TOWARDS AN ONTOLOGY-BASED APPROACH TO MEASURING PRODUCTIVITY FOR OFFSITE MANUFACTURING METHOD

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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

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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 nonfinancial (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.

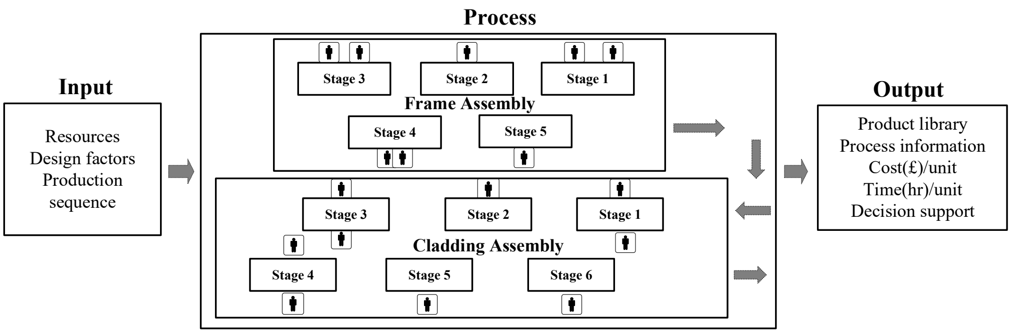

Figure 1: LSF panel system semi-automated linear production process

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 unit 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 Meth-ontology 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.

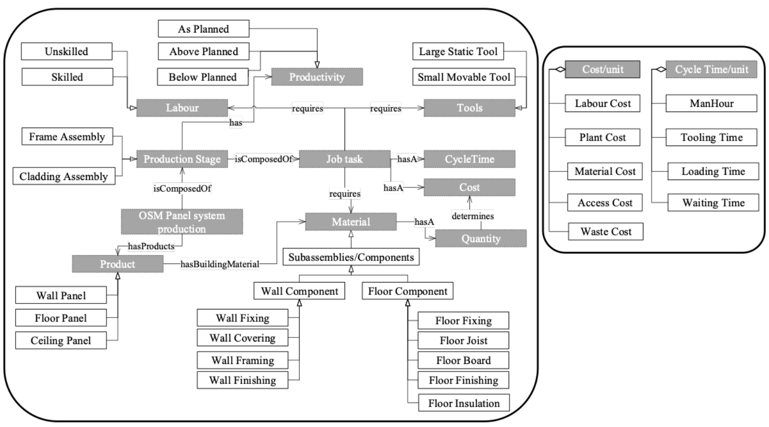

Figure 2: Structure of the OSM Panel System Productivity

(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 robot 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.

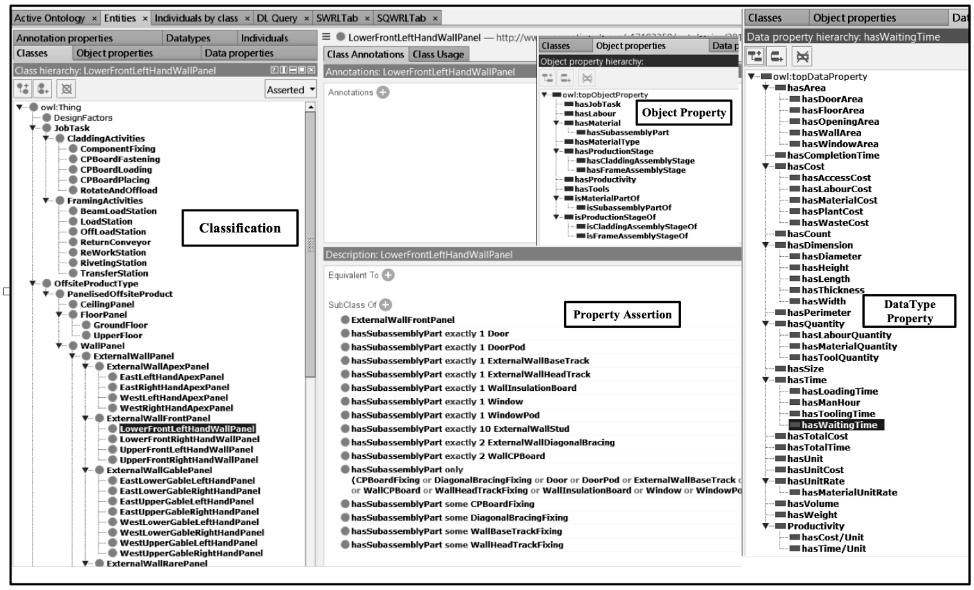

Figure 3: Modelled concepts in the ontology with Protégé

(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).

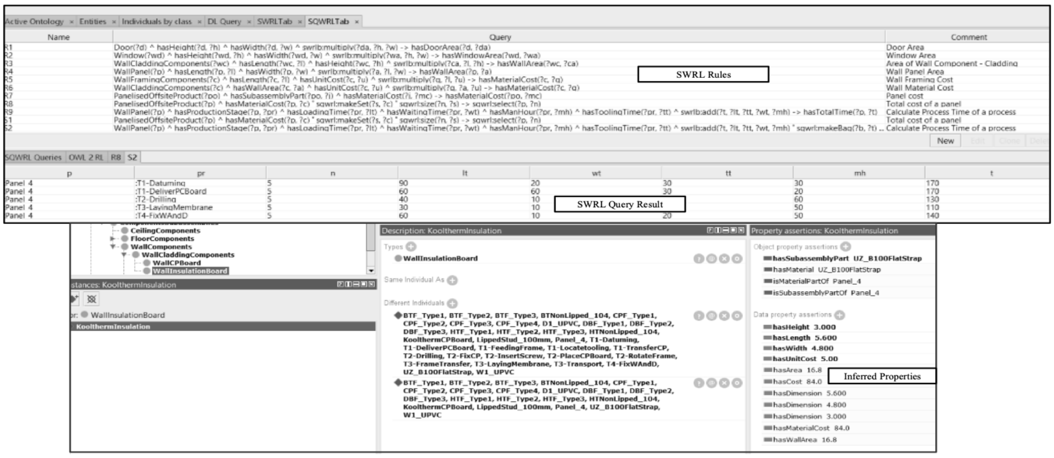

Figure 4: SWRL rules to enhance reasoning and computation in the ontology

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.

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