research*, 238 (2), 607–619.

Vakaj, E., F., C., H., T.A.-R., Pauwels, P., and Patlakas, P., 2021. Semanic representation of DfMA offsite housing.

Venables, T., Barlow, J., and Gann, D., 2004. *Manufacturing Excellence - UK Offsite Capacity in Off-Site Manufacturing*. Constructing Excellence.

Verhagen, W., Bermell-Garcia, P., Mariot, P., Cotton, J.-P., Ruiz, D., Redon, R., and Curran, R., 2010. (Costing) Knowledge-Based Cost Modelling of Composite Wing Structures. *International Journal of Computer Integrated Manufacturing*, pp.1.

Vernikos, V.K., Nelson, R., Goodier, C.I., and Robery, P.C., 2013. Implementing an offsite construction strategy: a UK contracting organisation case study. *In*: *Proceedings of the 29th Annual ARCOM Conference*. Reading, UK, 667–677.

Vibaek, K.S., 2014. *Architectural System and Structures - Integrating design complexity in industralised construction*. London: Routledge.

Volk, R., Stengel, J., and Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, 38 (October 2017), 109–127.

Voss, E., Jin, Q., and Overend, M., 2013. A BPMN-based process map for the design and construction of façades. *Journal of Facade Design and Engineering*, 1 (1–2), 17–29.

Wagner, A. and Uwe, R., 2019. BPO : The Building Product Ontology for Assembled Products. *In*: *Proceedings of the 7th Linked Data in Architecture and Construction Workshop - LDAC2019*. 106–119.

Wahab, A.N.A., Mukhtar, M., and Sulaiman, R., 2013. A Conceptual Model of Lean Manufacturing Dimensions. *Procedia Technology*, 11 (Iceei), 1292–1298.

Waissi, G.R., Demir, M., Humble, J.E., and Lev, B., 2015. Automation of strategy using IDEF0 - A proof of concept. *Operations Research Perspectives*, 2, 106–113.

Warszawski, A., 1999. *Industrialised and automated building systems*. First edit. London: E & FN Spon.

Willis, J.W., 2007. *World Views, Paradigms, and the Practice of Social Science Research*. London: Sage.

Wilson, L., 2010. *How to Implement Lean Manufacturing*. New York: McGrawHill.

Wong, R., Hao, J., and Ho, C., 2003. Prefabricated building construction systems adopted in Hong Kong. *In*: *Proc. of the International Association for Housing Science on Word Congress of Housing: Process and Product*. Canada.

Wu, S., Wood, G., Ginige, K., and Jong, S.W., 2014. A technical review of bim based cost estimating in UK quantity surveying practice, standards and tools. *Journal of Information Technology in Construction*, 19 (March), 535–563.

Xu, Y., Elgh, F., Erkoyuncu, J.A., Bankole, O., Goh, Y., Cheung, W.M., Baguley, P., Wang, Q., Arundachawat, P., Shehab, E., Newnes, L., and Roy, R., 2011. Cost engineering for manufacturing : current and future research. *International Journal of Computer Intergrated Manufacturing*, 25 (4–5), 300–314.

Xu, Z., Abualdenien, J., Liu, H., and Kang, R., 2020. An IDM-Based Approach for Information Requirement in Prefabricated Construction. *Advances in Civil Engineering*, 2020, 21.

Yaman, H. and Tas, E., 2007. A building cost estimation model based on functional elements. *ITU Journal of Faculty of Architecture*, 4 (1), 73–87.

Yang, H., Yeung, J.F.Y., Chan, A.P.C., Chiang, Y.H., and Chan, D.W.M., 2010. A critical review of performance measurement in construction. *Journal of Facilities Management*, 8 (4), 269–284.

Yi, W. and Chan, A.P.C., 2014. Critical Review of Labor Productivity Research in Construction Journals. *Journal of Management in Engineering*, 30 (2), 214–225.

Yin, R.K., 1994. *Case Study Research: Design and Methods*. Second. Bervely Hills: Sage Publishing.

Yin, R.K., 2009. *Case Study Reserach: Design and methods*. Fourth. London: SAGE Publications.

Yin, R.K., 2016. *Qualitative Research from Start to Finish*. Second Edi. London: Guilford Publications.

Yitmen, I., 2007. The challenge of change for innovation in construction : A North Cyprus perspective. *Building and Environment*, 42, 1319–1328.

Young, B., Harty, C., Lu, S., and Davies, R., 2015. Developing Temporary Manufacturing Facilities for Residential Building : a Case of the Modern Flying Factory. *Procs 31st Annual ARCOM Conference, 7-9 September 2015*, (September), 1033–1042.

Yunus, R. and Yang, J., 2012. Critical Sustainability Factors in Industrialised Building Systems Abstract. *Construction Innovation*, 12 (4), 447–463.

Zainal, Z., 2007. Case study as a research method. *Jurnal Kemanusiaan*, 9.

Zakaria, S.A., Gajendran, T., Rose, T., and Brewer, G., 2018. Contextual, structural and behavioural factors influencing the adoption of industrialised building systems: a review. *Architectural Engineering and Design Management*, 14 (1–2), 3–26.

Zhai, X., Reed, R., and Mills, A., 2014. Addressing sustainable challenges in China. *Smart and Sustainable Built Environment*, 3 (3), 261–274.

Zhang, S., Boukamp, F., and Teizer, J., 2015. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, 52, 29–41.

Zhang, X. and Skitmore, M., 2012. Industrialized housing in China: a coin with two sides. *International Journal of Strategic Property Management*, 16 (2), 143–157.

Zhang, Y., Fan, G., Lei, Z., Han, S., Raimondi, C., Al-Hussein, M., and Bouferguene, A., 2016. Lean-based diagnosis and improvement for offsite construction factory manufacturing facilities. *In*: *ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction*. 1090–1098.

Zhang, Y., Lei, Z., Han, S., Bouferguene, A., and Al-Hussein, M., 2020. Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance. *Journal of Construction Engineering and Management*, 146 (9).

Zhong, B.T., Ding, L.Y., Love, P.E.D., and Luo, H.B., 2015. An ontological approach for technical plan definition and verification in construction. *Automation in Construction*, 55, 47–57.

Zhuang, C., Miao, T., Liu, J., and Xiong, H., 2021. The connotation of digital twin, and the construction and application method of shop-floor digital twin. *Robotics and Computer-Integrated Manufacturing*, 68 (September 2020), 102075.

Process waste analysis for offsite production methods for house construction – A case study of factory wall panel production

Kudirat Ayinla[1] (Corresponding Author)

[1]School of Built Environment and Architecture, London South Bank University, UK.

Franco Cheung[2]

[2]School of Engineering and the Built Environment, Birmingham City University, UK.

Martin Skitmore[3]

[3]Faculty of Society and Design, Bond University, Australia.

Abstract

There is a growing interest in the use of offsite manufacturing (OSM) in the construction industry disregarding criticisms of lacking real improvement from some offsite approaches adopted by housebuilders as compared to their onsite counterparts. Quantitative performance measures from previous studies are based on conventional onsite methods, with little attention paid to the performance and process improvements derived from various OSM methods.

In response, a case study was conducted based on two OSM methods using standardized and non-standardized processes for the production stage of a factory-manufactured wall panel. Value system analysis and root cause analysis using the 5Whys method was adopted to evaluate possible improvements in terms of process waste. The study reveals that OSM production methods that replicate site arrangements and activities involving significant manual tasks do not necessarily provide a marked improvement from the conventional onsite method. Thus, there is a need to re-evaluate the processes involved to eliminate such embedded process wastes as non-value-added time and cost and to consider automating critical activities. The analysis adopted in the case study provides measurable evidence of the performance gained from having a structured workflow over a non-structured workflow. It also reveals how process wastes are generated in the production process of wall panels offsite.

Keywords: lean manufacturing; offsite manufacturing; process waste; process modeling; root cause analysis, 5whys.

Introduction

Offsite manufacturing (OSM) methods are becoming increasingly popular in the housing and construction sectors. OSM methods provide opportunities to exploit the lean production system in manufacturing and achieve “lean construction” − a concept to reduce and eliminate wastes (including both physical and process wastes) in the construction processes (Howell 1999, Dave *et al.* 2013). The benefits of OSM have been widely studied, including reduced construction time, health and safety risks, environmental impact and whole-life cost, increased quality, increased predictability, productivity, whole-life performance, and profitability (Blismas *et al*> 2006a, Pan>*et al*> 2008, Pan and Goodier 2012). According to Pasquire and Connolly (2002), these benefits are the outcome of process improvements from implementing lean manufacturing in a factory environment. However, although most of the benefits are linked to process improvements at the production phase, little attention has been paid to how the choice production method may improve or reduce their acquisition.

It is reported that offsite manufacturing companies are inheriting lean manufacturing approaches in their processes to minimize cost (Zhang *et al.* 2020) through optimization of the design and construction processes by taking into account lean principles (Gbadamosi *et al.* 2019). This sometimes necessitates various levels of automation to be implemented in OSM workflow to improve efficiency and productivity (Zhang *et al.* 2016), including the introduction of robotic systems in production, transportation, and assembly. While the offsite approach is continuously developing and advancing, the process benefits from lean implementation may not be fully realized depending on the approaches to production adopted due to practices in OSM processes being similar to conventional onsite methods (Zhang *et al.* 2020). For instance, researchers (Pasquire and Connolly 2002, Zhang *et al.* 2020) have reported non-standardized practices in OSM processes and emphasized the need to avoid repeating 'onsite practices under a roof'. This is because, compared to the traditional onsite method, OSM needs to be taken as a process-oriented approach, where the benefits of standardization and repetitions can be applied (Fernández-solís 2009). This implies the need for offsite manufacturers to take a process view to establish and quantify improvements in their product development practices and to make informed decisions on their choice of methods.

Several tools are available to support the analysis of processes. Of these, business process modeling (BPM) is used in various industries, such as Engineering, IT, and software development and Manufacturing (Nurcan *et al.* 2005, Doomun and Jungum 2008, Shi *et al.* 2008). This aims to eliminate functional boundaries − focusing on how things are done (the process) rather than what is done (the product) (Barber *et al.* 2003). BPM is well recognized for its ability to facilitate a shared understanding of the process by enabling an understanding and analysis of the product/service development process of an organization (Aguilar-Savén

2004, Akasah *et al.* 2010). It enables the modeling of actual (AS-IS) and proposed (TO-BE) processes in order to identify gaps in current practices and ways to address them (Doomun and Jungum 2008). The TO-BE model mainly involves a computer-simulated workflow, which provides anticipated results prior to investment, which in turn reduces the scheduling and financial risks of an organization (Nikakhtar *et al.* 2015).

This study evaluates the alternative production methods of OSM by quantifying and analyzing the process wastes embedded in these methods in practice, based on the activities involved in a typical factory housebuilding process. Applying a case study approach containing two units of analysis (i.e., two different OSM production methods representing the AS-IS and TO-BE processes), the root causes of eight categories of the process waste from the two alternative production methods are analyzed using business process modeling (BPM). The study contributes to presenting quantitative evidence of the performance of structured and non-structured OSM methods in terms of process waste, to support informed production workflow design decision making.

Process benefit realization of OSM method of construction

Traditional construction activities are labor-intensive by nature with mainly the performance of workers as a critical factor affecting productivity. OSM attempts to streamline and automate production in a controlled factory environment. It adopts a lean manufacturing approach to optimize production performance and efficiency (Vernikos *et al.* 2013, Gbadamosi *et al.* 2019). The benefits of OSM can be grouped into five types: process, product, organizational, marketing, and social/environmental benefits. The key aspects and examples of benefits for each type as identified in past literature are summarised in Table 1. These benefits may explain why the construction industries in many countries are being encouraged to standardize and automate the production processes through the application of OSM.

The OSM workflow involves a variety of concurrent and iterative activities, structured production sequences, and various levels of automation. It is significantly different from the activities, construction sequence, and use of plant and machinery for conventional linear onsite workflow (Zhang *et al.* 2020). OSM has been classified with respect to the product, process, and people (Gibb 1999, Arif and Egbu 2010, Quale *et al.* 2012, Ayinla *et al.* 2019), which provides the necessary elements for understanding the different systems in OSM. Although the various benefits are well recognized, the adoption of OSM in practice has been slow. The approaches for evaluating alternative production methods are not well understood. Also, there has been no quantification of the benefits of different types of OSM methods through systematic evaluation.

Table 1: Categories of OSM benefits

Benefits	Key aspects	Example	Reference
Process benefits	Time	Improved delivery in terms of better logistics due to fewer trades on site. Delivery speed of up to 50-60% less than conventional methods.	(Miles and Whitehouse 2013).
	Productivity	Standardisation and economy of scale. Improved working environment and less distractions. Incorporation of some sort of automation.	(Pasquire and Connolly 2002, Gibb and Isack 2003, Eastman and Sacks 2008, Pan and Sidwell 2011, Quale *et al.* 2012)
	Safety	Increased occupational health and safety by improved working conditions. Dry construction process.	(Pasquire and Connolly 2002, Bertelsen 2005, Höök and Stehn 2008, Lawson *et al.* 2010, Kolo *et al.* 2014).
	Performance	Lean production approach: standardising processes that leads to formalised procedures, specialisation and a controlled production process.	(Pasquire and Connolly 2002).
Product benefits	Quality	Better quality products resulting from improved working conditions and quality management.	(Gorgolewski 2005, Larsson and Simonsson 2012).
	Cost	Lower unit cost of components as a result of savings from mass production and standardisation. Increased cost certainty.	(Ozaki 2003),
Organisational benefits	Management	Project management and programme improvements also termed “the structural factor”.	(Zakaria *et al.* 2018).
Marketing benefits	Client satisfaction	Client satisfaction as a result of mass customisation – that allows	(Cheung *et al.* 2016).

		customers to interact with OSM suppliers and building relationships in the exchange.	
Social/environmental benefits	Waste	Waste reduction as OSM presents the advantage of executing projects with minimal amount of waste generation.	(Höök and Stehn 2008, Arif and Egbu 2010, Quale *et al.* 2012, Mao *et al.* 2013, Shamsuddin *et al.* 2013).
	Impact	Environmental impact reduction.	(Gorgolewski 2005, Nahmens and Ikuma 2012).
	Health	Improved health and safety practices.	(Pan and Sidwell 2011).

According to Lawson *et al.* (2010), OSM can take the form of simply replicating the onsite method, or automating activities using line manufacturing similar to automotive production. Automation is one core aspect for productivity gain, and OSM methods can be classified into four categories according to the level of automation involved:

- *Static* method – where prefabricated elements are manufactured in one position, and materials, services and personnel are brought to the fabrication point. This mostly replicates the onsite construction method in a factory environment.
- *Linear* method – where the process is sequential and carried out in a discrete number of individual stages. Most activities are carried out manually by factory operatives.
- *Semi-automated linear* method – which shares the same principles as the linear method but tends to have more dedicated stages and individual tasks may be automated.
- *Automated linear* method – which comprises linear production with fully automated sequential stages.

Although the four categories may be very similar, or identical, major tasks and products as a result, their activities and production and assembly specifications (such as resource requirement, information flow, and sequences of activities) can vary significantly. Previous studies (e.g., Pasquire and Connolly 2002, Zhang *et al.* 2020) criticized the approach by housebuilders using the static method as not realizing the full benefit of offsite production, and simply carrying out the manufacturing process as a ‘mini construction project’ in an enclosed space, thus replicating onsite construction inefficiencies. On the other hand, largely automating activities may not be always beneficial. This is due to the general trade-off between the level of automation in design and the amount of investment required to facilitate automation. Yet, while the static method may result in low productivity, it is flexible and arguably can be used to produce products with a wider range of designs. This poses the question of which benefits from Table 1 are obtained from which OSM methods, especially in the process category.

Previous research related to the evaluation of OSM methods in construction work includes studies of their approach to applying lean and the critical success factors involved (Meiling *et al*> 2012b, Pearce>*et al*> 2018), strategies for integrating offsite production technologies (Pan *et al.* 2012), barriers to lean implementation (Shang and Sui Pheng 2014), company's lean thinking implantation (Zhang *et al.* 2016) and design processes with reference to lean principles (Gbadamosi *et al.* 2019). These studies have typically evaluated the OSM approach at a high level. One aspect that has not been well researched is the process benefits acquired in terms of waste embedded in the competing OSM production methods.

Process waste in lean manufacturing

The traditional mass production line, known as the 'push system', contains standardized parts that are processed following a station-by-station plan. This can lead to an unsynchronised flow of processes, and often overproduction as a result (Wilson 2010). In contrast, the lean manufacturing method implements a 'pull system', involving such concepts as pulling products forward and a single unit flow (Howell and Ballard 1998). Implementing a balanced and synchronized operation helps reduce waste in the process and prevents inventory build-up as the process flows smoothly. The term 'lean' is used to denote 'less' resources (Koskela 1992). Lean manufacturing aims to minimize process waste and maximize value by meeting service demands with minimal inventory. In practice, it relies on the use of a set of tools that assist in the identification and steady elimination of process waste (Howell and Ballard 1998), which arises from activity-centered thinking (Howell 1999).

Process waste in this regard is anything in addition to the minimum requirement for a business operation to function, i.e., the minimum amount of equipment, materials, and manpower vital to production. Previous studies suggest that there are five major aspects of minimization: material, investment, inventory, space, and people (Wilson 2010). Process waste can be classified into seven categories as summarised in Table 2 (Melton 2005, Wahab *et al.* 2013, Nikakhtar *et al.* 2015). However, some researchers (e.g. Wahab *et al.* 2013) have argued that there should be additional waste relating to people's ability not being fully utilized: thus, leading to an additional category of "unused or underused talent" as explained in Table 2. Process waste can also be classified according to (i) waste generated from non-value-adding activities (NVA), and (ii) unavoidable waste generated due to the nature of the work, e.g., indirect work (Koskela 1992, Nikakhtar *et al.* 2015). The latter is unavoidable due to product quality, health and safety, or specific customer requirements. Thus, they are necessary non-value-adding activities (NNVA). For an activity carried out in a process to be considered value-adding (VA), three criteria must be fulfilled: (i) it must physically transform the product a step further, (ii) the customer must be willing to pay for the change, and (iii) it must be correctly carried out with no need for rework (Wilson 2010).

Table 2: Different types of process waste in manufacturing processes

Type	Description	Example of cause
Overproduction (OP)	Production of excess product thus leading to other types of waste such as the need to store, transport, inventory and rework on the waste.	• Result of making products too early. • Products that cannot be sold due to defects. • Imbalanced production process
Waiting (W)	Workers being ideal for whatever reasons either in the short or long term not adding value to the customer.	• Short-term waiting as a result of an unbalanced line • Long-term waiting for results from this, such as waiting due to machine failure. • Intermediate product waiting for processing.

		• Large amount of work in progress (WIP) inventory
Transportation (T)	Moving parts around between processing steps, production lines and shipping products to the end consumers.	• Moving pallets of intermediate products within the factory or between/to site • Movement of materials continuously before final destination
Over-processing (P)	Processes/steps in product development beyond the needs of customers.	• Over specification • Overdesign • Iterative design • Poor and inefficient processing equipment
Movement (M)	Unnecessary and non-value-adding movement of people. Active workers looking busy does not equate to adding value to a product or process.	• Looking for tools or materials • Inefficient workstation design
Inventory (I)	Intermediate storage of products, raw materials, equipment, tools, etc.	• Queued batches of materials waiting to be used. • Warehouse/site inventory not translating to sales
Defect (D)	Producing defective work requiring additional work or generating scrap leading to a waste of material, manpower and machine processing time and overall a loss of production unit.	• Error in design • Error in processing • Miscommunication • Omission
Un/Under used Talent (UT)	More people involved in the job than necessary and not leveraging the potential of workers to the optimum.	• Uneven work distribution • Unchallenged employees • Wrong staff to task • Wasteful admin task

There is considerable research pertaining to quantifying the process waste involved in various traditional onsite construction activities. For instance, Lee *et al.* (2012) analyzed the waste involved in an onsite steel erection process for a university building, recording 56.93% NVA activities. Mossman (2009) also reported 56-65% NVA, 30-35% NNVA and only 5-10% value-adding (VA) activities in the traditional construction process. Similarly, Forsberg and Saukkoriipi (2007) found the average time spent by workers on productive activities in the traditional construction method to be only 30% of the overall construction time. This form of quantification has not been well addressed for the various OSM methods. A recent study by Zhang *et al.* (2020) concluded that the lead time is reduced by 20% from the factory 'stick-built' method of OSM with the introduction of semi-automation in the production line. However, few published studies have analyzed process wastes in the OSM production workflow, particularly between the various OSM methods.

Evaluation tools for lean manufacturing and process modeling

The need to analyze process waste necessitates an evaluation of the techniques available in practice. There are various tools and techniques used in supporting lean manufacturing. Lean tools can be focused on various aspects, such as waste, inventory, quantity, quality, people, and process controls. However, techniques with objectives of identifying or eliminating process wastes or non-value-adding activities – including value system analysis (VSA) and the *5whys* method (Murugaiah *et al.* 2010) – are used for analyzing processes and identifying sources of waste located throughout the process and are the focus in this study. In order to visualize a process, business process modeling (BPM) tools are used as a means of systematically describing the activities in a process, such as their relationships and information flow: it helps to understand the best way to perform a task by describing its operational performance that produces an output (Nurcan *et al.* 2005).

There are various tools developed for modeling business processes that focus on one or a combination of aspects, such as functional, information, organization, or behavioral aspects in a process. Business Process Mapping Notation (BPMN) is an advanced language due to its more advanced explanatory power. BPMN is clearer and is easier to understand by non-experts since it is similar to a flow chart. There are also industry-specific tools used in manufacturing, e.g., Value Stream Mapping (VSM) as an approach to modeling materials and information flow in a production process as the product makes its way through the value stream (Sundar *et al.* 2014). BPMN is used in this study and some concepts from VSM, such as waste and cycle time, are included in the process model for analysis.

Research method

The study requires an in-depth analysis of processes, which is heavily data reliant. The presence of data silos, typically existing in the context of construction businesses, creates complexity in the modeling processes. Hence, a case study research method is chosen as it is known for its strength in allowing for a holistic in-depth exploration of a subject in its real-life context (Yin 2009). There are two types of case study design: multiple and single case study designs. A single case study involves the use of only one case, while a multiple case study involves a combination of two or more cases that are used to build a theory about a phenomenon (Yin 2016). For this study, a single case study design has been selected to conduct the exploratory research required – the standpoint being that the single case study approach is better for creating high-quality theory, and better when the aim is to shed light on a single setting (Yin 2009).

Data collection and strategy

Understanding a business organization and its operation is challenging as the researchers are detached from the business operation. This is overcome through an exploratory study investigating the production processes closely over a period by first observing the AS-IS process and then with the design and implementation of the TO-BE process. An iterative data collection process is followed, with the use of a wide range of data including observations, information from internal and published documents, interviews with key OSM experts within the case company, and consolidated opinions from focus groups. The purpose of the case is revelatory (Schell 1992), with an embedded single-case research design containing two units of analysis − the production processes of static and semi-automated linear OSM production methods − in order to obtain rich content in place of the breath that can be obtained in multiple case design (Sarvimaki 2017). The static method workflow is the AS-IS model (i.e., actual production workflow), while the semi-automated linear method is the TO-BE model (i.e., optimized production model). Figure 1 shows the combination of methods used for data collection and synthesis at different stages of the study.

The initial data collection process featured different approaches, starting from a review of technical documents that include the production flow diagram, station design, building design, and organization structure. Also identified is the key information required for analyzing process wastes on the activities performed including their sequences, together with data that could not be collected from documents, i.e., the primary data required for the analysis. For instance, questions were set to identify the quantifiable aspects of each activity, such as delays and waiting, as they cannot be captured directly in the documents. The primary data were then collected through interviews with key experts and observation of production in the factory. The output from this stage is used to develop an initial process model based on the activities performed on the shop floor, and to sketch the shop floor arrangement of production space. BPMN notations and protocols are used to represent the processes.

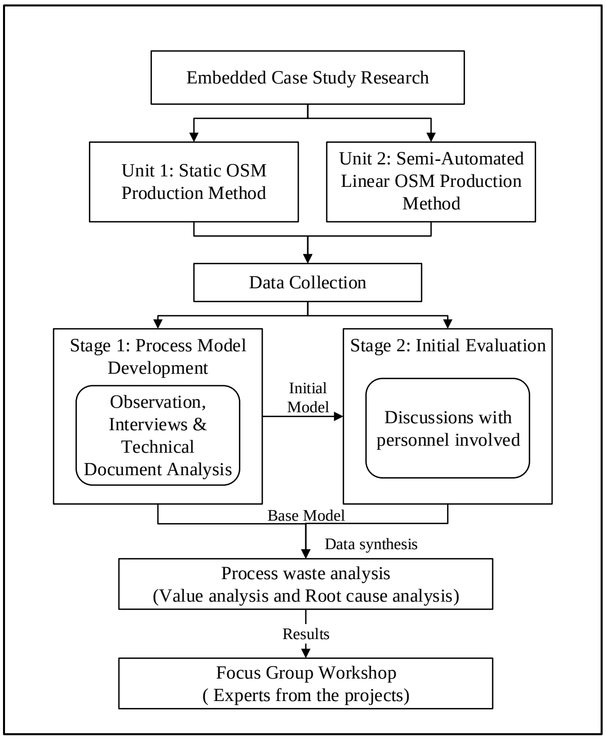


Fig. 1. Research Design

An evaluation of the initial process map was then organized with the parties involved to enable assessment of the model and ensure accurate representation of the activities, sequences, and resource requirements involved. The output from this stage (Stage 1 in Figure 1) provides a base model for analyzing the process waste. The identified lean tools from the review are used for value analysis and waste identification in the process according to the eight categories of process waste: this was used to categorize the activities into VA, NVA, and NNVA, respectively. Finally, a focus group comprising key experts of the existing production (such as the production manager, director for the project, and the commercial manager) was formed to identify the root causes of the waste using the *5Whys* lean tool for root cause (RC) analysis − a questioning method that identifies the root cause through asking the question, 'Why does the issue exist?'.

Case study – Panelised system OSM of light steel frame buildings

The case study is based on one of the largest housing associations located in the UK's West Midlands region (hereafter named HAX). HAX procures social housing using the traditional method through contracting. It has recently recognized the potential for integrating house delivery within the business after internal market research. The business decided to consider OSM as a major delivery approach to align with the new funding body's requirements and the national strategy to adopt Modern Methods of Construction (MMC) as well as to help meet the increased housing delivery target, i.e., 60% increase of the number of houses delivered per annum. A consortium was formed with a steel manufacturer, an architect production engineer, and a university to develop OSM house products.

While there is a need to determine a suitable OSM method to achieve the set objectives, this data is not readily available. During the 2-year study period, HAX used the static method of production for a house prototype to analyze the suitability of the method and the cost involved. Concurrently, an OSM scheme was developed for the production of panels forming the building frame and envelop of the houses using a semi-automated linear method. The semi-automated linear method in the case study is based on a scheme developed by the production engineer. The scheme incorporates the simulations based on actual production information and detailed workflow incorporating automated stages of sub-assemblies. For instance, the data for the time cycle study is derived from industry-known values for discrete activities. Operator times are based around MTM (Methods-time Measurement) standards while the transfer times are based upon conveyor speeds of 10 meters per min and screw insertion times are based upon trials carried out in previous applications for similar product production. The time cycle study was run with a full sized layout as per the proposed placement of the loading bay and the guarding, buffer station and pallet positions. The cycle time simulation was carried out using the engineer's company template that aggregates the cycle time taking into account the overlapped activities in the production process.

The workflows for wall panel production were chosen for a like-to-like comparison between the two methods. Lean manufacturing theory relating to the eight categories of process wastes is applied to analyze the constraints of the two methods and the waste involved to quantify the improvement in the TO-BE method and provide recommendations for CI.

Modeling and implementation

Static method OSM production process activities

The static production process of wall panel production as done in a HAX factory is used as a reference for the process modeling: this is an actual (AS-IS) workflow intended to be compared with the simulated workflow. For wall panel production, the key stages are to: 1) assemble the steel frame for wall panels, 2) install the cladding on steel frames, and 3) apply finishes on the cladded steel frames. In the static system, the production is done in silos. Various team members and trade specialists where needed are required to move from one station to another to render services on the panels. The station is arranged such that a team is working on a one-panel type/design while the processes within these stations follow no particular sequence. Also, there is no defined flow of materials or unfinished products between the various stations (see Figure 2) and stations sometimes have an individual production plan. Figure 3 illustrates the BPMN process map representing the activities in the static process (one of the stations, as the activities are the same and are repeated for each station), which is a typical push system of manufacturing.

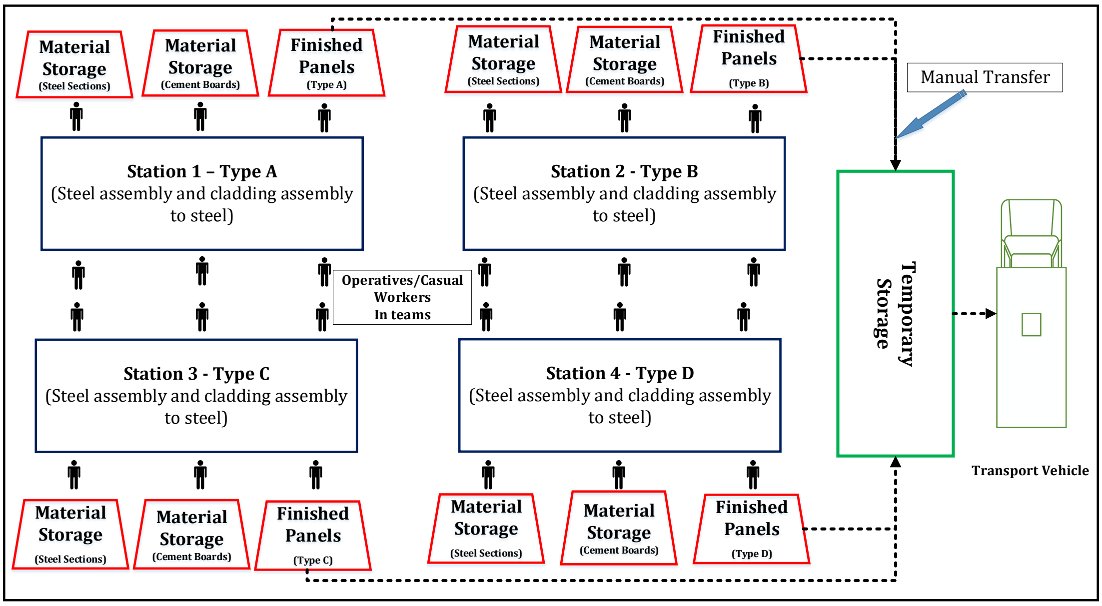


Fig. 2. Static Production Arrangement

The overall cycle time involved in a manufacturing process consists of (i) process time (relating to working directly on a product), (ii) waiting time (activities that involve waiting), (iii) loading time (relating to moving materials, partially completed products or completed products) and (iv) inspection time (relating to quality or health and safety). The activities as identified in the process map are classified into three types: value-adding (VA), non-value-adding (NVA), and necessary non-value-adding (NNVA). For the analysis, the VA activities are activities with a process time, NVA activities involve a waiting and loading time, while NNVAs are activities involving an inspection time.

However, the challenge with manual production is that the identified VA activities carried out by operatives may also include some idle time and it is difficult to identify or quantify the embedded waste involved. Hence, some of these may have been missed in the evaluation, which is a limitation. The eight process waste categories are used to identify the NVA and NNVA activities in the process and are denoted in Table 3.

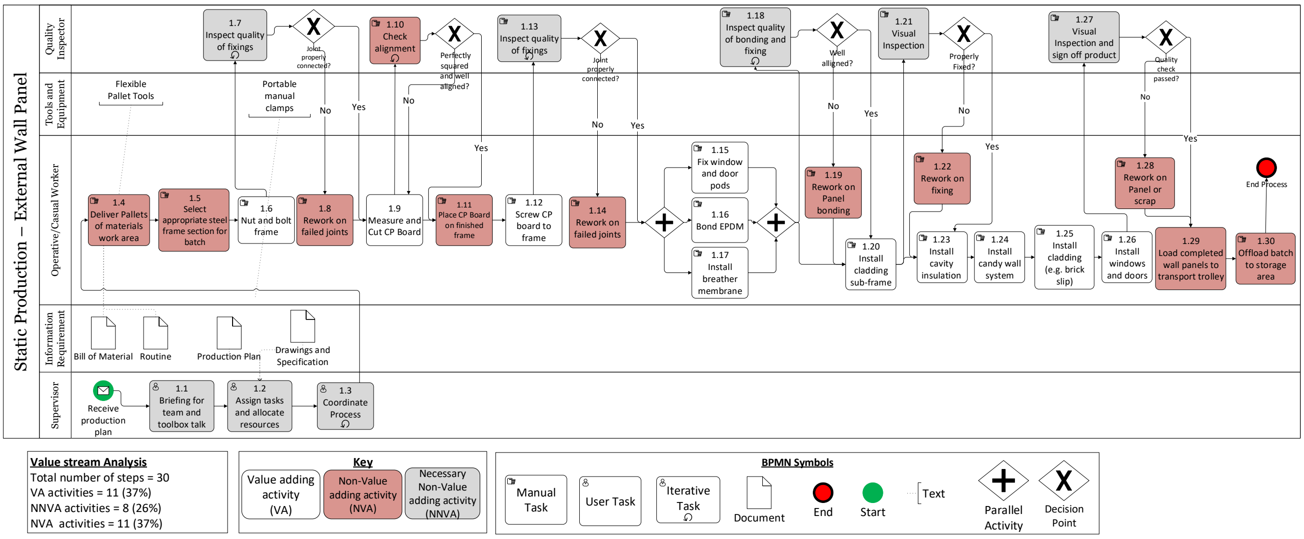


Fig. 3. Production process model for wall panel construction using static method.

The cycle time for each activity is modeled using the average time it takes to complete a unit of an offsite product of cladded wall panel for house construction. For each station, the work for a batch is completed by a team of 5 workers: 3 fixers (one is a senior fixer also acting as a supervisor), 1 casual worker, and 1 quality inspector. The activities performed can be categorized into different levels for the purpose of the cycle time estimation, unit or batch level activities. A unit-level activity is required to be carried out on each product while a batch-level activity is performed on a batch of products and the time taken to complete the activity is distributed equally to each unit. Activities 1.1 to 1.5, 1.29, and 1.30 are batch-level activities and the cycle time will be shared by all products from the batch. Other activities are to be performed on every unit of the product; hence, the cycle time recorded in Table 4 is the time taken to complete the activity for each wall panel. Based on observations of the process, the static method has a 15-20% chance of rework due to minor errors or deviations in the drawings and specifications requirements. That is, for every 10 panels built, there is a chance of additional rectification work being needed on at least 2 panels. Therefore, this assumption is considered when recording the cycle time for rework activities.

Table 3: Process waste analysis in static production method

Production Station			**Lean Waste Aspects**								**Time (min)**			
Activity Code	**Activity**	**Type**	**OP**	**W**	**T**	**P**	**M**	**I**	**D**	**UT**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA**
1.1	Team briefing	NNVA									1	-	-	1
1.2	Resource allocation	NNVA									1	-	-	1
1.3	Process coordination	NNVA									-	-	-	-
1.4	Material delivery	NVA		x	x		x				5	-	5	-
1.5	Choosing suitable steel profile sections	NVA		x				x			5	-	5	-
1.6	Nut and bolt frame	VA									60	45	15	-
1.7	Quality inspection	NNVA									10	-	5	5
1.8	Rework on frames	NVA		x					x		15	-	15	-
1.9	Measuring and cutting cement plasterboard	NVA	x								45	-	45	-
1.10	Check alignment	NVA	x								2	-	2	-
1.11	Load CP board on frame	NVA					x				10	-	10	-
1.12	Screw board to frame	VA									40	20	20	-
1.13	Quality inspection on fixings	NNVA		x		x					10	-	5	5
1.14	Rework on failed joints	NVA							x		15	-	15	-
1.15	Fix window and door pods	VA									40	20	20	-
1.16	Bond EPDM	VA									40	20	20	-
1.17	Install breather membrane	VA									20	15	5	-
1.18	Visual inspection on bonding	NNVA									5	-	-	5
1.19	Rework on bonding	NVA							x		5	-	5	-
1.20	Install cladding sub-frame	VA									120	60	60	-
1.21	Visual inspection on sub-frame fixing	NNVA									5	-	-	5
1.22	Rework	NVA							x		5	-	5	-
1.23	Install cavity insulation	VA									30	20	10	-
1.24	Install candy wall system (backing board)	VA									60	45	15	-
1.25	Install cladding–brick-slip system	VA									60	45	15	-
1.26	Install window and door	VA									80	60	20	-
1.27	Quality inspection and sign off	NNVA		x							5	-	-	5
1.28	Rework on defect or scrap	NVA							x		5	-	5	-
1.29	Load finished panels to transport trolley	NVA					x				5	-	5	-
1.30	Load to storage area	NVA	x					x			5	-	5	-
										Total Time (Min)	709	350	332	27
										Total Time (%)	100	49	47	4

Semi-automated linear method OSM production process activities

In the semi-automated linear method of wall panel production which is based on simulated results as an alternative to the static method, some of the root causes of constraints in the static method are addressed. This method comprises two automated lines for frame and cladding assembly with the use of automated machines and various robotic arms (see Figure 4).

Compared to the static method, production is in an assembly line with dedicated stations that allow synchronous flow. Each station has dedicated production team members. Partially completed units are moved in various dedicated interconnected stages. The units are moved on a conveyor belt and the completed units are picked up by fork-lift trucks to be stored or loaded on transport vehicles. The batch manufacturing method is used, which is a push system. Figure 5 illustrates the BPMN process map representing the activities in the semi-automated linear process of wall panel production.

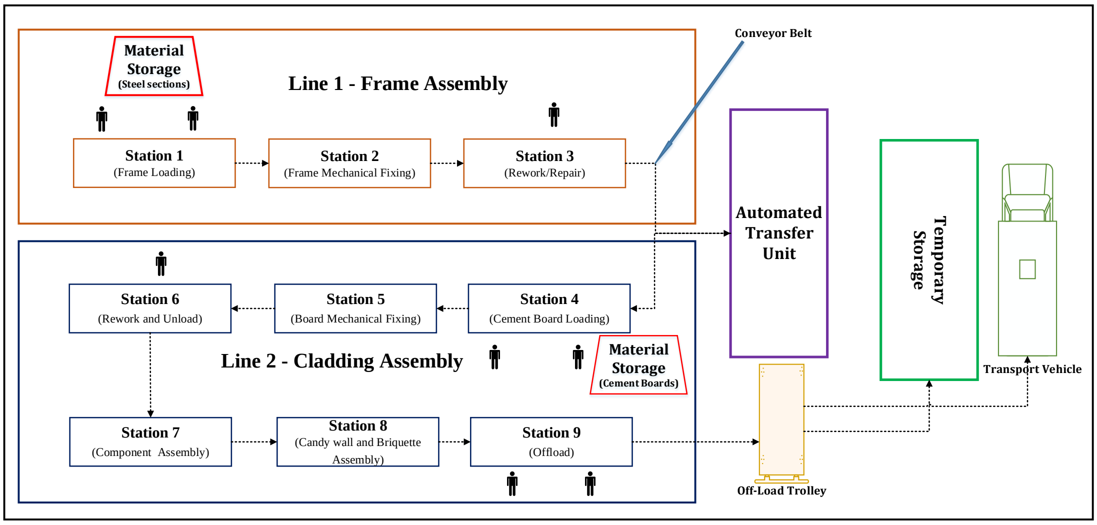


Fig. 4. Semi-automated linear production arrangement

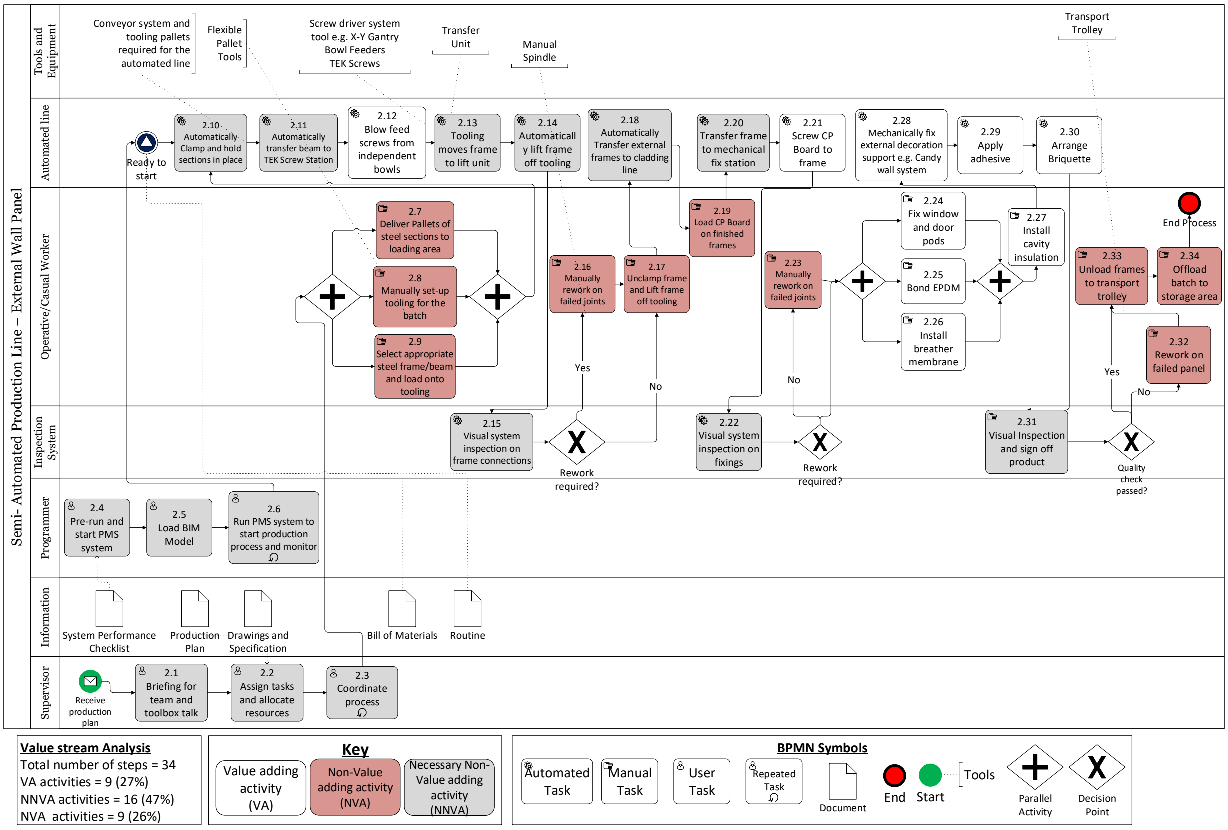


Fig. 5. Production process model for wall panel construction using semi-automated method.

Similar to the method used in analyzing the static process, the cycle time for each activity in the batch manufacturing line is modeled for the new production line using the estimated maximum process time for each activity in every station (Table 4). With this method, the time and waste predictions are based on the production engineers' estimates using the simulated production model according to the workflow arrangement and estimated time of product movement through different stages. The activities contained in the process are also categorized as either unit or batch level activities similar to the static method. In this case, activities 2.1 to 2.9, then 2.33 and 2.34 are batch-level activities, while others are unit-level activities: hence, the cycle time is shared by the number of units of wall panels produced for the batch.

Table 4: Waste analysis in semi-automated production method

Production Line			**Waste Aspects**								**Time (min)**			
Activity Code	**Activity**	**Type**	**OP**	**W**	**T**	**P**	**M**	**I**	**D**	**UT**	**Cycle time (CT)**	**VA Time**	**NVA Time**	**NNVA Time**

2.1	Team briefing	NNVA									1	-	-	1
2.2	Resource allocation	NNVA									1	-	-	1
2.3	Process coordination	NNVA									-	-	-	-
2.4	Pre-run PMS system	NNVA									2	-	-	2
2.5	Load BIM model	NNVA									2	-	-	2
2.6	Monitor system	NNVA									5	-	-	5
2.7	Material delivery	NVA		x	x		x				5	-	5	-
2.8	Tool set-up for batch	NVA		x							2	-	2	-
2.9	Choosing suitable steel profile sections	NVA		x							5	-	5	-
2.10	Clamp section in place	NNVA									0.5	-	-	0.5
2.11	Transfer to screw station	NNVA									0.5	-	-	0.5
2.12	Screw frame on both side	VA									6.78	6.78	-	-
2.13	Tooling return	NNVA									0.5	-	-	0.5
2.14	Lift frame off tooling	NNVA									1	-	-	1
2.15	Visual inspection by system	NNVA									1	-	-	1
2.16	Rework on failed joints	NVA							x		5	-	5	-
2.17	Unload frame from tooling	NNVA		x							2	-	2	-
2.18	Transfer frame to cladding line	NNVA									0.5	-	-	0.5
2.19	Load CP board	NVA		x							5	-	5	-
2.20	Transfer frame for mechanical fixing	NNVA									0.5	-	0.5	-
2.21	Screw CP board to frame	VA									6.78	6.78	-	-
2.22	Visual inspection by system	NNVA									1	1	-	-
2.23	Rework on failed joints	NVA								x	5	-	5	-
2.24	Fix window and door pod	VA									40	35	5	-
2.25	Bond EPDM	VA									20	20	-	-
2.26	Install breather membrane	VA									20	15	5	-
2.27	Install cavity insulation	VA									20	20	-	-
2.28	Fix external decoration support	VA									6.78	6.78	-	-
2.29	Apply adhesive	VA									5	5	-	-
2.30	Arrange briquette	VA									10	10	-	-
2.31	Visual inspection and sign off product	NNVA									5	-	-	5
2.32	Rework on failed panel	NVA								x	5	-	5	-
2.33	Unload frames to trolley	NVA				x	x				5	-	5	-
2.34	Offload batch to storage area	NVA				x					5	-	5	-
										Total Time (Min)	201	126	54	21
										Total Time (%)	100	63	27	10

Discussion

The process analysis of the two methods of OSM production revealed some data on the differences in the units of analysis. A summary of the results of the comparison of both OSM methods is provided in Figures 6 and 7. Based on Figure 3, for the static method, the total number of activities required to produce a unit of wall panel is 30, with 37% of these activities being non-value-adding (NVA). In contrast, the semi-automated method automates some of the key activities and introduces additional steps to enable a structured workflow. This method contains 34 activities in total, of which 26% are non-value-adding activities (NVA) since some human intervention is eliminated, which is an approximately 30% decrease in NVA activities compared to the static method (Figure 6).

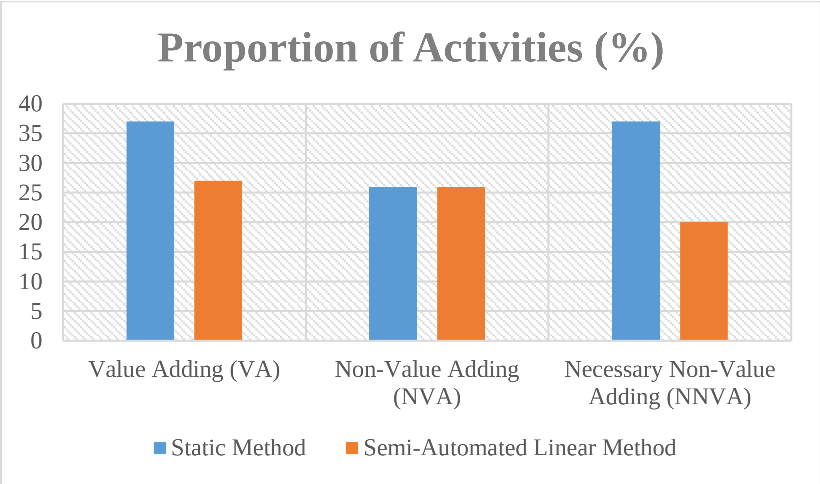


Fig. 6. Comparison of proportion of activities performed for wall panel production.

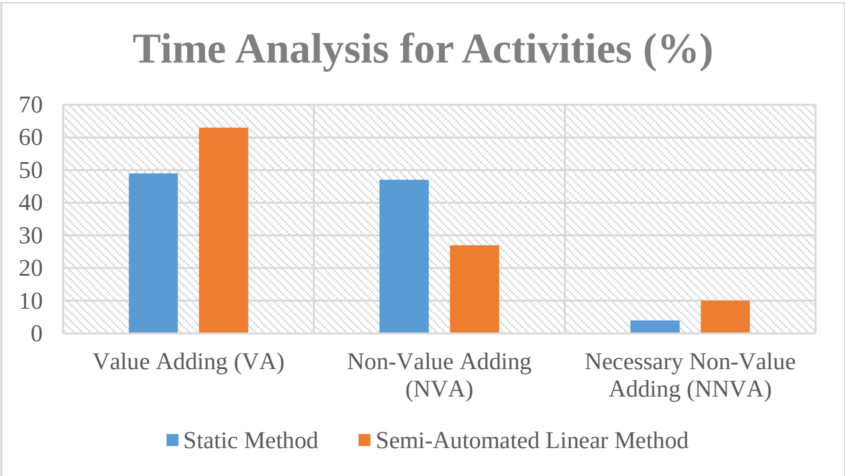


Fig. 7. Comparison of time taken for activities performed for wall panel production.

In terms of process time analysis, only 49% of the actual time spent in the production workflow is value-adding time in the static method (Figure 7), which is at a similar rate to the onsite methods reported in past literature, i.e., up to 50% non-value-added activities (Liu *et al.* 2011, Nikakhtar *et al.* 2015). This implies that there is little improvement to the static method of production in terms of reduced process waste, which supports the criticism by Zhang *et al.* (2020) that some factory house building methods simply replicate onsite construction inefficiencies. In contrast, in the semi-automated method, the use of robotic arms for the fabrication of the steel frame for wall panels significantly reduces the time required to manually assemble steel members. Therefore, the semi-automated method reported improved productivity with the VA time of 63% compared to 49% in the static method, which is an increase of approximately 29% in the VA time. Also, it takes 201 minutes of overall lead time (total time required from the first to the last workstation) to produce a single unit wall panel in the semi-automated method, with 126 minutes of value-added time (actual process time). In contrast, the static method takes 709 minutes based on the workflow to complete the processing of a unit wall panel, with only 350 minutes of value-added time. This implies that the semi-automated method provides a 70% reduction in the lead time from the static method, which is significantly greater than the 20% reported by Zhang *et al.* (2020). The variance can be explained as a result of the production line design, workflow arrangement and level of automation involved, as no two manufacturers incorporate the exact same process since the manufacturing environment offers different options for producing the same product.

Upon further analysis of the root cause (RC) of the waste generated with the static method, some constraints in the processes are revealed as detailed in Table 5. In terms of process waste resulting from waiting (W) and movement (M), factory/workstation arrangement and inefficient process flow were reported as the RC of the issues in the static method of production. The *ad-hoc* nature of activities led to a non-guaranteed cycle time for each activity, as no standardized sequence was adopted. Although activities relating to Quality Inspection (QI) are classified as NNVA, QI is major source of delay in the static method due to operatives waiting for inspections to be completed in order to move to the next step. Although QI is highly important for avoiding scrapping finished panels due to defects, it is observed that this causes over-processing waste (P) because of the excessive number of intermediate inspections incorporated in the process which, as seen in the semi-automated method, could be reduced with better efficiency enabled with the help of automation. For instance, the use of a manufacturing line with dedicated stages improves the workstation arrangement and flow as a result. A visual inspection system displaying the position of fault screws was included in the semi-automated method manufacturing line, which enables the operators stationed in the rework station to quickly rectify faults. This system was introduced after the analysis of the RC in the static method and results in the elimination of some waste relating to waiting and movement in the static method.

Another major waste in the static method is due to the frequent rework required in the process, where the chances of process waste due to defects, thus resulting in rework, is around 15-20%. In contrast, the need for rework is projected to be below 5% with the semi-automated method due to the efficiency of the robotic arm used for key activities (e.g., screwing and fixing) that are prone to error. The 5% rework is mainly due to some value-adding manual activities e.g., bonding the breather membrane.

Table 5: Root cause (RC) analysis for static production method NVA activities

Production Line		Waste	Issue/ Symptom	5Whys of lean				
Activity Code	**Activity**			Why 1	Why 2	Why 3	Why 4	*Why 5 (RC)*
1.4	Material delivery	Waiting	Operatives waiting for stock on production line.	Needs to be moved from store to production area	Inventory checks need to be carried out	Process too slow, causing impact on production flow	Variable task duration	*Inefficient process flow design*
		Movement and transportation	Moving and transporting materials from store to production area	Moving materials from storage	Storage not close to production line	Space management	Factory arrangement	*Inefficient factory arrangement*
1.5	Choosing suitable steel profile sections	Waiting	Operatives sorting appropriate frames from material batch	Variable task duration	Non-balanced line	Non-balanced flow	Ill-designed space to pick and store frames	*Inefficient workstation*
		Inventory	Batches of materials waiting to be processed	Inventory needs to be completed	To ensure correct materials are being chosen	Ensure specifications are being followed	Correct drawings in place	*Problem from the push production method*
1.8	Rework on frames	Waiting	Waiting for quality inspection to be completed, which slows down following process	Not enough QI inspectors to meet production flow	Bottleneck in production flow	Bottleneck in production flow	Trades not being used to full capacity during shifts	*Lack of investment in automated inspection systems*
		Defect	Frame joints not properly connected	Human error from operatives such as omission	Delay in target which causes work to be rushed	Time constraints to meet customer demands	Delay and waiting in the process, such as stage sign off by Q1	*Inefficient flow of production with many delays*
1.9	Measuring and cutting CP Board	Over-processing	Extra processing on cement board before being used.	Cement board not pre-cut	Process is slow due to dust generation	Process not automated for machine cut	Process not automated for machine cut	*Process not automated for machine cut*

				from supplier				
1.10	Check alignment	Over-processing	Too many quality checks that could be avoided	Human error from operatives	Inexperienced trades carrying out the works	Re-skilling of workforce not adequately invested in	Lack of investment in people and skills training	*Lack of investment in people and skills training*
		Waiting	Operatives having to wait for checks to be completed to execute next process	QI inspection process too slow	Quality inspector working on other jobs	Operatives not skilled to self-check	Lack of investment in automated inspection systems	*Lack of investment in automated inspection systems*
1.11	Load cement board on frame	Movement	Operatives moving from material storage to line.	Fork-lift truck not available	Not enough CAPEX invested for more than one fork-lift truck	Not forecasted correctly with new orders	Lack of understanding of supply & demand	*Lack of understanding of supply & demand*
1.14	Rework on joints	Defect	Wall joints not properly connected	Rushed work and quality of installation inadequate	Too much of a backlog	Work shifts not planned correctly	Work not planned correctly	*Inefficient process flow design*
1.19	Rework on joints	Defect	EPDM and window joints not properly fixed	Rushed and quality of installation inadequate	Too much of a backlog with too many defects	Not enough skilled workforce	Lack of investment in people and skills training	*Lack of investment in people and skills training*
1.22	Rework on sub frame	Defect	Sub-frame not properly fixed	Too many mistakes in joint fixings	Rushed work and quality of installation inadequate	Too much of a backlog	Work shifts not planned correctly	*Inefficient process flow design*
1.28	Final rework on defect wall	Defect	Panel did not pass quality checklist	Rushed work and quality of installation inadequate	Sequencing broken down due to too many defects in previous panels	Too much of a backlog with too many defects	Not enough skilled workforce	*Lack of investment in people and skills training*
1.29	Load finished panels to transport trolley	Movement	The need to move completed batch from work area	Movement of workers in the factory	Large amount of work in progress (WIP)	Overproduction	Overproduction	*Overproduction*
1.30	Transport and load finished panels to storage	Transportation	Movement of finished panels to storage area because not ready to deliver to site	Not due to arrive onsite	Overproduction	Push manufacturing system	Push manufacturing system	*Push manufacturing system*

Nonetheless, although the semi-automated method helped eliminate some of the process waste in the static method, some process waste relating to inventory (I) is similar in both methods due to the batch production system adopted. This method of production causes inventory to build up: thus a storage area is needed in the factory to stack the work-in-progress (WIP) panels until they are ready to be moved to the site – resulting in an additional estimated waiting time of between 4-5 days in the static method. This would consequently result in an added cost for a single unit of the product and perhaps increase the cost of offsite production. There is a need to consider and implement other lean practices targeted at preventing waste due to inventory in the manufacturing process to increase the competitiveness of OSM houses as compared to houses built onsite.

Conclusion

The case study presents a systematic analysis of two offsite house building methods using two lean tools of value system analysis and RC analysis. The efficiency of the production process of a wall panel in terms of the eight process waste types is analyzed. The result from the study reveals that up to 47% NVA time is spent in the production process in the static method involving non-structured workflow, and a potential to reduce this to 27% with the semi-automated method of production. From the case analyzed, it is revealed that the overall lead time taken to produce a unit wall panel (in the static method) can be reduced to up to 70% with a more structured workflow and the automation of critical activities in the process (using the semi-automated method). It is concluded, therefore, that the static method may not provide significant improvement in process waste when compared to the onsite production method based on the quantification results from previous studies. Similar unstructured processes are used in both methods, leading to the repetition of such constraints with the onsite method in factory production as wastes relating to waiting, movements, and defects. Thus, moving construction to a factory environment does not necessarily provide the leanness desired, unless approaches to lean manufacturing are incorporated (such as a structured workflow flow, repetition, and automation).

This study is based on a case study of a specific production line design and workflow, only an analytical generalization (Hyde 2000) can be achieved, e.g. based on the degree of similarity between the two similar contexts, such as offsite manufactured products with similar production to the steel framed panel in this case. In addition, while the study is based on only one OSM system, i.e., a panelized system, similar processes and constraints are likely to be present in other OSM systems such as volumetric or hybrid methods.

The study presents quantitative evidence of the performance of structured and non-structured OSM methods in terms of eliminating process waste. The implication of the result is the need for offsite manufacturers to take a process view of their production approach, recognizing the impact of automating critical activities and the importance of incorporating structured workflow and repetition to support mass customization. This paper also documents a simple approach that can be adapted to analyze other production methods and OSM processes to support decision-making relating to the choice of OSM methods.

Data Availability Statement

The data used in this study to support the findings such as the production line design, simulated production line process data and the wall panel design were provided by third parties and the industry partners working on innovate UK funded project No. 104798 and are confidential in nature. The data may only be provided with restrictions.

Acknowledgment

This research was supported by an Innovate UK funded project (Project no.104798) "Collaborative Knowledge-Based DfMA approach to building cost-efficient, low impact, and high-performance houses". Many thanks are due to the participating industrial partners of the research project, particularly Mr. Paul Nicol and Mr. Tim O'Shea of the WHG group, Mr. Ben Towe of the Hadley Group, Mr. Jason Glasse of QM systems, and Mr. Ged Connor of Northmill Architects for their contribution in this study.

References

AAQS, 2016. *Guide to Elemental Cost Estimating & Analysis for Building Works 2016*. Second.

Abanda, F.H., Tah, J.H.M., and Cheung, F.K.T., 2017. BIM in off-site manufacturing for buildings. *Journal of Building Engineering*, 14 (September), 89–102.

Abanda, F.H., Taj, J.H.M., Pettang, C., and Manjia, M.B., 2011. An ontology-driven building construction labour cost estimation in Cameroon. *Journal of Information Technology in Construction (ITcon)*, 16, 617–634.

Abdullah, M.. and Egbu, C.., 2010. Selection criteria frameword for choosing industrialized building systems for housing projects. *In*: C. Egbu, ed. *Procs 26th Annual ARCOM Conference, 6-8 September 2010*. Leeds: Association of Researchers in Construction Management.

Abdullah, M.R. and Egbu, C.O., 2009. *Industrialised building system in Malaysia: Issues for research in a changing financial and property market*. Proceedings of the BUHU 9th International Post Graduate Research Conference.

Abdulmalek, F.A. and Rajgopal, J., 2007. Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of Production Economics*, 107 (1), 223–236.

Abosoad, H., Underwood, J., and Boreny, S., 2009. Towards an Information System Representation of off Site Manufacturing (OSM) in Facilitating the Virtual Prototyping of Housing Design. *In*: *9th International Postgraduate Research Conference (IPGRC)', University of Salford, Salford, UK*. 509–520.

Adamides, E.D. and Karacapilidis, N., 2006. A knowledge centred framework for collaborative business process modelling. *Business Process Management Journal*, 12 (5), 557–575.

Adeli, H. and Wu, M., 1998. Regularization neural network for construction cost estimation. *Journal of Construction Engineering and Management*, 124 (1), 18–23.

Afsari, K. and Eastman, C.M., 2016. A Comparison of Construction Classification Systems Used for Classifying Building Product Models. *In*: *52nd ASC Annual International Conference Proceedings*. Associated Schools of Construction.

Aguilar-Savén, R.S., 2004. Business process modelling: Review and framework. *International Journal of Production Economics*, 90 (2), 129–149.

Ahmed, V., Opoku, A., and Aziz, Z., 2016. *Research Methodology in the Built Environment: A selection of case studies*. New York: Routledge.

Akasah, Z.A., Amirudin, R., and Alias, M., 2010. Maintenance management process model for school buildings: An application of IDEF 0 modelling methodology . *Australian Journal of Civil Engineering*, 8 (1), 1–12.

Akintoye, A. and Fitzgerald, E., 2000. A survey of current cost estimating practices in the UK A. *Construction Management & Economics*, 18, 161–172.

Akyol, D.E., Tuncel, G., and Bayhan, G.M., 2007. An Analysis of Activity-Based Costing in a Manufacturing System. *International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering*, 1 (11), 1040–1043.

Aldridge, G., Pasquire, C., Gibb, A., and Blismas, N., 2001. Methods for Measuring the "Unmeasurable": Evaluating the Benefits of Pre-Assembly and Standardization in Construction. *In*: *17th Annual ARCOM Conference, 5-7 September 2001, University of Salford. Association of Researchers in Construction Management*. 311–9.

Almeida, A. and Cunha, J., 2017. The implementation of an Activity-Based Costing (ABC) system in a manufacturing company. *Procedia Manufacturing*, 13, 932–939.

Alonso, R., Borras, M., Koppelaar, R.H.E.M., Lodigiani, A., Loscos, E., and Yöntem, E., 2019. SPHERE: BIM Digital Twin Platform. *Proceedings*, 20 (1), 9.

Arafa, M. and Alqedra, M., 2011. Early Stage Cost Estimation of Building Construction Projects using Artificial Neural Networks. *Journal of Artificial Intelligence*, 4 (1), 63–75.

Arbizzani, E. and Civiero, P., 2013. Technical solutions and industrialised construction systems for advanced sustainable buildings. *In*: *PORTUGAL SB13 - CONTRIBUTION OF SUSTAINABLE BUILDING TO MEET EU 20-20-20 TARGETS*. 371–378.

Arditi, D. and Mochtar, K., 2000. Trends in productivity improvement in the US construction industry. *Construction Management & Economics*, 18 (1), 15–27.

Arif, M. and Egbu, C., 2010. Making a case for offsite construction in Making a case for offsite construction in China. *Engineering Construction & Architectural Management*, 17 (6), 536–548.

Assaf, S.A. and Al-Hejji, S., 2006. Causes of delay in large construction projects. *International Journal of Project Management*, 24, 349–357.

Awuzie, B. and McDermott, P., 2017. An abductive approach to qualitative built environment research: A viable system methodological exposé. *Qualitative Research Journal*, 17 (4), 356–372.

Ayachit, A.C., Attarde, P.M., and Kulkarni, S., 2014. Activity Based Costing in Construction. *International Journal of Advanced Engineering Research and Studies*, 4 (1), 9–14.

Ayinla, K.O., Cheung, F., and Tawil, A.R., 2019. Demystifying the concept of offsite manufacturing method: Towards a robust definition and classification system. *Construction Innovation*, 20 (2), 223–246.

Badir, Y.F., Kadir, M.R.A., and Hashim, A.H., 2002. Industrialized Building Systems Construction in Malaysia. *Journal of Architectural Engineering*, 8 (1).

Baghchesaraei, A., Kaptan, M.V., and Baghchesaraei, O.R., 2015. Using prefabrication systems in building construction. *International Journal of Applied Engineering Research*, 10 (24), 44258–44262.

Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., and Wong, I., 2006. Designing out waste in high-rise residential buildings : analysis of precasting and methods and traditional construction. *In*: *The International Conference on Asia-European Sustainable Urban*

Development. Chongqing, China.

Baloi, D., 2003. Sustainable construction: Challenges And Opportunities. *In*: *19th Annual ARCOM Conference*. 289–97.

Barber, K.D., Dewhurst, F.W., Burns, R.L.D.H., and Rogers, J.B.B., 2003. Business-process modelling and simulation for manufacturing management: A practical way forward. *Business Process Management Journal*, 9 (4), 527–542.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertran, N., and Brown, S.V., 2017. *Reinventing construction through a productivity revolution*.

Bari, N.A.A., Abdullah, N.A., Yusuff, R., Ismail, N., and Jaapar, A., 2012. Environmental Awareness and Benefits of Industrialized Building Systems (IBS). *Procedia - Social and Behavioral Sciences*, 50 (July), 392–404.

Baxter, P. and Jack, S., 1990. Qualitative case study methodology: study design and implementation for novice researchers. *The Qualitative Report*, 13 (4), 544–559.

Baxter, P. and Jack, S., 2008. Qualitative Case Study Methodology : Study Design and Implementation for Novice Researchers. *The Qualitative Report*, 13 (4), 544–559.

Ben-Arieh, D. and Qian, L., 2003. Activity-based cost management for design and development stage. *International Journal of Production Economics*, 83 (2), 169–183.

Bertelsen, S., 2005. Modularization – a third approach to making construction lean? *In*: *13th annual conference in the International Group for Lean Construction*. Sydney, Australia, 1–11.

Blismas, N., Pasquire, C., and Gibb, A., 2006a. Bene t evaluation for o ff-site production in construction. *Construction Management & Economics*, 24 (2), 121–130.

Blismas, N., Pasquire, C., and Gibb, A., 2006b. Benefit evaluation for off - site production in construction. *Construction Management and Economics*, 24 (2), 121–130.

Blismas, N. and Wakefield, R., 2007. Drivers constraints and the future of off-site manufacture in Australia. *Construction Innovation Special Edition*.

Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y., 2020. Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114 (January), 103179.

Bottom, D., Gann, D., Groak, S., and Meikle, J., 1996. *Innovation in Japanese Prefabricated House-Building Industries: Department of Trade and Industry Overseas Science and Technology Expert Mission Visit Report*. Construction Industry Research and Information Association.

Brockmans, S., Haase, P., Hitzler, P., and Studer, R., 2006. A Metamodel and UML Profile for Rule-extended OWL DL Ontologies. *In*: Y. Sure and J. Domingue, eds. *ESWC 2006*. Berlin Heidelberg: Springer-Verlag, 303–316.

Bryman, A., 2012. *Social Research Methods*. 4th editio. New York: Oxford University Press.

buildingSMART, 2016. IFC4 Add2 - Addendum 2 [online]. *buildingSMART International Ltd*. Available from: http://www.buildingsmart-tech.org/ifc/IFC4/Add2/html/ [Accessed 2 Jan 2019].

Cabinet Office, 2011. *Government Construction Strategy*. London.

Caputo, A.C. and Pelagagge, P.M., 2005. Parametric and Neural Methods for Cost Estimation Of Process Vessels. *In*: *18th International Congress of Mechanical Engineering*.

Carli, G. and Canavari, M., 2013. Introducing Direct Costing and Activity based Costing in a Farm Management System: A Conceptual Model. *Procedia Technology*, 8 (Haicta), 397–

405.

Carr, R.I., 1989. Cost - Estimating Principles. *Journal of Construction Engineering and Management*.

Chan, C.W. and Johnstonb, M., 1996. Knowledge modelling for constructing an expert system to support reforestation decisions. *Knowledge-Based Systems*, 9, 41–59.

Chan, E.H.W. and Tse, R.Y.C., 2003. Cultural Considerations in Cultural Considerations in International Construction Contracts. *Journal of Construction Engineering and Management*, 129 (4), 375–381.

Chau, K.W., 1995. The validity of the triangular distribution assumption in Monte Carlo simulation of construction costs : empirical evidence from Hong Kong. *Construction Management and Economics*, 13 (1), 15–21.

Chau, K.W. and Anson, M., 2002. A Knowledge-Based System for Constr uction Site Level Facilities Layout, 2358, 393–402.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010a. Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction*, 19 (2), 235–244.

Chen, Y., Okudan, G.E., and Riley, D.R., 2010b. Automation in Construction Decision support for construction method selection in concrete buildings : Prefabrication adoption and optimization. *Automation in Construction*, 19, 665–667.

Cheng-Leong, A., Pheng, K.L., and Leng, G.R.K., 1999. IDEF: A comprehensive modelling methodology for the development of manufacturing enterprise systems. *International Journal of Production Research*, 37 (17), 3839–3858.

Cheung, F.K.T., Kurul, E., and Oti, A.H., 2016. A case study of hybrid strategies to create value for a contracting business in the education sector in England and Wales. *Construction Management and Economics*, 34 (4–5), 335–352.

Chevallier, Z., Finance, B., and Boulakia, B.C., 2020. A reference architecture for smart building digital twin. *CEUR Workshop Proceedings*, 2615, 1–12.

Chiang, Y.H., Hon-Wan Chan, E., and Ka-Leung Lok, L., 2006. Prefabrication and barriers to entry-a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, 30 (3), 482–499.

Chou, J.-S., Yang, I.-T., and Chong, W.K., 2009. Probabilistic simulation for developing likelihood distribution of engineering project cost. *Automation in Construction*, 18 (August), 570–577.

Chou, J.S., 2011. Cost simulation in an item-based project involving construction engineering and management. *International Journal of Project Management*, 29 (6), 706–717.

Corcho, O., Fernandez-Lopez, M., and Gomez-Perez, A., 2003. Methodologies , tools and languages for building ontologies . Where is their meeting point ? *Data & Knowledge Engineering*, 46, 41–64.

Corcho, O. and Gómez-Pérez, A., 2000a. Evaluating Knowledge Representation and Reasoning Capabilities of Ontology Specification Languages. *In*: *Applications of Ontologies and Problem Solving Methods 14th European Conference on Artificial Intelligence (ECAI'00)*. 3.1 – 3.9.

Corcho, O. and Gómez-Pérez, A., 2000b. A roadmap to ontology specification languages. *In*: R. Dieng and O. Corby, eds. *EKAW*. Berlin Heidelberg: Springer-Verlag Berlin, 80–96.

Cox, R.F., Issa, R.R.A., Asce, M., and Ahrens, D., 2003. Management ' s Perception of Key Performance Indicators for Construction. *Journal of Construction Engineering &*

Management, 129 (2), 142–151.

Creswell, J.W., 2009. *Research Design_ Qualitative, Quantitative, and Mixed Methods Approaches*. Third edit. London: SAGE Publications.

Cutting-Decelle, A.-F., Young, B.I., Das, B.P., Case, K., Rahimifard, S., Anumba, C.J., and Bouchlaghem, D.M., 2007. A Review of Approaches to Supply Chain Communications: From Manufacturing to Construction. *ITcon*, 12, 73–102.

Datta, P.P. and Roy, R., 2009. Cost Modelling Techniques for Availability Type Service Support Contracts : a Literature Review and Empirical Study. *In*: *Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2)*. 216.

Dave, B., Koskela, L., and Kiviniemi, A., 2013. *Implementing Lean in construction: Lean construction and BIM*. CIRIA Guide C725 - Construction Industry Research and Information Association. London: CIRIA.

Delany, S., 2015. Classification [online]. *National Building Specification (NBS) BIM Toolkit*. Available from: https://toolkit.thenbs.com/articles/classification#classificationtables [Accessed 4 Feb 2019].

Denzin, N.K. and Lincoln, Y.S., 2000. *Handbook of Qualitative Research*. Second. London: SAGE Publications.

Djurić, D., Gašević, D., and Devedžić, V., 2005. Ontology modeling and MDA. *Journal of Object Technology*, 4 (1), 109–128.

Doomun, R. and Jungum, N.V., 2008. Business process modelling, simulation and reengineering: Call centres. *Business Process Management Journal*, 14 (6), 838–848.

Doran, D. and Giannakis, M., 2011. An examination of a modular supply chain : a construction sector perspective. *An International Journal of Supply Chain Management*, 16 (4), 260–

270.

Dubois, A. and Gadde, L.-E., 1999. Case studies in business market research: An abductive approach. *In*: M. Damien and C. Horan, eds. *Proceedings of the 15th Annual IMP Conference*. Dublin, 1–20.

Duncheva, T. and Bradley, F.F., 2016. A comparison between Volumetric Timber Manufacturing Strategies in the UK and mainland Europe. *In*: *2016 Modular and Offsite Construction (MOC) Summit*. Edmonton, Alberta, Canada, 10–17.

Durdyev, S. and Mbachu, J., 2011. On-site Labour Productivity of New Zealand Construction Industry : Key Constraints and Improvement Measures. *Australasian Journal of Construction Economics and Building*, 11 (3), 18–33.

Duverlie, P. and Castelain, J.M., 1999. Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method. *The International Journal of Advanced Manufacturing Technology,* 15, 895–906.

Eastman, C.M. and Sacks, R., 2008. Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134 (7), 517–526.

Egan, J., 1998. *Rethinking Construction*. The Report of the Construction Task Force.

El-Diraby, T.A., Lima, C., and Feis, B., 2005. Domain Taxonomy for Construction Concepts : Toward a Formal Ontology for Construction Knowledge. *JOURNAL OF COMPUTING IN CIVIL ENGINEERING*, 19 (4), 394–406.

El-Gohary, N.M. and El-Diraby, T.E., 2015. Domain Ontology for Processes in Infrastructure and Construction. *Journal of Construction Engineering and Management ASCE,* (January).

Elhag, T.M.S. and Boussabaine, A.H., 1998. An Artificial Neural System for Cost Estimation Of Construction Projects. *In*: *14th Annual ARCOM Conference*. 219–226.

Elnaas, E., 2014. The Decision To Use Off-Site Manufacturing (OSM) Systems for House Building Projects in the UK. University of Brighton. UK.

Elo, S. and Kyngäs, H., 2008. The qualitative content analysis process. *Journal of Advanced Nursing*, 62 (1), 107–115.

Enshassi, A., Mohamed, S., and Abushaban, S., 2009. Factors affecting the performance of construction projects in the Gaza strip. *Journal of Civil Engineering and Management*, 15 (2), 269–280.

Farmer, M., 2016. *Modernise or die: The Framer Review of the UK construction labour market*. The Farmer Review of the UK Construction Labour Model.

Fellows, R.F. and Liu, A.M.M., 2015. *Research Methods for Construction*. Fourth Edi. West Sussex: John Wiley & Sons Ltd.

Fensel, D., 2000. Relating Ontology Languages and Web Standards Ontology Languages.

Fernández-solís, J.L., 2009. How the Construction Industry does differ from manufacturing ? *In*: *Associated Schools of Construction International Proceedings of the 45th Annual Conference*. Gainesville.

Fernández, L.M., 1999. Overview Of Methodologies For Building Ontologies. *Proceedings of the IJCAI99 Workshop on Ontologies and ProblemSolving Methods Lessons Learned and Future Trends CEUR Publications*, 1999 (2), 1–13.

Fernandez, M., Gomez-Perez, A., and Juristo, N., 1997. *METHONTOLOGY : From Ontological Art Towards Ontological Engineering*.

Finnimore, B., 1989. *Houses from the Factory: System Building and the Welfare State*. California: Rivers Oram Press.

Flick, U., 2007. *Designing Qualitative Research*. London: SAGE Publications.

Flick, U., 2014. *The SAGE Handbook of Qualitative Data Analysis*. London: SAGE Publications.

Formoso, C.T., 1991. A Knowledge-based Framework for Planning House Building Projects. University of Salford.

Forsberg, A. and Saukkoriipi, L., 2007. Measurement of waste and productivity in relation to lean thinking. *In*: *Lean Construction: A New Paradigm for Managing Capital Projects - 15th IGLC Conference*. 67–76.

Fortineau, V., Paviot, T., Louis-Sidney, L., and Lamouri, S., 2012. SWRL as a rule language for ontology-based models in power plant design. *IFIP Advances in Information and Communication Technology*, 388 AICT, 588–597.

Froese, T., 2003. FUTURE DIRECTIONS FOR IFC-BASED INTEROPERABILITY. *ITcon*, 8 (December 2002), 231–246.

Future Focus, 2017. *Offsite and Modular Building Market Research*.

Gann, D.M., 1996. Construction as a manufacturing process ? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics*, 14 (5), 437–450.

Gbadamosi, A.Q., Mahamadu, A.M., Oyedele, L.O., Akinade, O.O., Manu, P., Mahdjoubi, L., and Aigbavboa, C., 2019. Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, 215, 1180–1190.

Giacobbi, P.R., Poczwardowski, A., and Hager, P., 2005. A pragmatic research philosophy for applied sport psychology. *Sport Psychologist*, 19 (1), 18–31.

Gibb, A.G.F., 1999. *Off-site fabrication: Prefabrication, Pre-assembly and Modularisation*. New York: John Wiley & Sons.

Gibb, A.G.F., 2001. Standardization and pre-assembly – distinguishing myth from reality using case study research. *Construction Management and Economics*, 19, 307–315.

Gibb, A.G.F. and Isack, F., 2003. Re-engineering through pre-assembly : client expectations and drivers. *Building Research & Information*, 31 (2), 146–160.

Girmscheid, G. and Scheublin, F., 2010. New perspective in industrialisation in construction - a state of the art report. *International Council For Research And Innovation In Building And Construction (CIB)*, (May).

Golbreich, C., 2004. Combining Rule and Ontology Reasoner for the Semantic Web. *In*: Grigoris Antoniou and H. Boley, eds. *Third International Workshop, RuleML 2004*. Berlin: Springer, ??? ????

Gómez-Pérez, A. and Corcho, O., 2002. Ontology languages for the semantic web. *IEEE Intelligent Systems and Their Applications*, 17 (1), 54–60.

Goodier, C. and Gibb, A., 2005. *The value of the UK market for offsite*. London.

Gorgolewski, M.T., 2005. The Potential for Prefabrication in UK Housing to Improve Sustainability. *In*: J. Yang, P.S. Brandon, and A.C. Sidwell, eds. *Smart & Sustainable Built Environments*. Oxford, UK.: Blackwell Publishing Ltd, 1–8.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012a. Offsite Construction : Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1, 62–73.

Goulding, J., Rahimian, F.P., Arif, M., and Sharp, M., 2012b. Offsite Construction: Strategic Priorities for Shaping the Future Research Agenda. *Architectoni.ca*, 1 (1), 62–73.

Goulding, J.S., Pour Rahimian, F., Arif, M., and Sharp, M.D., 2015. New offsite production and business models in construction: priorities for the future research agenda. *Architectural Engineering and Design Management*, 11 (3), 163–184.

GOV.UK, 2020. Live tables on house building [online]. *Ministry of Housing, Communities & Local Government*. Available from: https://www.gov.uk/government/statistical-data-sets/live-tables-on-house-building [Accessed 1 Feb 2020].

Grani, H.K., 2016. BIM Classification - Giving your Model some Class [online]. *Areo blog - Lifecycle BIM and smart FM*.

Griffith, M. and Jefferys, P., 2013. *Solutions for the housing shortage: How to build the 250.000 homes we need each year*. London.

Gruber, T.R., 1995. Toward principles for the design of ontologies used in knowledge sharing. *International Journal of Human Computer Studies*, 43, 907–928.

Gu, N. and London, K., 2010. Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, 19 (8), 988–999.

Guba, E.G. and Lincoln, Y.S., 1994. Competing Paradigms in Qualitative Research. *In*: N.K. Denzin and Y.S. Lincoln, eds. *Handbook of qualitative research*. 105–117.

Guizzardi, G., 2007. On Ontology, ontologies, Conceptualizations, Modeling Languages, and (Meta)Models. *In*: O. Vasilecas et al., ed. *Databases and Information Systems IV*. IOS Press.

Gunasekaran, A. and Kobu, B., 2002. Modelling and analysis of business process reengineering. *International Journal of Production Research*, 40 (11), 2521–2546.

Gunasekaran, A. and Sarhadi, M., 1998. Implementation of activity-based costing in manufacturing. *Intern. Journal of Production Economics*, 56–57 (1998), 231–242.

Gunaydın, H.M. and Dogan, S.Z., 2004. A neural network approach for early cost estimation of structural systems of buildings. *International Journal of Project Management*, 22 (2004), 595–602.

Gunduz, M., Ugur, L.O., and Ozturk, E., 2011. Parametric cost estimation system for light rail transit and metro trackworks. *Expert Systems with Applications*, 38 (3), 2873–2877.

Gurcanli, G.E., Bilir, S., and Sevim, M., 2015. Activity based risk assessment and safety cost estimation for residential building construction projects. *Safety Science*, 80 (112), 1–12.

Hairstans, R. and Smith, R.E., 2018. Offsite HUB (Scotland): establishing a collaborative regional framework for knowledge exchange in the UK. *Architectural Engineering and Design Management*, 14 (1–2), 60–77.

Haron, N.A., Abdul-Rahman, H., Wang, C., and Wood, L.C., 2015. Quality function deployment modelling to enhance industrialised building system adoption in housing projects. *Total Quality Management and Business Excellence*, 26 (7–8), 703–718.

Hashemi, A., 2015. Offsite Manufacturing: A Survey on the Current Status and Risks of Offsite Construction in Iran, 9, 141–152.

Hashemi, A. and Hadjri, K., 2014. Offsite Construction, a Potential Answer to the Iranian Housing Shortages. *In*: *Construction Technology and Management CTM 2014 International Scientific Conference*. 189–199.

Hause, M., 2006. The SysML Modelling Language. *In*: *Fifteenth European Systems Engineering Conference*. 12.

HM Government, 2013. *Construction 2025. Industrial Strategy: Government and industry in* *partnership*.

Holten, M. and Ferdinand, G., 2020. BOT : the Building Topology Ontology of the W3C Linked Building Data Group. *Semantic Web*, 12 (1), 143–161.

Höök, M. and Stehn, L., 2008. Lean principles in industrialized housing production : the need for a cultural change Lean culture. *Lean Construction Journal 2008*, (April), 20–33.

Horrocks, I., 2002. DAML+OIL: a Description Logic for the Semantic Web. *Bulletin of the Technical Committee on Data Engineering*, 25 (1).

Horrocks, I. and Sattler, U., 2001. Ontology reasoning in the SHOQ(D) description logic. *IJCAI International Joint Conference on Artificial Intelligence*, 199–204.

Howell, G. and Ballard, G., 1998. Implimenting construction: understanding and action. *Proceedings International Group for Lean Construction*, 0, 9.

Howell, G.A., 1999. What is Lean Construction. *In*: I.D. Tommelein, ed. *IGLC 2012 - 20th Conference of the International Group for Lean Construction*. UNIVERSITY OF CALIFORNIA BERKELEY, CALIFORNIA, USA.

Hueber, C., Horejsi, K., and Schledjewski, R., 2016. Review of cost estimation: methods and models for aerospace composite manufacturing. *Advanced Manufacturing: Polymer and Composites Science*, 2 (1), 1–13.

Hyde, K.F., 2000. Recognising deductive processes in qualitative research. *Qualitative Market Research: An International Journal*, 3 (2), 82–90.

Ijomah, W.L. and Childe, S.J., 2007. A model of the operations concerned in remanufacture. *International Journal of Production Research*, 45 (24), 5857–5880.

Jabar, I. laili, Ismail, F., and Mustafa, A.A., 2013. Issues in Managing Construction Phase of

IBS Projects. *Procedia - Social and Behavioral Sciences*, 101, 81–89.

Jaillon, L. and Poon, C.S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment : a Hong Kong case study. *Construction Management and Economics*, 26 (9), 953–966.

Jaillon, L. and Poon, C.S., 2009. The evolution of prefabricated residential building systems in Hong Kong : A review of the public and the private sector. *Automation in Construction*, 18 (3), 239–248.

Jaillon, L., Poon, C.S., and Chiang, Y.H., 2009. Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management*, 29 (1), 309–320.

Jarkas, A.M. and Bitar, C.G., 2012. Factors Affecting Construction Labor Productivity in Kuwait. *Journal of Construction Engineering and Management*, 138 (7), 811–820.

Ji, S., Park, M., and Lee, H., 2011. Cost estimation model for building projects using case-based reasoning. *Canadian Journal of Civil Engineering*, 38, 570–581.

Jones, D., Bench-capon, T., and Visser, P., 1998. Methodologies for Ontology Development. *In*: *Proc. IT&KNOWS Conference of the 15th IFIP World Computer Congress*. Budapest.

Jonsson, H. and Rudberg, M., 2014. Classification of production systems for industrialized building : a production strategy perspective. *Construction Management and Economics*, 32 (1–2), 53–69.

Jung, J., 2002. Manufacturing cost estimation for machined parts based on manufacturing features. *Journal of Intelligent Manufacturing*, 13, 227–238.

Kalemi, E.V., Cheung, F., Tawil, A., Patlakas, P., and Alyania, K., 2020. ifcOWL-DfMA a new ontology for the offsite construc- tion domain. *In*: *Proceedings of the7578th Linked*

Data in Architecture and Construction Workshop - LDAC2020 ifcOWL-DfMA. 105–117.

Kamar, K.A., Abd Hamid, Z., Azman, M.N.A., and Ahamad, M.S.S., 2011. Industrialized Building System (IBS): Revisiting Issues of Definition and Classification. *International Journal of Emerging. Sciences*, 1 (2), 120–132.

Karhu, V., 2000. Formal Languages for Construction Process Modelling. *Construction Information Technology 2000, Taking the construction industry into the 21st century, CIB W78.*, 525–534.

Kenley, R., 2014. Productivity improvement in the construction process Productivity improvement in the construction process. *Construction Management and Economics*, 32 (6), 489–494.

Kenley, R., Kanjanabootra, S., Ouyang, C., and Wynn, M., 2012. Procuring OSM: base-line models of off-site manufacture business processes in Australia. *In*: *16th Pacific Association of Quantity Surveyors Congress-Innovation and Sustaining: Challenges and Opportunities*. 1–10.

Khajavi, S.H., Motlagh, N.H., Jaribion, A., Werner, L.C., and Holmstrom, J., 2019. Digital Twin: Vision, benefits, boundaries, and creation for buildings. *IEEE Access*, 7, 147406–147419.

Khosrowshahi, F. and Kaka, A.P., 1996. Estimation of Project Total Cost and Duration for Housing Projects in the U.K. *Building and Environment*, 31 (4), 373–383.

Kifer, M., 2008. Rule Interchange Format: The Framework. *In*: N. Bassiliades, G. Governatori, and A. Paschke, eds. *International Symposium, RuleML 2008*. Berlin: Springer-Verlag.

Kim, C.H., Weston, R.H., Hodgson, A., and Lee, K.H., 2003. The complementary use of IDEF and UML modelling approaches. *Computers in Industry*, 50 (1), 35–56.

Kim, S. and Shim, J.H., 2014. Combining case-based reasoning with genetic algorithm optimization for preliminary cost estimation in construction industry. *Canadian Journal of Civil Engineering*, 41 (November 2013), 65–73.

Kim, Y.-W., 2017. *Activity Based Costing for Construction Companies*. First Edit. West Sussex: John Wiley & Sons Ltd.

Kim, Y. and Ballard, G., 2001. Activity-based costing and its application to lean construction. *International Group for Lean Construction*, (January), 1–13.

Kim, Y. and Ballard, G., 2002. Case Study - overhead costs analysis. *In*: *Proceedings IGLC-10*. Gramado, Brazil, 1–13.

Kolo, S.J., Rahimian, F.P., and Goulding, J.S., 2014. Housing delivery in Nigeria and the opportunity for offsite manufacturing. *In*: *Creative Construction Conference*. 85–90.

Koskela, L., 1992. *Application of the new production philosophy to construction*. Stanford, CA.

KPMG, 2016. *Smart construction - How offsite manufacturing can transform our industry*.

Lang, R., Goodier, C., and Glass, J., 2016. Are housebuilders' production strategies a barrier to offsite construction uptake in the UK? *Proceedings of the 32nd Annual ARCOM Conference, ARCOM 2016*, 1245–1253.

Larsson, J. and Simonsson, P., 2012. Barriers and drivers for increased use of off-site bridge construction in Sweden. *In*: *28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 751–761.

Latham, M., 1994. *Constructing the Team*. Joint Review of Procurement and Contractual Arrangements in the United Kingdom Construction Industry.

Lawson, M., Ogden, R., and Goodier, C., 2010. *Design in Modular Construction*. Taylor & Francis Group.

Lee, S., Kim, K., and Yu, J., 2014. Automation in Construction BIM and ontology-based approach for building cost estimation. *Automation in Construction*, 41, 96–105.

Leishman, C. and Warren, F., 2006. Private housing design customization through house type substitution. *Construction Management and Economics*, 24, 149–158.

Lemaignan, S., Siadat, A., Dantan, J.-Y., and Semenenko, A., 2006. MASON : A proposal for an ontology of manufacturing domain. *In*: *Proceedings of the IEEE Workshop on Distributed Intelligent Systems: Collective Intelligence and Its Applications (DIS'06) 0-7695-2589-X/06*.

Lere, J.C., 2000. Activity-based costing: A powerful tool for pricing. *Journal of Business and Industrial Marketing*, 15 (1), 23–33.

Lessing, J., Stehn, L., and Ekholm, A., 2015. Industrialised house-building – development and conceptual orientation of the field. *Construction Innovation*, 15 (3), 378–399.

Li, Z.C., Hong, J., Xue, F., Shen, G.Q., Xu, X., and Luo, L., 2016. SWOT analysis and Internet of Things-enabled platform for prefabrication housing production in Hong Kong. *Habitat International*, 57, 74–87.

Liao, S., 2004. Expert system methodologies and applications - a decade review from 1995 to 2004. *Expert Systems with Applications*, 1–11.

Lim, E.C. and Alum, J., 1995. Construction productivity: Issues encountered by contractors in Singapore. *International Journal of Project Management*, 13 (1), 51–58.

Lin, Y.C., Wang, L.C., and Tserng, H.P., 2006. Enhancing knowledge exchange through web map-based knowledge management system in construction: Lessons learned in Taiwan.

Automation in Construction, 15 (6), 693–705.

Liu, H., Lu, M., and Al-hussein, M., 2016. Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry. *Advanced Engineering Informatics*, 30 (2), 190–207.

Liu, X., Li, Z., and Jiang, S., 2016. Ontology-Based Representation and Reasoning in Building Construction Cost Estimation in China. *Future Internet*, 8 (39).

Liu, Z., Osmani, M., Demian, P., and Baldwin, A.N., 2011. The potential use of BIM to aid construction waste minimalisation. *In*: –Sophia Antipolis, ed. *Proceedings of the CIB W78-W102 2011*. France.

Lou, Y.-I., Wang, H.C., and Lan, J.-S., 2017. Design and Implement the Activity-Based Costing in Taiwan Firm. *IOSR Journal of Business and Management*, 19 (01), 41–46.

Lovett, P.J., Ingram, A., and Bancroft, C.N., 2000. Knowledge-based engineering for SMEs - a methodology. *Journal of Materials Processing Technology*, 107, 384–389.

Lu, Q., Xie, X., Heaton, J., Parlikad, A.K., and Schooling, J., 2020. From BIM towards digital twin: Strategy and future development for smart asset management. *Studies in Computational Intelligence*, 853, 392–404.

Lucko, G. and Rojas, E.M., 2010. Research Validation: Challenges and Opportunities in the Construction Domain. *Journal of Construction Engineering and Management*, 136 (1).

Luo, L., Mao, C., Shen, L., and Li, Z., 2015. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system. *Engineering, Construction and Architectural Management*, 22 (6), 622–643.

Ma, Z.M. and Wang, X., 2012. Rule interchange in the semantic web. *Journal of Information Science and Engineering*, 28 (2), 393–406.

Mao, C., Shen, Q., Shen, L., and Tang, L., 2013. Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods : Two case studies of residential projects. *Energy & Buildings*, 66, 165–176.

McKay, L.J., 2010. The effect of offsite construction on occupational health and safety. *A Doctoral Thesis Submitted In Partial Fulfilment Of The Requirements For The Award Of Doctor Of Philosophy*. Loughborough University.

Meiling, J., Backlund, F., and Johnsson, H., 2012a. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Meiling, J., Backlund, F., and Johnsson, H., 2012b. Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19 (2), 141–158.

Melão, N. and Pidd, M., 2000. A conceptual framework for understanding business processes and business process modelling. *Information Systems Journal*, 10 (2), 105–129.

Melton, T., 2005. The benefits of lean manufacturing: What lean thinking has to offer the process industries. *Chemical Engineering Research and Design*, 83 (6 A), 662–673.

Miah, S.J. and Genemo, H., 2016. A Design Science Research Methodology for Expert Systems Development. *Australasian Journal of Information Systems*, 20, 1–29.

Miles, J. and Whitehouse, N., 2013. *Offsite Housing Review*. London.

Milton, N., 2008. *Knowledge Technologies*. Italy: Polimetrica ®.

Mizoguchi, R. and Ikeda, M., 1998. Towards ontology engineering. *Journal-Japanese Society for Artificial Intelligence*, 13 (1), 259–266.

Montali, J., Overend, M., Pelken, P.M., and Sauchelli, M., 2018. Knowledge-Based Engineering in the design for manufacture of prefabricated façades: current gaps and future trends. *Architectural Engineering and Design Management*, 14 (1–2), 78–94.

Morgan, D.L., 2007. Paradigms Lost and Pragmatism Regained: Qualitative and Quantitative Methods. *Journal of Mixed Methods Research*, 1 (48), 48–76.

Mossman, A., 2009. Creating value: A sufficient way to eliminate waste in lean design and lean production. *Lean Construction Journal*, 2009, 13–23.

Mostafa, S., Chileshe, N., and Abdelhamid, T., 2016. Lean and agile integration within offsite construction using discrete event simulation. *Construction Innovation*, 16 (4), 483–525.

Motawa, I. and Almarshad, A., 2013. A knowledge-based BIM system for building maintenance. *Automation in Construction*, 29, 173–182.

Mtech Group, 2007. *Offsite Construction Industry Survey 2006*. BuildOffsite. London.

Murtaza, M.B., Fisher, D.J., and Skibniewski, M.J., 1993. Knowledge-Based Approach to Modular Construction Decision Support. *Journal of Construction Engineering and Management*, 119, 115–130.

Murugaiah, U., Benjamin, S.J., and Marathamuthu, M.S., 2010. Scrap loss reduction using the 5-whys analysis. *International Journal of Quality & Reliability Management*, 27 (5), 527–540.

Musa, M.F., Mohammad, M.F., Yusof, M.R., and Mahbub, R., 2015. The Way Forward for Industrialised Building System (IBS) in Malaysia. *In*: *InCIEC 2014*. Singapore: Springer, pp 163-175.

Nadim, W. and Goulding, J.S., 2011. Offsite production : a model for building down barriers. *Engineering, Construction and Architectural Management*, 18 (1), 82–101.

Nahmens, I. and Ikuma, L.H., 2012. Effects of Lean Construction on Sustainability of Modular Homebuilding. *Journal of Architectural Engineering*, 18 (2), 155–163.

Nasereddin, M., Mullens, M.A., and Cope, D., 2007. Automated simulator development : A strategy for modeling modular housing production. *Automation in Construction*, 16, 212–223.

Naufal, A., Jaffar, A., Yusoff, N., and Hayati, N., 2012. Development of kanban system at local manufacturing company in Malaysia-Case study. *Procedia Engineering*, 41 (Iris), 1721–1726.

Nawari, N.O., 2012. BIM Standard in Off-Site Construction. *Journal of Architectural Engineering*, 18 (2).

NBS, 2015. Uniclass 2015 [online]. *National Building Specification (NBS)*. Available from: https://www.thenbs.com/our-tools/uniclass-2015 [Accessed 2 Jan 2019].

Nepal, M.P., Staub-French, S., Pottinger, R., and Zhang, J., 2013. Ontology- based feature modeling for construction information extraction from a build- ing information model. *Journal of Computing in Civil Engineering*, 27 (5), 555–569.

Neuman, L.W., 2014. *Social Research Methods: Qualitativr and Quantitative Approaches*. Seventh Ed. Essex, England: Pearson Education Limited.

Niazi, A. and Dai, J.S., 2006. Product Cost Estimation : Technique Classification and Methodology Review. *Journal of Manufacturing Science and Engineering*, 128 (May).

Nicholls, D., 2017. Qualitative research. Part 2: Methodologies. *International Journal of Therapy and Rehabilitation*, 24 (2), 71–77.

Nikakhtar, A., Hosseini, A.A., Wong, K.Y., and Zavichi, A., 2015. Application of lean construction principles to reduce construction process waste using computer simulation:

A case study. *International Journal of Services and Operations Management*, 20 (4), 461–480.

Nurcan, S., Etien, A., Kaabi, R., Zoukar, I., and Rolland, C., 2005. A strategy driven business process modelling approach. *Business Process Management Journal*, 11 (6), 628–649.

O'Connor, M., Knublauch, H., Tu, S., Grosof, B., Dean, M., Grosso, W., and Musen, M., 2005. Supporting rule system interoperability on the semantic Web with SWRL. *In*: Y. Gil et al., ed. *ISWC 2005*. Berlin: Springer-Verlag, 974–986.

Ochieng, E.G. and Price, A.D.F., 2009. Managing cross-cultural communication in multicultural construction project teams : The case of Kenya and UK. *International Journal of Project Management* ·, (July).

Ofori, G., 2000. Challenges of Construction Industries in Developing Countries : Lessons from Various Countries. *In*: *2nd International Conference on Construction in Developing Countries: Challenges Facing the Construction Industry in Developing Countries*. Gabarone, 1–13.

Ogunlana, S.O., 1989. Accuracy in design cost estimating.

Ong, N.S., 1995. Manufacturing cost estimation for PCB assembly : An activity-based approach. *International Journal of Production Economics*, 38, 159–172.

Ormerod, R.J., 2010. Rational inference: Deductive, inductive and probabilistic thinking. *Journal of the Operational Research Society*, 61 (8), 1207–1223.

Ou-Yang, C. and Lin, T.S., 1997. Developing an Integrated Framework for Feature-Based Early Manufacturing Cost Estimation. *International Journal of Advanced Manufacturing Technology*, 13, 618–629.

Ozaki, R., 2003. Customer-focused approaches to innovation in housebuilding. *Construction*

Management and Economics, 21, 557–564.

Ozbayrak, M., Akgun, M., and Turker, A.K., 2004. Activity-based cost estimation in a push / pull advanced manufacturing system. *International Journal of Production Economics*, 87, 49–65.

Pan, W., Dainty, A.R.J., and Gibb, A.G.F., 2012. Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, 138 (11), 1239–1250.

Pan, W., Gibb, A.G.F., and Dainty, A.R.J., 2008. *Leading UK housebuilders' utilisation of offsite modern methods of construction*. Building Research & Information.

Pan, W. and Goodier, C., 2012. House-Building Business Models and Off-Site Construction Take-Up. *Journal of Architectural Engineering*, 18 (2), 84–93.

Pan, W. and Sidwell, R., 2011. Demystifying the cost barriers to offsite construction in the UK. *Construction Management & Economics*, 29, 1081–1099.

Pasquire, C., Gibb, A., and Blismas, N., 2005. What should you really measure if you want to compare prefabrication with traditional construction? *In*: *Proceedings IGLC*. Sydney, Australia, 481–491.

Pasquire, C.L. and Connolly, G.E., 2002. Leaner construction through off-site manufacturing. *In*: *Proceedings 10th of the Internationa Group of Lean Construction Conference, Gramado, Brazil*. 1–13.

Pauwels, P. and Terkaj, W., 2016. EXPRESS to OWL for construction industry : Towards a recommendable and usable ifcOWL ontology. *Automation in Construction*, 63, 100–133.

Pearce, A., Pons, D., and Neitzert, T., 2018. Implementing lean—Outcomes from SME case studies. *Operations Research Perspectives*, 5, 94–104.

Persson, S., Malmgren, L., and Johnsson, H., 2009. Information management in industrial housing design and manufacture. *Electronic Journal of Information Technology in Construction*, 14 (June), 110–122.

Pheng, L.S. and Leong, C.H.Y., 2000. Cross-Cultural project management for international construction in China. *International Journal of Project Management*, 18 (5), 307–316.

Post, 2003. *Modern methods of house building*. Parliamentary Office of Science and Technology. London.

Pulido, J.R.G., Ruiz, M.A.G., Herrera, R., Cabello, E., Legrand, S., and Elliman, D., 2006. Ontology languages for the semantic web: A never completely updated review. *Knowledge-Based Systems*, 19 (7), 489–497.

Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., and Zimmerman, J.B., 2012. Construction Matters Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*, 16 (2), 243–254.

Rahani, A. and Muhammad, A.-A., 2012. Production Flow Analysis through Value Stream Mapping : A Lean Manufacturing Process Case Study. *Procedia Engineering - International Symposium on Robotics and Intelligent Sensors*, 41 (Iris), 1727–1734.

Rahman, N.A.A., Sharif, S.M., and Esa, M.M., 2013. Lean Manufacturing Case Study with Kanban System Implementation. *Procedia Economics and Finance*, 7 (Icebr), 174–180.

Rahman, S., Perera, S., Odeyinka, H., and Bi, Y., 2008. A Conceptual Knowledge-Based Cost Model for Optimizing the Selection of Materials and Technology for Building Design. *24th Annual ARCOM Conference*, (September), 217–225.

Raz, T. and Elnathan, D., 1999. Activity based costing for projects. *International Journal of Project Management*, 17 (1), 61–67.

Rezgui, Y., Hopfe, C.J., and Vorakulpipat, C., 2010. Generations of knowledge management in the architecture , engineering and construction industry : An evolutionary perspective. *Advanced Engineering Informatics*, 24 (2), 219–228.

Richard, R.B., 2005. Industrialised building systems: Reproduction before automation and robotics. *Automation in Construction*, 14 (4), 442–451.

RICS, 2012a. *NRM1: Order of Cost Estimating and Cost Planning for Capital Building Works*. 2nd Editio. Coventry UK: Royal Institution of Chartered Surveyors (RICS).

RICS, 2012b. *NRM 2: Detailed Measurement for Building Works*. 1st Editio. Coventry: Royal Institution of Chartered Surveyors (RICS).

La Rocca, G., 2012. Knowledge based engineering : Between AI and CAD . Review of a language based technology to support engineering design. *Advanced Engineering Informatics*, 26 (2), 159–179.

Roy, A.U.K., Roy, M., and Saha, P.S., 2007. Mass-Industrialized Housing to Combat Consistent Housing Shortage in Developing Countries : Towards an Appropriate System for India. *In*: *World Congress on Housing National Housing Programmes- New Visions November 03-07, Kolkota, India*. Kolkata, India, 1–7.

Roy, R., Souchoroukov, P., and Shehab, E., 2011. Detailed cost estimating in the automotive industry : Data and information requirements. *Intern. Journal of Production Economics*, 133 (2), 694–707.

Rožanec, J.M., Jinzhi, L., Košmerlj, A., Kenda, K., Dimitris, K., Jovanoski, V., Rupnik, J., Karlovčec, M., and Fortuna, B., 2020. Towards actionable cognitive digital twins for manufacturing. *CEUR Workshop Proceedings*, 2615, 1–12.

Rundora, R., Ziemerink, T., and Oberholzer, M., 2013. Activity-based costing in small manufacturing firms: South African study. *Journal of Applied Business Research*, 29 (2), 485–498.

Saad, A. and Shaharin, S., 2016. The Methodology for Ontology Development in Lesson Plan Domain. *International Journal of Advanced Computer Science and Applications (IJACSA)*, 7 (4), 557–562.

Sabol, L., 2008. *Challenges in Cost Estimating with Building Information Modeling*. Washington, DC.

Sarvimaki, M., 2017. *Case Study Strategies for Architects and Designers : Integrative Data Research Methods: Integrative Data Research Methods*. London: Taylor & Francis Group.

Saunders, M., Lewis, P., and Thornhill, A., 2009. *Research Methods for Business Students*. New York: Pearson.

Schell, C., 1992. *The Value of the Case Study as a Research Strategy*.

Schreiber, A.T., Akkermans, J.M., Anjewierden, A.A., de Hoog, R., Shadbolt, N.R., Velde, W. Van de, and Wielinga, B.J., 2001. *Knowledge Engineering and Management - The CommonKADS Methodology*. Cambridge,Massachusetts: MIT Press.

Schuh, K.L. and Barab, S.A., 2008. Philosophical Perspectives. *In*: J. David, S.J. Michael, D. Marcy, M. David, and M. Jeroen, eds. *Handbook of Research on Educational Communications*. New York: Taylor & Francis, 67–82.

Schwitter, R., 2010. Controlled natural languages for knowledge representation. *In*: *Coling 2010 - 23rd International Conference on Computational Linguistics, Proceedings of the Conference*. Beijing, 1113–1121.

Secretary of State for Communities and Local Government, 2017. *Fixing our broken housing* *market*. Department for Communities and Local Government. London: Crown.

Shadbolt, N. and Milton, N., 1999. From Knowledge Engineering to Knowledge Management. *British Journal of Management*, 10, 309–322.

Shamsuddin, S.M., Zakaria, R., and Mohamed, S.F., 2013. Economic Attributes in Industrialised Building System in Malaysia. *Procedia - Social and Behavioral Sciences*, 105, 75–84.

Shang, G. and Sui Pheng, L., 2014. Barriers to lean implementation in the construction industry in China. *Journal of Technology Management in China*, 9 (2), 155–173.

Shi, J.J., Lee, D.E., and Kuruku, E., 2008. Task-based modeling method for construction business process modeling and automation. *Automation in Construction*, 17 (5), 633–640.

Shostak, L. and Houghton, J., 2008. The credit crunch and the housing shortage - Time for a radical new approach to building affordable homes. *Local Economy*, 23 (3), 121–126.

Sivakumar, R. and Arivoli, P.V., 2011. Ontology Visualization Protégé Tools - A Review. *International Journal of Advanced Information Technology*, 1 (4), 39–39.

Smith, A.E. and Mason, A.K., 1996. Cost Estimation Predictive Modeling : Regression versus Neural Network. *The Engineering Economist*.

Sobh, R. and Perry, C., 2006. Research design and data analysis in realism research. *European Journal of Markerting*, 40 (11), 1194–1209.

Sodikov, J., 2005. COST ESTIMATION OF HIGHWAY PROJECTS IN DEVELOPING COUNTRIES : ARTIFICIAL NEURAL NETWORK APPROACH. *Journal of the Eastern Asia Society for Transportation Studies*, 6, 1036–1047.

Soiferman, L.K., 2010. Compare and Contrast Inductive and Deductive Research Approaches.

Inductive and Deductive Research Approaches, (April), 1–23.

Song, J., Fagerlund, W.R., Haas, C.T., Tatum, C.B., and Vanegas, J.A., 2005. Considering Prework on Industrial Projects. *Journal of Construction Engineering and Management*, 131 (6), 723–733.

Spens, K.M. and Kovács, G., 2006. A content analysis of research approaches in logistics research. *International Journal of Physical Distribution and Logistics Management*, 36 (5), 374–390.

Spyns, P., Meersman, R., and Jarrar, M., 2002. Data modelling versus ontology engineering. *ACM SIGMOD Record*, 31 (4), 12–17.

Staub-french, S., Fischer, M., Kunz, J., Paulson, B., and Ishii, K., 2002. *A Feature Ontology to Support Construction Cost Estimating*.

Steinhardt, D., Manley, K., and Miller, W.F., 2014. Reshaping housing using prefabricated systems. *Proceedings of World Sustainable Building Conference (SB14)*.

Studer, R., Benjamins, V.R., and Fensel, D., 1998. Knowledge Engineering : Principles and methods. *Data & Knowledge Engineering*, 25, 161–197.

Sundar, R., Balaji, A.N., and Satheesh Kumar, R.M., 2014. A review on lean manufacturing implementation techniques. *Procedia Engineering*, 97, 1875–1885.

Szuba, J.S., Grabska, E.G., and Borkowski, A., 1999. Graph Visualization in ArchiCAD. *In*: *Proceedings of the International Workshop on Applications of Graph Transformations with Industrial Relevance*. 241–246.

Tam, V.W.Y., Tam, C.M., Zeng, S.X., and Ng, W.C.Y., 2007. Towards adoption of prefabrication in construction. *Building and Environment*.

Tang, J., Zhang, M., Tang, H., and Chen, Y., 2015. Research on Cost Management of Construction Project based on Activity-based Costing. *In*: *International Conference on Civil, Materials and Environmental Sciences (CMES 2015)*. 51–54.

Taylor, S., 2009. *Offsite Production in the UK Construction Industry, abrief overview*. HSE.

Tennant, S., McCarney, M., Tong, M.K., and Tennant, G., 2012. Re-Engineering the Construction Supply Chain: Transferring on-Site Activity, Off- Site. *In*: *Procs 28th Annual ARCOM Conference*. Edinburgh, UK: Association of Researchers in Construction Management, 3–5.

Terkaj, W. and Urgo, M., 2014. Ontology-based modeling of production systems for design and performance evaluation. *Proceedings - 2014 12th IEEE International Conference on Industrial Informatics, INDIN 2014*, 748–753.

Thanoon, W.A., Peng, L.W., AbdulKadir, M.R., Jaafar, M.S., and Salit, M.S., 2003. The Essential Characteristics of Industrialised Building System. *In*: *International Conference on Industrialised Building Systems*. 10–11.

Thomas, G., 2011. Qualitative Inquiry A Typology for the Case Study in Social Science Following a Review of Definition , Discourse , and Structure. *Qualitative Inquiry*, 17 (6), 511 –521.

Tran, V. and Tookey, J., 2007. Labour Productivity in the New Zealand Construction Industry : A Thorough Investigation. *Australasian Journal of Construction Economics and Building*, 11 (1), 41–60.

Trehan, V., Chapman, C., and Raju, P., 2015. Informal and formal modelling of engineering processes for design automation using knowledge based engineering. *Journal of Zhejiang University: Science A*, 16 (9), 706–723.

Tsai, W.H., Yang, C.H., Chang, J.C., and Lee, H.L., 2014. An Activity-Based Costing decision model for life cycle assessment in green building projects. *European Journal of Operational Research*, 238 (2), 607–619.

Vakaj, E., F., C., H., T.A.-R., Pauwels, P., and Patlakas, P., 2021. Semanic representation of DfMA offsite housing.

Venables, T., Barlow, J., and Gann, D., 2004. *Manufacturing Excellence - UK Offsite Capacity in Off-Site Manufacturing*. Constructing Excellence.

Verhagen, W., Bermell-Garcia, P., Mariot, P., Cotton, J.-P., Ruiz, D., Redon, R., and Curran, R., 2010. (Costing) Knowledge-Based Cost Modelling of Composite Wing Structures. *International Journal of Computer Integrated Manufacturing*, pp.1.

Vernikos, V.K., Nelson, R., Goodier, C.I., and Robery, P.C., 2013. Implementing an offsite construction strategy: a UK contracting organisation case study. *In*: *Proceedings of the 29th Annual ARCOM Conference*. Reading, UK, 667–677.

Vibaek, K.S., 2014. *Architectural System and Structures - Integrating design complexity in industralised construction*. London: Routledge.

Volk, R., Stengel, J., and Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings - Literature review and future needs. *Automation in Construction*, 38 (October 2017), 109–127.

Voss, E., Jin, Q., and Overend, M., 2013. A BPMN-based process map for the design and construction of façades. *Journal of Facade Design and Engineering*, 1 (1–2), 17–29.

Wagner, A. and Uwe, R., 2019. BPO : The Building Product Ontology for Assembled Products. *In*: *Proceedings of the 7th Linked Data in Architecture and Construction Workshop - LDAC2019*. 106–119.

Wahab, A.N.A., Mukhtar, M., and Sulaiman, R., 2013. A Conceptual Model of Lean Manufacturing Dimensions. *Procedia Technology*, 11 (Iceei), 1292–1298.

Waissi, G.R., Demir, M., Humble, J.E., and Lev, B., 2015. Automation of strategy using IDEF0 - A proof of concept. *Operations Research Perspectives*, 2, 106–113.

Warszawski, A., 1999. *Industrialised and automated building systems*. First edit. London: E & FN Spon.

Willis, J.W., 2007. *World Views, Paradigms, and the Practice of Social Science Research*. London: Sage.

Wilson, L., 2010. *How to Implement Lean Manufacturing*. New York: McGrawHill.

Wong, R., Hao, J., and Ho, C., 2003. Prefabricated building construction systems adopted in Hong Kong. *In*: *Proc. of the International Association for Housing Science on Word Congress of Housing: Process and Product*. Canada.

Wu, S., Wood, G., Ginige, K., and Jong, S.W., 2014. A technical review of bim based cost estimating in UK quantity surveying practice, standards and tools. *Journal of Information Technology in Construction*, 19 (March), 535–563.

Xu, Y., Elgh, F., Erkoyuncu, J.A., Bankole, O., Goh, Y., Cheung, W.M., Baguley, P., Wang, Q., Arundachawat, P., Shehab, E., Newnes, L., and Roy, R., 2011. Cost engineering for manufacturing : current and future research. *International Journal of Computer Intergrated Manufacturing*, 25 (4–5), 300–314.

Xu, Z., Abualdenien, J., Liu, H., and Kang, R., 2020. An IDM-Based Approach for Information Requirement in Prefabricated Construction. *Advances in Civil Engineering*, 2020, 21.

Yaman, H. and Tas, E., 2007. A building cost estimation model based on functional elements. *ITU Journal of Faculty of Architecture*, 4 (1), 73–87.

Yang, H., Yeung, J.F.Y., Chan, A.P.C., Chiang, Y.H., and Chan, D.W.M., 2010. A critical review of performance measurement in construction. *Journal of Facilities Management*, 8 (4), 269–284.

Yi, W. and Chan, A.P.C., 2014. Critical Review of Labor Productivity Research in Construction Journals. *Journal of Management in Engineering*, 30 (2), 214–225.

Yin, R.K., 1994. *Case Study Research: Design and Methods*. Second. Bervely Hills: Sage Publishing.

Yin, R.K., 2009. *Case Study Reserach: Design and methods*. Fourth. London: SAGE Publications.

Yin, R.K., 2016. *Qualitative Research from Start to Finish*. Second Edi. London: Guilford Publications.

Yitmen, I., 2007. The challenge of change for innovation in construction : A North Cyprus perspective. *Building and Environment*, 42, 1319–1328.

Young, B., Harty, C., Lu, S., and Davies, R., 2015. Developing Temporary Manufacturing Facilities for Residential Building : a Case of the Modern Flying Factory. *Procs 31st Annual ARCOM Conference, 7-9 September 2015*, (September), 1033–1042.

Yunus, R. and Yang, J., 2012. Critical Sustainability Factors in Industrialised Building Systems Abstract. *Construction Innovation*, 12 (4), 447–463.

Zainal, Z., 2007. Case study as a research method. *Jurnal Kemanusiaan*, 9.

Zakaria, S.A., Gajendran, T., Rose, T., and Brewer, G., 2018. Contextual, structural and behavioural factors influencing the adoption of industrialised building systems: a review. *Architectural Engineering and Design Management*, 14 (1–2), 3–26.

Zhai, X., Reed, R., and Mills, A., 2014. Addressing sustainable challenges in China. *Smart and Sustainable Built Environment*, 3 (3), 261–274.

Zhang, S., Boukamp, F., and Teizer, J., 2015. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, 52, 29–41.

Zhang, X. and Skitmore, M., 2012. Industrialized housing in China: a coin with two sides. *International Journal of Strategic Property Management*, 16 (2), 143–157.

Zhang, Y., Fan, G., Lei, Z., Han, S., Raimondi, C., Al-Hussein, M., and Bouferguene, A., 2016. Lean-based diagnosis and improvement for offsite construction factory manufacturing facilities. *In*: *ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction*. 1090–1098.

Zhang, Y., Lei, Z., Han, S., Bouferguene, A., and Al-Hussein, M., 2020. Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance. *Journal of Construction Engineering and Management*, 146 (9).

Zhong, B.T., Ding, L.Y., Love, P.E.D., and Luo, H.B., 2015. An ontological approach for technical plan definition and verification in construction. *Automation in Construction*, 55, 47–57.

Zhuang, C., Miao, T., Liu, J., and Xiong, H., 2021. The connotation of digital twin, and the construction and application method of shop-floor digital twin. *Robotics and Computer-Integrated Manufacturing*, 68 (September 2020), 102075.