Tolerance management in prefabrication of mechanical, electrical, and plumbing installations

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Prefabrication in construction has advanced. However, mechanical, electrical, and plumbing (MEP) works still lag behind structural and interior applications. Inaccuracies in design and installation can undermine the benefits of prefabrication, making dimensional accuracy critical. Despite this, the literature lacks clear, unified methods for managing tolerances in MEP prefabrication. This research aims to advance tolerance management in MEP prefabrication by formulating prescriptive principles based on best practices. A multiple case study approach with five projects was adopted. Four cases with advanced prefabrication and/or tolerance management approaches and one with tolerance issues were studied. The cases included two hospitals, two apartment buildings, and one laboratory, representing projects with differing functional requirements and tolerance environments. Thematic analysis was applied to interviews, documents, and site visits. Seven prescriptive principles for tolerance management in MEP prefabrication are the primary contribution of the study. Among these, the role of communication, detailed design, and quality control are emphasized, while buffer assembly is identified as a distinctive MEP tolerance management method. The novelty and industry impact of the principles are underscored by the lack of systematic research on tolerance management in MEP prefabrication and by the fact that none of the case projects applied all the principles. Adoption of these principles is recommended to guide design, manufacturing, and installation to improve productivity, reduce lead times, and enhance quality.

Keywords: tolerance management, prefabrication, industrialization, MEP, variation

Introduction

Effective tolerance management is key to improving dimensional accuracy, enabling prefabrication, and tackling construction's persistent quality and productivity issues. In industrialised processes, measuring and controlling dimensional variation is essential (Deming, 1982; Womack, 1990). Similarly, in construction, managing tolerances and

reducing improvisation and variation are necessary conditions for systematic improvement. However, tolerance management remains poorly understood in the construction industry. Designers and contractors often overestimate the dimensional accuracy achieved on-site, and there is limited clarity on what levels of tolerance are realistically attainable or required to ensure reliable assembly (Baker, 2003).

The construction industry is unique in that tolerances can range from less than a millimetre for many factory-made components to tens of millimetres for numerous in situ components (Milberg, 2006; Ballast, 2007). Some trades adhere to tolerances derived from established standards, while others adopt tolerances based on project-specific requirements. Often, tolerances are not specified in the design documents or elsewhere, and trades may rely solely on workers' experience (Koskela, 2000; Ballast, 2007; Talebi, 2019). The insufficient integration of tolerance requirements in design leads to time and material waste, and effectively, to the unintended transfer of design tasks to workers. It also results in buildings failing to meet specifications due to discrepancies between design and installation requirements (Talebi et al., 2021; Valkonen and Seppänen, 2023; Seppänen and Görsch, 2022).

Several studies have documented problems related to dimensional accuracy in construction and identified their root causes (e.g., Alshawi and Underwood, 1996; Jingmond and Ågren, 2015; Milberg and Tommelein, 2019). Talebi et al. (2021) reported eleven such issues that can be categorized as follows: (1) inadequate tolerance management in design, (2) insufficient communication of tolerance requirements and methods, and (3) failure to adhere to requirements or to select appropriate construction methods. Furthermore, generic frameworks for TM in typical construction projects have been outlined (e.g., Talebi et al., 2020; Milberg and Tommelein, 2019; Milberg, 2005; Milberg and Tommelein, 2004). More recent tolerance management studies have

primarily focused on quantitative and analytical methods for measuring and analysing dimensional variation, while the organisational processes through which tolerance requirements are defined, communicated, and enforced remain underexplored (Long et al., 2023; Zhang et al., 2024; Huang et al., 2024). However, previous research does not consider Mechanical, Electrical and Plumbing (MEP) installations.

MEP is among the most complex construction activities. It remains highly reliant on experience to execute designs (Seppänen and Görsch, 2022). MEP systems consist of numerous interconnected components installed in confined spaces, often in proximity to other systems constructed by separate contractors (Korman et al., 2003). Managing such installations is inherently difficult, and the quality of execution directly influences the performance of the systems. In the context of MEP systems, failure to meet specifications can cause problems such as leaks, poor energy performance, and bacterial contamination (Zalejska, 2019; Gurmu, 2023). In addition to these functional issues, studies on the time use of MEP installers indicate significant wasted effort in the construction phase (Görsch et al., 2024). While the literature provides valuable insights into tolerance management in general, it does not specifically address MEP installations. This omission highlights a significant research gap, as tolerance management in MEP work presents distinct challenges that remain underexplored.

In view of this, the aim of the present study is to identify principles for TM in MEP prefabrication. The study adopts an exploratory, principle-building approach, in which the research questions function as analytical lenses for structuring empirical observations rather than as variables for statistical testing. To identify such principles, we present four research questions based on the categorization by Talebi et al. (2021):

- Identification: What tolerances should be defined, and what are causes of variation affecting MEP installations?
- Planning: What are appropriate tolerance management methods in MEP installations to accommodate tolerance requirements?
- Communication: How can tolerance requirements and tolerance management methods be effectively communicated between design and construction?
- Control: How can the fulfilment of design intent be guaranteed?

The rest of the paper is structured as follows: First, a literature review of tolerance management is presented. Second, the research methods used are described. Third, the results from five case projects are presented, and a cross-case analysis is conducted. Based on this analysis, seven principles for TM in MEP prefabrication are proposed, followed by the Discussion and Conclusions.

Tolerance management

Importance of Tolerances

The concept of tolerances in manufacturing has its roots in the early days of industrial manufacturing, driven by the need for the interchangeability of parts and the division of labor (Womack, 1990). Tolerances are defined as the maximum allowable geometric or positional deviations. They are crucial to ensure that parts can be assembled without modifications and that the assembled systems operate correctly (Gerth, 1997; Ballast, 2007). This approach facilitated mass production through the parallel manufacturing of subassemblies, with tolerances influencing both the production process and the quality of the final product (Hopp and Spearman, 2001).

The construction industry has long sought industrialisation to improve productivity

(Kadir et al., 2006; Eriksson et al., 2013). Much of site work remains rooted in craft production, akin to manufacturing before mass production. Skilled tradespeople are required for complex on-site coordination and fitting of components. Removing the need for such coordination through management of tolerances is a key step towards industrialisation of construction (Talebi et al., 2016). This shift parallels an assembly plant, where tasks are simple, standardized, and require minimal training (Liker, 2020). Precast concrete elements exemplify this approach, whereas MEP systems remain largely site-built and subject to significant variation.

Managing tolerances is essential for ensuring both quality and production efficiency in construction. When parts must be modified to fit, quality issues often arise, leading to deviations in function or appearance (Talebi et al, 2021). Such variations can accumulate, resulting in cascading problems throughout the assembly or construction process (Milberg, 2006). These issues not only affect the final product but also complicate future maintenance, as replacement parts must be adjusted to non-standard conditions (Milberg et al., 2002). Production efficiency likewise suffers from time-consuming modifications and rework, in comparison to the situation where components that fit as designer are connected (Tommelein et al., 1999).

Managing tolerances

Tolerance management deals with the entire process of achieving a product that meets the design intent from functional and process perspective (Milberg, 2006). Three core concepts of tolerance management are used here. First, variation denotes dimensional or positional deviation in components or assemblies caused by inaccuracies in machining or human work. Second, tolerance requirements specify the maximum permitted variation in location, shape, or size to ensure fit and function. Third, a tolerance issue

arises when a variation exceeds the specified requirements (Thornton and Tata, 2000).

Tolerance management begins with assigning tolerance requirements. These may be project-specific or product-specific requirements designed to guarantee fit and function. Product-specific requirements can be adopted from industry standards, such as American Concrete Institute (ACI) (2015) and American Institute of Steel Construction (AISC) (2022). Project-specific tolerances should be selected in accordance with functional requirements and process capability (Milberg, 2009). Project capability refers to the ability of tools and the production team to achieve a certain level of accuracy (Milberg, 2009). Implementing unnecessarily stringent tolerances, beyond what functional requirements demand, can lead to waste and avoidable rework. For example, in Milberg's (2006) bolt case, overemphasis on accuracy led to unnecessary corrections and delays. Too long bolts were replaced, although being too long had no effect on functionality (Milberg, 2006). Conversely, overly loose tolerances can also lead to re-work to ensure fit (Milberg and Tommelein, 2019).

After assigning tolerances, the buildability of the design must be validated. Buildability refers to the ease of assembly (CIRIA, 1983). In the context of tolerances, buildability includes analysis of tolerance compatibility (Sfantsikopoulos, M. M., 1993; Milberg and Tommelein, 2019). The tolerance of the overall assembly results from the combined tolerances of its individual components. For example, manufacturing tolerances of two interconnected components must be such that positional tolerances for both components can still be achieved. Established analytical approaches, such as tolerance mapping, linear stack-up analysis, and tolerance loops (Milberg and Tommelein, 2005; 2019), support the detection of inconsistencies and the selection of construction methods that can achieve the specified accuracy. The present study does not apply these analytical tools directly, but it draws on their principles to motivate prescriptive practices for MEP

prefabrication. Incorporating buildability and tolerance compatibility into design requires detailed knowledge of construction.

The involvement of a detailer is often associated with improving buildability or constructability in MEP design coordination (Court, 2019). In the US market, engineering design is often separated from detailed design regardless of the mode of construction (Khanzode et al., 2008). This practice is commonly justified by the assumption that contractors possess the most accurate understanding of work sequencing and installation techniques, which are typically beyond the scope of engineering design. A similar division of responsibilities can be seen in precast concrete construction, where structural engineers develop the conceptual design, and manufacturers further detail the elements for production. In contrast in Finland, contractors are less frequently involved in detailed MEP modeling, and they often lack advanced modeling capabilities (Lavikka et al., 2021; Alhava et al., 2024). Based on the authors' observations, this is the case in many European countries.

In manufacturing, the equivalent of detailed design is referred to as design for manufacture and assembly (DfMA). DfMA generally implies a high level of detail and an explicit alignment of design with the production system. Literature on DfMA emphasizes that design should be undertaken by individuals with a deep understanding of the manufacturing process and its efficiency constraints (Gao et al., 2018). While detailed design in construction serves a similar purpose, it typically addresses assemblies with lower levels of repetition as buildings are often unique. One key role of detailed design in construction is to reduce variation by eliminating uncertainties during design and installation (Montazeri, 2024).

Variation is an inherent characteristic of any production system and can never be fully

eliminated but it must be managed. In construction this can be achieved through designed buffers, taking different forms depending on the context. For example, inventories act as buffers between production and demand in manufacturing (Hopp and Spearman, 2001), while time buffers are commonly applied in scheduling to absorb variation in production rates (Seppänen et al., 2010). In the management of dimensional variation in construction, quantified variation must similarly be anticipated and managed (Shahtaheri et al., 2017). This is critical for ensuring flush and functional connections between building elements. For instance, floor assemblies must form a continuous surface. A floor made of concrete elements such as hollow-core slabs and beams each exhibit manufacturing and installation tolerances. To accommodate these, the opening for the slabs is intentionally slightly wider than the slabs themselves. This ensures that the slabs can always be installed, though it results in a narrow seam that must later be grouted with concrete. MEP installations face similar challenges. All connections must be water- or airtight, and the inevitable dimensional variation must be accounted for in design and installation. Examples of buffers in MEP installations are scarce. One such example is the use of a flexible duct connector in ventilation systems (Tommelein and Gholami, 2012).

Tolerance requirements must be visible, consistent and actionable in the information handed from design to manufacture and installation. Prior studies report requirements being set out in drawings and specifications, often with reference to standards (Milberg, 2006; Milberg and Tommelein, 2019; Talebi et al., 2021) and propose structured artefacts such as unified tolerance reports to consolidate them (Talebi et al., 2019). Ambiguous, hard-to-find or contradictory information has repeatedly been linked to tolerance issues. While geometric dimensioning and tolerancing (GD&T) has been explored for construction as a compact visual language (Talebi et al., 2020), it has not

been yet adopted widely. Therefore, the present study focuses instead on practices that ensure clarity and traceability of requirements irrespective of notation.

Building information models (BIM) also holds promise for communicating tolerance requirements by storing attributes at object level and by checking clearances using clash detection (Rausch et al., 2022). However, standard BIM workflows are not optimal for managing tolerances in construction, as they lack the necessary infrastructure, such as indication of tolerance zones, stack-ups across interfaces or the propagation of variation through assemblies. Nor do they provide integrated links between tolerance requirements, measurement methods and quality-control evidence. For this reason, in the context of tolerance management, BIM is mainly limited to the concept of clearance, referring to sufficient distance between components to serve as installation space and buffer for variation. Consequently, BIM is a useful carrier of selected information (e.g., minimum clearances), but it is not, on its own, a comprehensive tolerance management system. Complementary documentation and control processes are required.

In addition to defining requirements and outlining methods for compliance, quality control is a crucial aspect of TM. Its purpose is to document adherence to specified tolerance requirements. Failure to comply with these requirements can result in incompatibility in subsequent installation, ultimately leading to defective subassemblies (Li et al., 2020). It is essential to identify the root causes of any tolerance issues documented in quality control and take corrective action to prevent recurrence. This can include removing errors from designs for future assemblies, thereby contributing to a more efficient and reliable process (Talebi et al., 2020). Identifying problems and their root causes is not yet sufficient for continuous improvement, this is achieved via effective communication.

Communication underpins tolerance management and prefabrication. To support industrialised delivery, requirements, methods and measurement evidence should be communicated through a single consistent source. Deviation reports and root cause analyses should be communicated to influence upcoming design and work. In this study, communication is treated as an enabling condition that interacts with identification, planning and control of tolerances.

Point of departure

Tolerance management is a long-established practice in industrial manufacturing. It has been partially adopted in construction, particularly for structural and architectural elements. However, its application has largely stalled at this stage. MEP installations remain a domain of craft production, and there is a notable absence of both scholarly literature and established practices addressing tolerance management in MEP prefabrication and installation.

In the construction context, MEP systems exhibit a high degree of complexity, understood here as systems comprising many interconnected parts (Baccarini, 1996). This complexity is further intensified by the sequential nature of construction, where earlier phases affect subsequent phases through physical and informational connections, thereby generating variation (Bertelsen, 2003; Bertelsen & Koskela, 2003). The need for managing such project complexity has been emphasized in prior research (Luo et al., 2017), and in MEP installations tolerance management can be interpreted as a system-specific managerial response to complexity-induced variation.

Consequently, existing tolerance-management methods are not directly transferable to MEP without adaptation. Translation and tailoring of established tolerance-management knowledge to the specific conditions of MEP prefabrication and installation is required.

This highlights a critical need for research focused specifically on tolerance management for MEP systems.

Research methods

The research paradigm guiding this study is pragmatism. While the existence of an objective reality, as emphasized in positivism (Crotty, 1998), is acknowledged, the domain of construction management relies heavily on processes devised and performed by humans. Consequently, it is essential that practitioners' perception and experiences are the focus of inquiry (Kelly and Cordeiro, 2020). Taken together, these individual accounts constitute a representation of truth. This truth is inherently dynamic, being a man-made construct, and evolves over time, unlike natural truths governing the nature of reality (Lincoln and Guba, 1985).

An exploratory multiple case study was conducted on five case projects to examine tolerance issues and tolerance management practices in MEP prefabrication and installation. Case study research is well suited for answering questions on contemporary phenomena without the need to control studied events (Yin, 2018). Case study research can be used to collect qualitative or quantitative data. While quantitative data, such as measurements of variation or occurrences of tolerance issues, can be collected, this type of numerical data alone would not provide the depth of understanding required to explore the complexities of TM practices in the case projects. Case study research, as noted by Flyvbjerg (2006) and Fellows and Liu (2015), is particularly useful for gaining rich, contextual insights into complex phenomena, such as the nuanced practices involved in TM. Qualitative approach is chosen to consider the case projects as whole instead of reducing them to separate variables (Yin, 2018). The need to understand current processes and issues related to them before proposing solutions (Liker, 2020)

also supports choosing case study research and qualitative approach.

The five case projects were chosen to address the research questions using purposive sampling. Purposive sampling is appropriate for case study research where cases with specific qualities are of interest (Brinkman, 2013).

The cases were selected from a population of construction projects with MEP installation work. A research consortium of 21 Finnish major construction and consulting companies and one university was asked for cases based on the selection criteria, making use of purposive sampling. The selection criteria focused on capturing a variety of MEP installation scenarios, including both traditional on-site construction and prefabrication methods as well as different levels of quality control implementation. Figure 1 shows the matrix used for case selection, where on x-axis is the relative level of MEP prefabrication and on the y-axis is the relative level of quality control. The aim was to have at least one project in each quadrant for comprehensive coverage of different variables. However, no projects with both advanced quality control and advanced prefabrication could be found, which is an interesting finding itself. In addition to the four quadrants the criterion of availability was used. All projects should be ongoing or recently finished to guarantee reliability and availability of data gathered via interviews and site visits.

[Placeholder for Figure 1]

Cases 1 and 5 did not use prefabrication. Case 2 used prefabricated ventilation shafts, which represent a small part of all MEP installations in the project. Case 3 prefabricated large part of the MEP installations in the apartment renovation project. However, due to the small project scope the quantity of installations and the number of systems was

lower compared to case 4. In Case 4, MEP and special systems of a large laboratory building were largely prefabricated.

In terms of quality control, Case 1 had the least developed quality control during the construction, and case 5 had the most advanced and systematic quality control. In between, Case 3 did not report any systematic quality control methods, issues were selectively reported to a group chat. Case 4 highlighted the need for BIM quality control to guarantee buildability. Case 2 also highlighted buildability of designs and tested connections between subassemblies. The case projects and their characteristics are presented in Table 1.

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Data collection and analysis

Data were collected via semi-structured interviews, document reviews, and site visits in all cases. Semi-structured interviews were selected as a research method to investigate the problems in depth and allow for dialogue (Brinkman, 2013). The interviewees were selected based on initial interviews with the case project's contact person. Snowballing was used to identify more interviewees in each interview. Each case had only a few people with deep understanding of tolerances, and they were recommended for interview. The interviewed people are presented in Table 2, and the themes of the interviews are presented in Figure 2.

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[Placeholder for Figure 2]

The objective of these interviews was to obtain a comprehensive overview of the case

project, and to address the selected interview themes based on the research questions. The document review included analyzing design drawings and models to identify causes of tolerance issues, tolerance requirements, and tolerance management methods. Data were collected as notes, photos, recordings, and design documents.

The data analysis was conducted in two phases. First, each case was analyzed individually using thematic analysis, integrating data from documents, interviews, and site visits. In the second phase, a cross-case analysis was performed to identify commonalities and differences across cases. These two phases also reflect two levels of triangulation: method triangulation within individual cases and source triangulation across cases (Patton, 1999). The resulting seven prescriptive principles for tolerance management in MEP prefabrication are grounded in the cross-case analysis and the recurring themes that emerged from the data. Principles as an outcome of research is justifiable as they can be used to capture and communicate generalised knowledge from cases (Chandra et al., 2015). The critical role of principles as boundary objects transferring information between research and practice also enables continuous reconstruction of such principles (Romme and Edenburg, 2006).

Results

Tolerance Issues and Their Causes in MEP Installations (Case Project 1)

In case project 1, which involved traditional on-site MEP installations, a comprehensive evaluation was carried out to identify tolerance issues. These issues primarily manifested due to the absence of TM methods in the design phase. Observations and interviews indicated that insufficient design coordination resulted in poor buildability, causing installers to solve problems on-site and to deviate from designs. These tolerance issues were avoidable, and they were tacitly accepted by laborers. They attributed

largely to the poor buildability of the initial designs.

Subsequent sections delineate three examples of tolerance issues that were identified and documented on the construction site of case project 1. These issues are presented because they were highly recurring and severe thus establishing a deeper understanding of tolerance issues in MEP installations. The three examples of tolerance issues are duct crossing in suspended ceiling, conduit pipe in cast in situ slab, and rerouting of duct and silencer. The recurrence of these three issues is shown in Table 3.

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Duct Crossing in Suspended Ceiling

The first tolerance issue was related to a duct crossing. The design included two round ducts, but the actual construction used a special crossing part. The part was used to fit the installation into the ceiling space and to rectify a clash between the ducts and the suspended ceiling. Solving the problem required using components that were not designed and a minor alteration of duct routes. The original design would have resulted in lowering the suspended ceiling. This would have caused contractual complications, as the ceiling height had been a feature in the project's marketing materials. The duct-crossing problem occurred in nearly all apartments and caused the need for the installer to re-route ducts and design the new routes on-site. The actual installation is presented in Figure 3.

[Placeholder for Figure 3]

Clash with conduit pipe and silencer

The second tolerance issue concerned the misalignment between electrical conduit pipes

in cast-in-situ slabs and ventilation parts. Variability in the locations of conduit pipes resulted from faulty measurements, lack of specifications, and poor coordination. Conduit pipes were not included in the design model and thus could not be coordinated. This led to complications in both the electrical and ventilation installations, notably altering the height of the ventilation system. The issue could have been resolved by specifying locations and positional tolerances for all components. An example of a collision between a silencer and conduit pipes is presented in Figure 4.

[Placeholder for Figure 4]

Rerouting of Duct and Silencer

Regarding the third tolerance issue, the necessity of rerouting a duct and a silencer into adjacent space was scrutinized. The underlying cause was spatial limitations in the bathroom. The ventilation components within the bathroom were designed to be in close proximity, not affording the space necessary for installation or positional variations. The original design and the final installation are illustrated in Figures 5a and 5b, respectively. A buildability analysis in the design phase could have revealed a more effective strategy for solving the issue.

[Placeholder for Figures 5a and 5b]

Tolerance Management Related to a Prefabricated Ventilation Shaft (Case Project 2)

In case project 2, a new hospital construction project used prefabricated ventilation shafts. The prefabricated shaft consisted of a steel frame, insulated ductwork, and a heavy plastic envelope protecting the shaft element. A separate supplier was commissioned to design, manufacture, and install the shaft elements. The shaft elements

were installed inside the concrete shafts during the framework erection. The case gave valuable insights into basic tolerance requirements and tolerance management methods related to MEP prefabrication.

Designing for prefabrication required collaboration between the HVAC designer, structural designer, steel frame provider, and shaft manufacturer. Initial duct sizes and provisional locations were proposed by the HVAC designer and were subject to modification if the element manufacturer recommended changes to streamline the manufacturing process. The shaft connection to the building structure was coordinated with the structural designer. The steel frame provider, who was subcontractor to the shaft manufacturer, made designs and a BIM for the steel frame based on required sizes. The shaft manufacturer was responsible for coordination, actual assembly, and installation of shaft elements.

Four critical tolerances were identified: 1) the height of connections to horizontal ducts, 2) vertical connections between shaft elements, 3) shaft element size, and 4) shaft element connections to structures. These requirements were not documented anywhere but had been learned by trial and error by the manufacturer.

The height of connections to horizontal ducts, the first critical tolerance, had to be correct to fit to all MEP installations in corridors. No specific tolerance requirement was reported by the manufacturer. The connection heights were fixed in workshop installations and could not be changed later without major rework.

The second critical tolerance, the horizontal accuracy of connections between elements, required millimeter-level accuracy of duct locations within the prefabricated elements. This accuracy allowed for ease of assembly on-site, with minor deviations addressable through hanger adjustments. Before shipping, all element connections were rigorously

tested and fine-tuned in the workshop. All elements were vertically connected via sliding connectors, allowing for absorption of vertical variation and ease of connection on site.

Element size constituted the third critical variable controlled by a tolerance. The element size was affected by the dimensions of the shaft opening, transportation logistics, and workshop capabilities. Tolerance requirements for size came from shaft size and variations in the concrete work. The manufactured element had to fit into the shaft space. Concrete work has loose tolerances in precast element manufacturing and installation, with the potential of significant variation in shaft size compared to designs. To mitigate the risk of fitting issues, a clearance of 50 mm was used between the elements and all structural features during the design phase.

Finally, the fourth critical tolerance involved the shaft element's connections to building structures. These connections had to absorb both geometric variations within the concrete work and positional variations of the shaft element. Furthermore, these connections had to fit into the building structure without cutting rebars.

Tolerance Management in Prefabrication of Apartment Building Ventilation (Case Project 3)

In case project 3, the general contractor had determined, based on experience from previous projects, that the MEP designer's construction drawings are non-buildable for prefabrication manufacturing and assembly. The designs had unresolved clashes, missing hangers, and no manufacturer-specific parts, therefore not enabling prefabrication. Accurate drawings for manufacture and assembly using manufacturer-specific parts and millimeter accuracy had to be drafted at the expense of the main contractor. During installations, it was noticed that accurate prefabricates were not

compatible with inaccurate concrete elements. Three sources of variation and three respective tolerance management methods were identified for precast concrete buildings. These are presented in Figure 6.

[Placeholder for Figure 6]

The first source of variation was the height difference of ducts in a modular bathroom unit and prefabricated ductwork. A method using two 45° bends to make a 90° change in direction and simultaneously accommodating for small differences in height was devised. It required a change of direction that had to be designed to accommodate variation in connection heights.

The second source of variation was the difference in distance between two points in designs and on site. This was caused by inaccuracies in concrete element manufacturing and installation, as well as the installation accuracy of MEP elements. The difference had to be absorbed in directions x and y, which was done by means of a telescopic connector allowing for 100 mm of variation in both directions.

The third source of variation was the rotation deviation of a precast concrete element caused by installation tolerance. The rotated element caused misalignment between the prefabricated duct assembly and duct connection in the element. This variation was absorbed by leaving one end of a 90° bend unfastened, allowing for angled installation of the connecting duct.

All the above-mentioned methods required a change in the direction of the duct. The change of direction had to be designed to avoid improvisation on site. To avoid unnecessary changes in direction, these methods (changing 90° bends to two 45° bends, telescopic connectors, and unfastened connectors in assemblies) should be combined to

absorb variation from all three sources in one connection.

Tolerance Management in State-of-the-Art Prefabrication (Case Project 4)

Extensive use of MEP prefabrication in a state-of-the-art example from California, case project 4, gave insight into best practices in TM for MEP. The MEP provider employed a design build contract. This project structure enables seamless collaboration across design, manufacturing, and installation. Solving tolerance issues at all stages becomes a common interest, as additional gains or costs stay in the company.

Four methods for managing tolerances in MEP prefabrication were identified. The first is detailed model coordination for all involved trades. The second method is the application of installation-level experience in design, resulting in buildable designs. The third practice involves establishing close collaboration throughout the design, manufacturing, and installation phases. The fourth practice is the incorporation of strategic buffer assemblies within the prefabrication process. The absence of installation tolerances in this case project is noteworthy. The focus, instead, was on formulating and implementing methods that guarantee accuracy in installations. These methods are recognized as the project's approach to tolerance management.

The buildability of designs is a foundational requirement for the implementation of prefabrication, and it can also be seen as a TM strategy. The MEP contractor in case project 4 considered buildability so important they were willing to lead the BIM coordination, should the general contractor have lacked the needed proficiency. Accurate use of prefabrication requires solving all clashes in design models and then adhering to these models during construction. This requires design models with a high level of detail (LOD), which enables all potential issues to be addressed during the design phase, thus mitigating the risk of tolerance issues. The company employed

models at an LOD range of 400–450, a level that includes hangers in the modeling.

In the MEP design process, responsibilities were allocated between an engineer and a detailer. The engineer was tasked with system design and spatial allocation for primary routes and essential components. The detailer finished the models by adding details, coordinating designs, and designing for manufacturing. The detailer provided the workshop with isometric drawings including the bill of materials. The detailer had previous installer experience and training in modelling. According to the case company, the detailer's experience in field was critical to improve buildability. Through close collaboration, the engineer and detailer aimed to produce systems that were both functional and easily buildable.

While the company did not explicitly identify installation tolerances as a challenge, they had developed "strategic buffer assemblies" to accommodate variations. A strategic buffer assembly is a custom-built connection part designed to fit an empty space between prefabricated elements. Measurements for buffer assembly were taken after element installation, and the parts were manufactured in the workshop to exact measures. To reduce the number of custom-built parts, buffer assemblies were not used between all elements; they were used only in specified locations. A visualization of a buffer assembly is presented in Figure 7.

[Placeholder for Figure 7]

Quality Control as a Tolerance Management Method (Case Project 5)

Advanced quality control of MEP installations in a large hospital project afforded good understanding of TM in a large, multi-system project. Case project 5 used BIM in designing, installation, and quality control. The quality control process required designs

to be buildable and installers to follow designs.

The quality control process started from dividing buildings into sections for inspection. Inspection proceeded sequentially, one section and one construction trade at a time. The current stage of inspection was recorded into a matrix (Figure 8). The contractors were required to follow the BIM in installation. Additionally, other design documents specified parts, equipment, and hanger requirements. The first step in quality control was contractors' self-inspection and fixing of possible errors. This self-inspection was deemed a critical phase; all deviations recorded later by the inspectors required significant work in documenting problems and resolutions. Fixing problems based on self-inspection did not require documentation of problems or fixes.

[Placeholder for Figure 8]

After self-inspection, the section was inspected with the inspector, contractor, foreman, and subcontractors together. All deviations from BIM and other design documents (i.e., tolerance issues) by visual comparison were documented in a digital system. A deviation could be a different routing, different components, or missing hangers. The tolerance for these deviations was variable, contingent on the availability of space; looser tolerances were permitted in less constrained areas, and vice versa.

For all recorded deviations, the inspector required either a change of installation or update of designs to align the as-built with the as-designed. For installation changes, contractors executed the modifications and logged them into the same digital system used for recording deviations. Inspectors then accepted or rejected these fixes. For deviations not requiring changes in installation, the contractor was required to deliver the as-built drawing or model for designers to update the main model. This rigorous process led to contractors taking self-inspections seriously and fixing problems in

advance to avoid the process of validating fixes. Another attribute supporting the successful quality control process was the collaborative alliance contract between stakeholders. The quality improved significantly, measured in number of reported deviations, as the project advanced. Once all the required changes were accepted and as-built models were delivered to designers, the inspectors marked the section completed for the trade. The process for quality control is presented in Figure 9.

[Placeholder for Figure 9]

Tolerance requirements for the project were not specified in any systematic way. However, a common understanding existed between the inspector and contractor on what constituted a deviation. The installers stated that installation accuracy with the used methods was 50–100 mm. The inspectors stated that while situational consideration was used for positional tolerances, a variation of 500 mm or more was certainly a deviation. Most common deviations were missing or inadequately installed hangers, or different routing of pipes or ducts due to buildability issues in designs.

Cross-case Analysis

The insights from the five case projects illuminate TM in MEP prefabrication. Case project 1 served as a cautionary tale, highlighting the challenges arising when tolerances are neglected and providing valuable insights into the critical tolerances for MEP prefabrication. Case project 2 offered a view into TM in limited use by a MEP prefabricator and a separate supplier, while case projects 3 and 4 represented advanced examples of MEP prefabrication and related TM. Case project 5 demonstrated the necessity of quality control to ensure adherence to design specifications and presented a methodology for implementing such control. Key findings from the cases are presented in Table 4.

[Placeholder for Table 4, table at the end of the document]

Based on cross-case analysis of five MEP projects with varying degrees of prefabrication and tolerance management, seven prescriptive principles were identified to support the successful implementation of MEP prefabrication. These principles address the entire lifecycle of construction from design to installation, with a focus on managing dimensional variation. The principles are interdependent, forming a continuous loop that begins with setting tolerance requirements and ends with learning through feedback and communication. Table 5 summarises the seven principles. The analysis of the cases and Table 5 shows that none of the studied case projects used all the seven principles. This finding, combined with the fact that none of the companies had systematic and documented TM in place, indicates the novelty of the principles.

[Placeholder for Table 5, table at the end of the document]

Defining tolerance requirements is necessary. Essentially, tolerance requirements state how accurately designs must be implemented. Not assigning tolerance requirements means that there is no clear requirement to follow designs. Judgement on whether a deviation is too large is left to the individual installers, managers, or inspectors. Ultimately this leads to unnecessary improvisation and waste in the construction process. Although literal interpretation of missing tolerance requirements is that no deviation is allowed, the practice is different as Case 1 demonstrates. All prefabricating cases (2, 3, 4) highlighted the need for dimensional accuracy and following designs. Case 5 indicates that tolerances can vary depending on the location, crowded areas need tighter tolerances. In Case 1, it can be argued that the lack of tolerance requirements contributed to tolerance issues. The results clearly indicate a causal relationship between tolerance requirements and achieved accuracy. The first principle states the

necessity of assigning tolerance requirements. These requirements for accuracy necessitate changes in the upstream processes of designing, namely the required accuracy must be supported by buildability and tolerance-compatibility of designs.

The requirement of buildability follows directly from the requirement of accuracy. The designs must be feasible to be executed within the tolerance limits. Tolerance issues can arise either from designs that are non-buildable or from improvisation during implementation regardless of buildable designs. Installation according to design can only be achieved with buildable designs. Considering tolerances, the buildability analysis must also include a tolerance compatibility analysis. Essentially, is the entire installation still possible in the case of the occurrence of maximum allowed variation considering all the possible combinations of accumulated variations to different directions? Especially important is to notice that MEP installations experience outside variation from dimensions and locations of structures for example. Tolerance compatibility analysis is an extension of the commonplace practice of clash detection. Buildability of designs was essential in all the prefabricating cases (2, 3, 4) and Case 5 regardless of their diverse nature. In turn, Case 1 was an example of unwanted consequences of unbuildable designs. Hence the second principle is to ensure buildability of designs by means of tolerance compatibility analysis. Variation can be quantified but not eliminated and as a result, the remaining variation must be addressed by buffers.

Buffers are required to address the unavoidable existence of variation. In on-site construction, variation can be absorbed by every consecutive part as they are cut to length based on both designs and measurements on-site. In prefabrication, however, assemblies are manufactured according to precise measurements from designs representing ideal situations. Buffers are needed to bridge the gap between the ideal and

the actual. The benefits of prefabricating are tightly linked with the usability of the assemblies: if on-site modifications are needed, the benefits diminish rapidly. Buffer assemblies, alongside other TM methods, allow the effective use of prefabrication. The location and method of absorption must be carefully planned for each project and installation as the mechanisms and magnitudes of variation are diverse. Absorption mechanisms for variation were similar in cases 2, 3 and 4. Cases 2 and 3 used telescopic connectors for duct systems. The strategic buffer assembly used in case project 4 was slightly different, as it was not used for every connection but only in selected locations where cumulated variation was absorbed. Additionally, clearances to concrete structures were reported as a method for absorbing variation in case project 2. The third principle of absorbing variation by means of buffer assemblies is supported by similar findings from all prefabrication cases. Combining principles I, II, and III requires skilled knowledge in engineering, installation and manufacturing from the designer.

A detailer transforms the engineers' system design to an actionable plan. Where the engineers' design states how a system should operate, the detailer's design states how the system should be constructed. In the case of MEP prefabrication, a detailer is a person, often but not necessarily employed by the contractor, responsible for the abovementioned transformation in accordance with principles I, II, and III. The detailer works in co-operation with the entire supply chain from engineering to installation via manufacturing and transportation. The negative effects of building with the engineers' designs were shown by Case 1. All prefabricating cases had employed a detailer separate from the engineering roles. For these reasons, principle four states that addressing tolerance requirements, buildability, and buffers is directly connected to construction and should therefore be performed by a detailer familiar with the installation methods. However, not even the best design intent will be fulfilled if it is

not effectively communicated.

Unambiguous visual representation is key to successful communication of design intent, tolerances, and TM methods. In traditional MEP construction information is scattered to multiple different documents and these documents often have contradictory information. BIM models contain information on location and dimensioning of components but might not contain the required component types. In Case 5, it was found that issues had been caused by contradicting information in BIM and other design documents. For prefabrication, the design model must include all the right components, and the detailed information should be consolidated in a single manufacturing document. Isometric drawings and manufacturing bills of materials were used in case projects 3 and 4. Therefore, the fifth principle states that unambiguous visual outputs should be used for communication. Once these preconditions are met, the next step is to verify compliance during and after installation.

Systematic compliance control is key to both achieving the design intent and continuous development. The best of designs do not guarantee successful installation, this can be achieved only by rigorous quality control. Control enforces the tolerance requirements and serves as a feedback loop back to designing. The root causes of tolerance issues must be determined and addressed to continuously develop the process. Results from Case 5 indicate that implementing systematic quality control improves the performance of installers and the quality of designs, since unbuildable solutions are returned for the designer to solve. Surprisingly, no prefabricating case did highlight the role of quality control. This might be due to the high accuracy generally achieved in prefabrication. Case 2 did mention testing of connections in the workshop before transportation. Based on these findings we propose systematic quality control with root cause analysis as

principle VI. Besides this, achieving continuous improvement necessitates open communication.

Effective communication is vital throughout the project and across projects. Tolerance requirements (principle I), buildable designs (principle II) and buffer assemblies (principle III) must be communicated via clear visual representations (principle V) drafted by a detailer (principle IV). These principles deal with inter project communication. Quality control (principle VI) deals with both inter and intra project communication. It is necessary to communicate tolerance issues within projects to prevent reoccurrence in future installations. Likewise, it is necessary to communicate tolerance issues between projects to transfer learnings and to continuously develop the tolerance management process across projects. The absence of effective communication during the design phase, as well as between design and construction, and within construction, was a significant contributor to tolerance issues observed in Case 1. The importance of communication was particularly emphasized in the prefabrication cases. In Case 4, being the most advanced in regard to prefabrication adoption, it was considered crucial to consistently communicate across design, manufacturing, and construction teams. When all three processes, designing, manufacturing, and installation, are managed by one company, communication is more seamless. This was seen as a major advantage. For these reasons the seventh and final principle emphasizes communication within and across projects.

Discussion

Tolerance management in construction research and MEP prefabrication

Tolerance management in manufacturing industry is an established methodology. The construction industry has taken steps towards adoption of TM in some areas like

structural works and research regarding TM in construction exists (Milberg and Tommelein, 2009; Talebi et al., 2020; Rausch et al., 2022). However, TM for MEP has not been researched, even though it is a significant, complex, and unique part of construction. Industrialization and prefabrication of MEP has received interest from researchers (Court, 2019) but tolerances are barely mentioned.

The seven principles presented here together serve as a novel contribution to knowledge.

Setting tolerance requirements (**Principle I**) is a fundamental part of tolerance management both in manufacturing industry and construction (Womack, 1990; Drake, 1999; Milberg, 2006; Talebi, 2019). Essentially tolerance requirements determine the quality of a product with precise, unambiguous language.

Buildability of designs (**Principle II**) has been discussed in relation to tolerances by Milberg (2006) and Talebi (2019) for example. Both make a connection between the themes of tolerance management and buildability. Milberg (2006) uses the term "process capability" as synonymous to buildability consideration in assigning tolerances that can be achieved. In Milberg's (2010) example of soldier piles the assigned tolerances were not achieved and this caused problems in the subsequent welding of roof beams. Milberg argues that buildability analysis must be conducted to ensure that chosen construction methods (process capabilities) can achieve the assigned tolerances. The misalignment of piles and beams was solved by trimming the beam to fit the weld seam. In MEP installations' variation exceeding tolerance causes cascading variation since a clash can only be solved by also exceeding the tolerance for the adjoining component.

For absorbing variation (**Principle III**) clearance is commonly used as TM method in

construction. Milberg and Tommelein (2019) gave an example in their concrete wall and window frame example. Using clearance for MEP is necessary to ensure fitting of elements, to shafts for example. However, for variation between MEP components of the same system clearances cannot be used. Here, buffer assemblies were found as a MEP specific method for absorption of variation. Buffer assemblies as TM method for MEP is a novel finding. To determine the necessary absorption for MEP it is necessary to know the variation in concrete works and the methods for variation control used in concrete work.

The use of detailer (**Principle IV**) links the three previous principles together. To assess buildability (process capability), assign tolerance requirements, and design for absorption of variation the detailer needs to know manufacturing and installation methods. The role of detailer is present in the literature related to buildability and design coordination (Tatum and Korman, 1999; Khanzode et al., 2008). Tetik et al. (2019) reported a case where the general contractor employed detailers, using significant additional design hours, to achieve buildable models (to reduce improvisation on site). While design coordination and buildability are linked to TM, the role of detailer has not been explicitly identified as a TM method before and this is a novel contribution.

Visual representation of design intent and isometric drawings as one example (**Principle V**) is suggested to reduce the number of documents and therefore reduce ambiguousness. Tolerancing has been defined as communication of design, manufacturing, and inspection intent (Milberg, 2006; Henzold, 1995; Zai and Cutkosky 1997). Talebi et al. (2020) suggested a unified report as means of conveying tolerance information from designing to construction. Reporting tolerance information in design drawings makes the information easier to access for the installers. The result of this study additionally suggests that minimizing the number of documents where

information is scattered is beneficial.

Importance of compliance control (**Principle VI**) is highlighted by Talebi et al. (2020). Quality control is an important part of TM in the manufacturing industry (Henzold, 1995). Tolerances are also a description of inspection intent (Henzold, 1995; Milberg, 2006). The need for compliance control or quality control is not new. It is, however, a crucial part of TM to prevent the accumulation of variation and remove the causes of excessive variation in repetitive installations. This is especially important in MEP installations due to their complexity. Compliance control serves as feedback loop for re-iteration of the design and construction process and therefore must be one principle in TM.

The need for communication (**Principle VII**) is a crucial part of TM as whole. It has been highlighted in relation to design coordination. Collaborative project delivery systems have reported benefits over traditional delivery methods (Rodrigues and Lindhard, 2021). In TM, designing, manufacturing, installation, and compliance control are inseparably linked to each other. Failure of communication between any of the phases results in tolerance issues. Communication is often encouraged within a project, but for accumulation of learnings communication between projects is equally important. Without communication between projects, all projects end up solving the same issues over and over.

While individual elements of these principles have been addressed in prior studies, primarily in the context of structural works (Milberg, 2006) or manufacturing (Drake, 1999), this study is the first to synthesize and contextualize all seven principles within the domain of MEP prefabrication. The literature on tolerance management has largely overlooked MEP systems, despite their complexity and critical role in modern

construction. This study addresses that gap by adapting and extending tolerance management concepts to the specific conditions of MEP prefabrication and installations. The seven principles collectively form a structured and practical foundation upon which projects and organizations can build systematic tolerance management practices. By doing so, they enable more predictable prefabrication outcomes and support the broader industrialization of building services.

Practical implications

For prioritizing the order of implementation of the principles, we draw insights from the case selection and Figure 1. It may be hypothesised that the developmental trajectory from the lower left (no prefabrication and no quality control) to the upper right quadrant (advanced prefabrication and quality control) proceeds via adoption of prefabrication rather than through advanced quality control. The results show that advanced quality control was implemented in case 5 for achieving accurate as-built data and improving the construction process in traditional on-site construction. However, reinforcing the traditional production system through improvements of quality might not be the best way to implement the systemic transformations needed for industrialization of construction. Instead, we suggest that priority should be given to adoption of prefabrication in conjunction with principles II (buildability of designs), IV (use of detailer) and V (isometric drawings). Thereafter focus can be shifted to assigning tolerance requirements (Principle I), absorbing variation (Principle III), quality control (Principle VI) and communication (Principle VII). We recommend this order since it might not be feasible to implement all the seven principles simultaneously.

As stated in the case selection criteria, it is notable that no cases exhibited both advanced prefabrication and advanced quality control. While all the prefabricating cases

employed some form of quality control, none of them were as systematic and comprehensive as Case 5. This is potentially due to the emphasis on dimensional accuracy in prefabrication projects; the accuracy is such that quality control is not needed for documenting compliance. Instead, in traditional construction variations are much larger, as shown in Case 1, and systematic quality control is needed to control and document this variation. This is not to suggest that systematic quality control would not be beneficial for prefabricating projects, but merely a hypothesis on the reason for not finding examples of such quality control.

Potential barriers and solutions

Prevailing procurement methods and accustomed ways of working accompanied with resistance to change are significant barriers for implementing principles II, IV, VI, and VII (buildability, detailer, quality control, and communication). Barriers for buildability and detailer are related to combining construction knowledge with modelling skills, communication, and redistribution of design work. Installers must be trained in modelling tasks. Design work for engineers increases or decreases depending on who employs the detailer (designer or contractor) and this needs to be overcome by new procurement methods and contractual details. Communication is hindered by separation of designing and contracting, but also by separation of contractors by subcontracting. Communication between projects, transferring learnings, is limited by changing project organizations and lack of systematic methods for documenting and resolving recurring issues. Barriers in communication can be overcome by collaborative delivery methods and by implementing principles II and IV (buildability and detailer) for bridging the gap between designing and construction. Implementing all principles (systematic tolerance management) has the potential to help in knowledge transfer between projects.

Determining tolerance requirements and respective methods for absorbing variation requires knowledge of construction and can cause waste in too strict or too loose requirements. Too strict tolerance requirements lead to unnecessary accuracy and too loose tolerance requirements cause clashes or non-functioning systems. Similarly, absorption of variation should be carefully planned to avoid the need for large number of custom-built buffer assemblies. The right balance between too strict and too loose requirements is location and system dependent and can be learned through iterations. Tolerance requirements should always be determined on project basis in accordance with functional requirements and process capabilities. National guidelines or standards for tolerance requirements should be drafted as a baseline for project specific requirements. This type of standardization can help in unifying methods for compliance control across projects and in making expectations of quality non-project dependent.

One major barrier in implementing tolerance management is the need for a system for compliance control and communication. The system would need to enable documentation of tolerance issues, assigning responsible people for fixing the issue, tracing the status of the issue over time, documenting solution, and communicating the solution to installers and to next project. Tetik et al. (2019) documented a case using total stations to measure 600 points daily to compare installations and designs. Their study, however, did not specify a system of communication used in the project. Now information is scattered to multiple sources and maintaining an intact situational picture is difficult. To the knowledge of the authors, such a system does not exist, and its development needs further research.

The seven principles identified in this study demonstrate that tolerance management is fundamentally a managerial activity rather than a technical adjustment of dimensional limits. Effective tolerance management requires processes for early deviation detection,

structured information flows, and timely coordination across trades. These are organizational capabilities shaped by managerial decisions. The findings therefore position tolerance management as a core dimension of construction management practice, where the ability of organizations to anticipate, absorb, and mitigate variation directly influences production outcomes. In this sense, the principles contribute to the broader literature on construction production systems by clarifying how managerial interventions can stabilize workflows and improve the reliability of prefabricated MEP installation.

Limitations

This study has two primary limitations. First, four of the five cases were from the Finnish construction market, which may influence the generalisability of the findings. However, one case from the United States showed similar patterns, partially mitigating this concern. Second, the results are based on expert interviews and observed practices, rather than performance metrics. While consistent findings across multiple cases lend credibility to the principles, further validation through quantitative studies is recommended.

Conclusions

This study developed seven principles for tolerance management in MEP prefabrication based on five case studies. The five researched cases contributed to an overall increase in understanding of TM in MEP prefabrication. Seven principles for TM in MEP prefabrication were identified in addition to causes of tolerances issues. All seven principles must be adopted for successful TM. The principles state that tolerance requirements must be determined to achieve design intent, tolerance requirements must be communicated via manufacturable designs, and a feedback loop for improving

within and between projects are needed. Implementing systematic TM in design and installation has the potential to enable adoption of prefabrication for MEP.

The primary contributions of this study are MEP specific TM methods such as the buffer assembly, the need for a detailer in designing for manufacture, the use of isometric drawings, and communication within and across projects. Additionally, seven prescriptive principles are introduced to form a holistic approach for TM in MEP prefabrication. None of the studied cases followed all the principles, indicating their combination as useful and novel for both industry and academia. Success of TM for MEP is dependent on success of TM for preceding work like structural work. Most of the variation for MEP systems comes from sizes and locations of structures. This variation must be accounted for in TM for MEP.

Future research should focus on drafting a formal framework for tolerance management for MEP prefabrication and validation of this framework. The validation should focus on two levels, namely the theoretical and practical viability of the framework. Theoretical validation should determine if critical phases are missing or if some steps are unnecessary. Practical validation should focus on applicability in a project, quantification of additional work caused by detailed design, benefits from buildable designs, and reduction of improvisation and rework on the construction site. Current design tools do not support tolerance analysis or identifying possible tolerance issues without expert knowledge of construction methods and causes of variation; this could be addressed by developing a suitable tool.

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Tables

Table 1. Details of the five selected case projects

	Case Project 1	Case Project 2	Case Project 3	Case Project 4	Case Project 5
Country	Finland	Finland	Finland	USA/California	Finland
Project phase during research	MEP installations ongoing	Project ongoing, prefabrication installations complete	MEP manufacturing and installation ongoing	MEP manufacturing and installation ongoing	MEP installations ongoing
Project type	New apartment project by developer/contractor	New hospital realized through the alliance model	New apartment project by developer/contractor	New laboratory building realized through design build contract	New hospital realized through the alliance model
MEP onsite or prefabricated	On-site	Prefabricated ventilation shafts	Prefabricated ventilation installations	Multiple prefabricated MEP systems	On-site
MEP design and installation	Separate engineering design and installation	Engineering separate from detailing and installation	Engineering separate from detailing and installation	Engineering, detailing and installation by the contractor	Engineering design and separate installation
Research methods	Comparing installations to designs (first author)	Semi-structured interviews, site visits, and document review (first author)	Semi-structured interviews, site visits, and document review (third author)	Semi-structured interviews, site visits, and document review (second author)	Interviews and observations with installers and inspectors (first author); observation of one installation inspection
Focal point of research	Documenting tolerance issues in terms of deviation in routing, component selection, or equipment location compared to designs	Evaluating the design from the point of prefabrication; tolerance management	Evaluating the design from the point of prefabrication; tolerance management	Evaluating the design from the point of prefabrication; tolerance management	Quality control system for installation compliance with BIM was studied

Table 2. People interviewed in cases 1–5.

Interviewee	Case	Role	Duration [min]
1	1	Foreman 1, Main contractor	30
2	1	Foreman 2, Main contractor	30
3	1	Ventilation installer 1	20
4	1	Ventilation installer 2	20
5	1	Plumbing installer	10
6	2	HVAC construction manager 1	120
7	2	HVAC construction manager 2	120
8	2	Prefabrication manager	60
9	3	MEP designer 1	180
10	3	MEP designer 2	180
11	3	Prefabrication engineer	180
12	3	Ventilation fabricator	60
13	3	Ventilation installer 1	240
14	3	Ventilation installer 2	240
15	4	Design engineer	120
16	4	Prefabrication manager	60
17	4	Operations manager	60
18	4	Workshop lead	60
19	4	Detailer	120
20	4	Production manager	60
21	5	HVAC design manager	30
22	5	Inspection manager	120
23	5	Inspector	60
24	5	Sewer installer	60
25	5	Plumbing installer	20

Table 3. Recurrence of tolerance issues in Case 1. (*Issue in all apartments of the same type)

Problem type	Apartments with problems	% of all apartments
Duct crossing in suspended ceiling	100	87 %
Conduit pipe in cast in place slab	36	31 %
Re-routing of duct and silencer*	10	9 %

Table 4. Summary of findings.

	Case 1	Case 2	Case 3	Case 4	Case 5	Conclusion
Were tolerances defined?	No. Required installation accuracy not acknowledged.	Yes, not quantified. Accuracy is required to align connections between assemblies.	Yes, not quantified. Subassemblies manufactured to millimeter accuracy. Installation accuracy determined by TM method.	Yes, not quantified. Precision of prefabrication is high to support efficient installation.	Yes, not quantified. Tolerance contingent on location and effect on functionality and following installations.	Not having a requirement for accuracy leads to deviations. Ambiguity in the requirements also leads to deviations.
What tolerances were or should be defined	Installation tolerances should be defined to eliminate improvisation.	Manufacturing tolerance for size of subassemblies and location of components (connections to other assemblies and on-site installations).	Manufacturing and installation tolerance for ventilation installations. Installation tolerance for on-site installations.	Manufacturing and installation tolerances.	Installation tolerances (quantified) for different locations or individual components.	Manufacturing and installation tolerances for MEP components. Tolerances for surrounding structures.
What are causes of variation affecting MEP installations?	Variation was caused by non-buildable designs, deviating from designs, and variation in locations of openings.	Variation in concrete work affecting the size of shaft is source of significant variation.	Variation in concrete structures and locations of connections (manufacturing and installation tolerance of shaft and bathroom module). On-site installed components.	Uncoordinated designs cause variation preventing efficient prefabrication. Lack of model detail.	Improvisation of installers, missing model components, and buildability of designs.	Variation in MEP installations themselves, either from poor designs or from not following designs. Variation in surrounding structures and connections.
TM methods/ practices used in MEP installations	No Tm methods.	DfMA using detailer. Clearance to structures. Adjustable hangers. Testing connections in workshop. Sliding connectors between assemblies.	DfMA using detailer. Identifying connections with variation and using sliding connector, 2x45° bends, or unfastened connection.	Detailed design and rigorous model coordination. Strategic buffer assembly.	Requirement of buildability of designs. Quality control to guarantee compliance to designs.	In addition to a buildable detailed design allowed variation must be compensated. Adjustable fastenings, buffer assemblies are examples.
Communication of tolerance requirements and TM methods	No tolerance requirements or communication regarding installation accuracy.	Isometric drawings. Detailed instructions for installation.	Isometric drawings with bill of materials for manufacturing. Locations of TM methods in designs.	Isometric drawings with bill of materials for manufacturing.	Buildable BIM. Communication of quality control plan.	Tolerance requirements and TM methods must be clearly communicated to installers
Quality control	No quality control. Deviations accepted as a norm.	Testing connections between assemblies in workshop (manufacturing accuracy).	Self-reporting of issues by installers if assemblies don't fit without modifications.	Recognizing sources of variation and using buffer assemblies to mitigate it.	Rigorous quality control where either design or installation is changed to achieve equivalency.	To achieve design intent quality must be actively managed. Buildable designs or tolerance requirements don't alone guarantee compliance.
Buildability	Limited consideration of buildability led to deviating from design	Buildability considered for both manufacturing and assembly	Buildability improved by DfMA and TM methods	Buildability recognized as key aspect of design and supported by installer background of designers for manufacture and assembly.	Emphasized in design by removing clashes and using clearances.	Buildability must be a key consideration of design for prefabrication.
Design	Traditional design by MEP engineer	Engineering design and separate DfMA	Engineering design and separate DfMA	Engineering design and separate DfMA	Traditional design by MEP engineer with emphasis on buildability	Efficient prefabrication requires separate DfMA phase.

Table 5. Seven prescriptive principles and respective generic cause of failure leading to tolerance issues.

Principles of tolerance management in MEP prefabrication	Contributing cases	Corresponding causes leading to tolerance problems
Principle I. Define tolerance requirements contributing to the fulfilment of design intent (construction executed as planned, and systems that work).	1, 2, 3, 4, 5	Incomplete or incompatible tolerance information in design documents.
Principle II. Ensure buildability of designs by ensuring tolerance compatibility within MEP systems and between MEP and structural systems.	1, 3, 4	Designs with buildability issues. Occurrence of maximum allowed tolerance makes the design un-buildable.
Principle III. Design for absorption of allowed variation by means of buffer assemblies, adjustable connectors, or clearances.	2, 3, 4	Absorption not designed or not adequate.
Principle IV. Employ a detailer with installation experience to design for manufacture and assembly in accordance with principles I, II, and III.	1, 3, 4	Missing model details and incomplete coordination.
Principle V. Use unambiguous visual representation (i.e. isometric drawings) with a bill of materials as the product of design to communicate tolerance information between design and manufacturing.	3, 4	Design documents not conveying design intent.
Principle VI. Systematically control compliance to the assigned tolerances and identify tolerance issues and their causes.	2, 5	Noncompliance not identified.
Principle VII. Communicate across and within projects. Communicate what is expected (tolerance requirement), how to achieve this (tolerance management methods), how compliance is determined (quality control plan), and learnings from noncompliance (tolerance issues and their causes).	1, 2, 3, 4, 5	Lack of communication of tolerance information. Repeating issues. Prevention of continuous learning.

Figure 1.

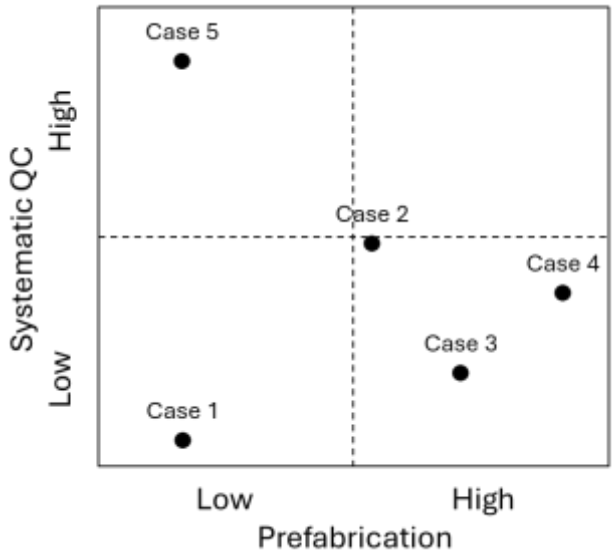

Case 5
Case 2
Case 4
Case 3
Case 1
Systematic QC
High
Low
Low
High
Prefabrication

Figure 2.

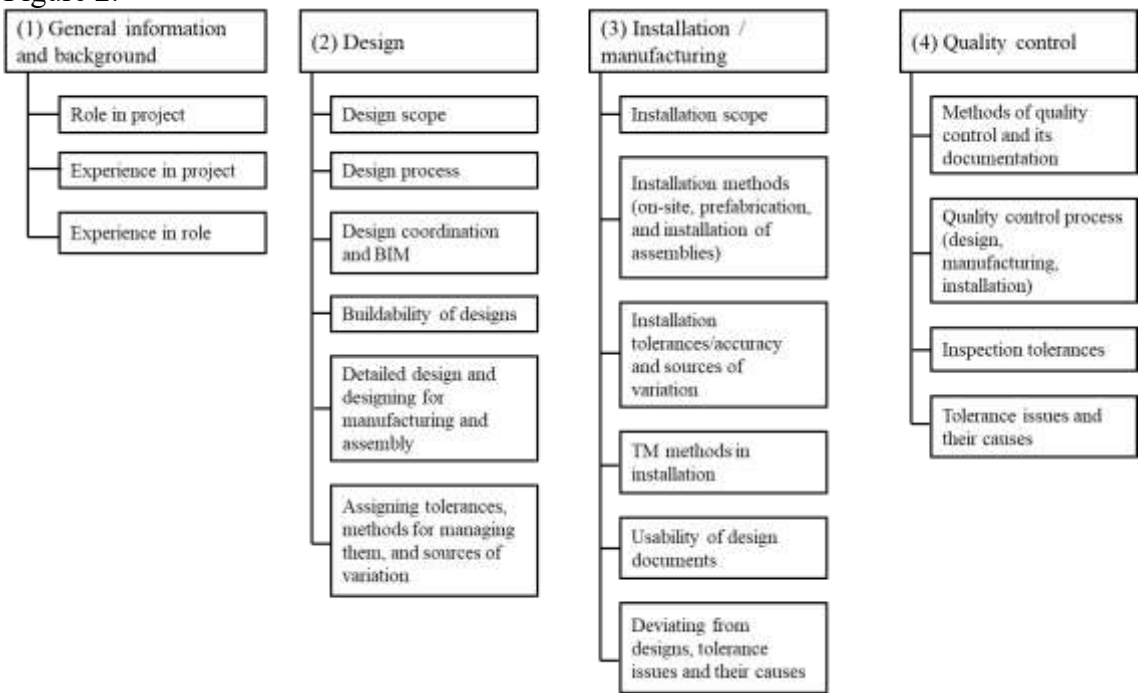

(1) General information and background
Role in project
Experience in project
Experience in role
(2) Design
Design scope
Design process
Design coordination and BIM
Buildability of designs
Detailed design and designing for manufacturing and assembly
Assigning tolerances, methods for managing them, and sources of variation
(3) Installation / manufacturing
Installation scope
Installation methods (on-site, prefabrication, and installation of assemblies)
Installation tolerances/accuracy and sources of variation
TM methods in installation
Usability of design documents
Deviating from designs, tolerance issues and their causes
(4) Quality control
Methods of quality control and its documentation
Quality control process (design, manufacturing, installation)
Inspection tolerances
Tolerance issues and their causes

Figure 3.

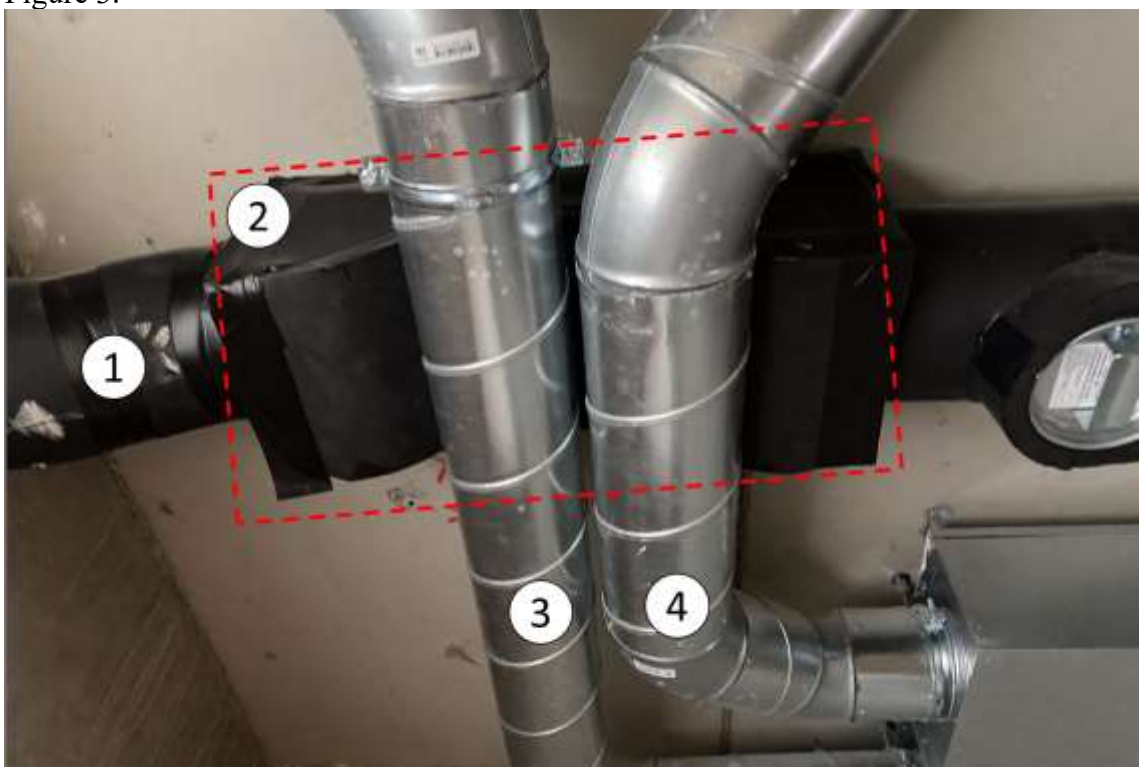


Figure 4.

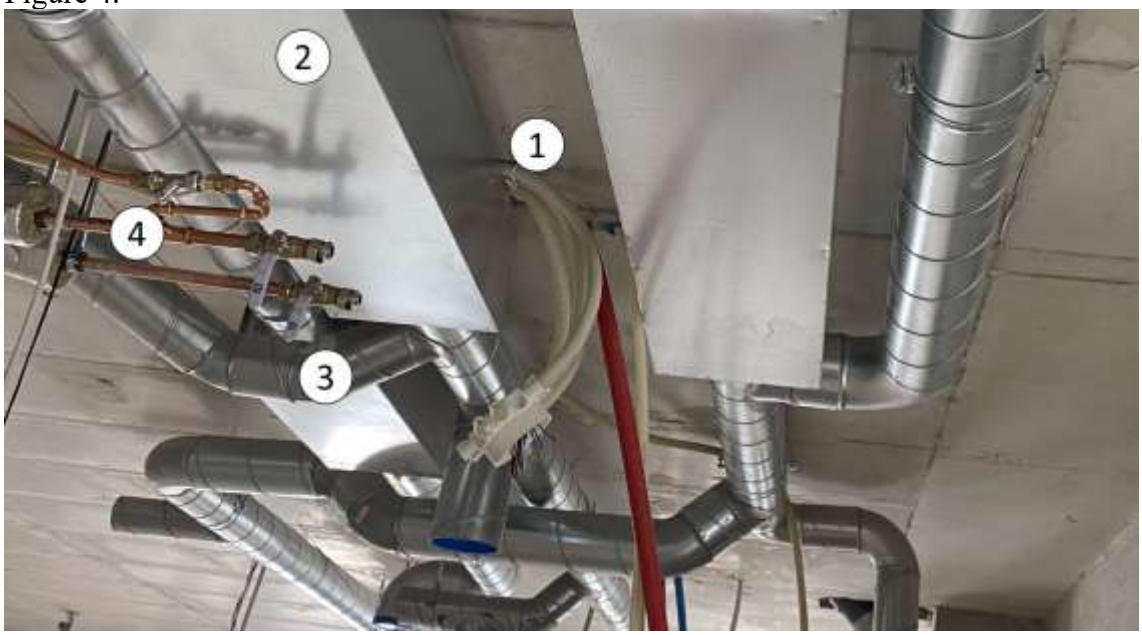


Figure 5a and 5b.

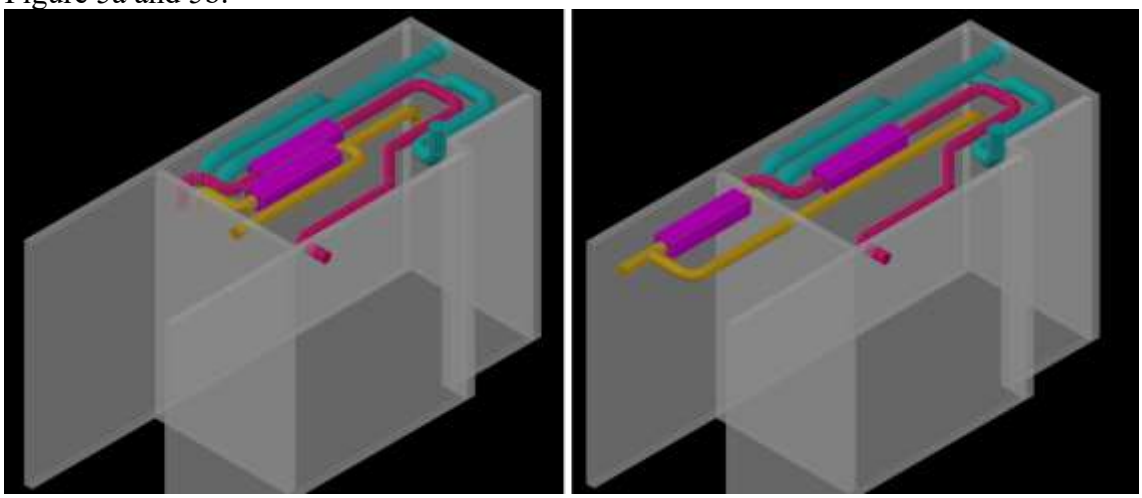


Figure 6.

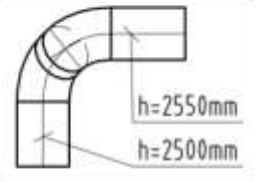
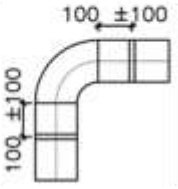
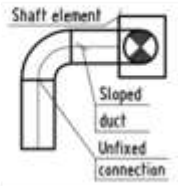
Source of variation	TM method to accommodate variation	
Height difference between prefabricated bathroom module and prefabricated concrete shaft element	Two 45° bends instead of 90° bend	
Difference in actual and designed distance between connection to shaft element and terminal unit	Telescopic connector to absorb variation	
Rotation deviation of precast concrete shaft element	Leaving first connection to 90° bend un-fixed in prefabrication	

Figure 7.

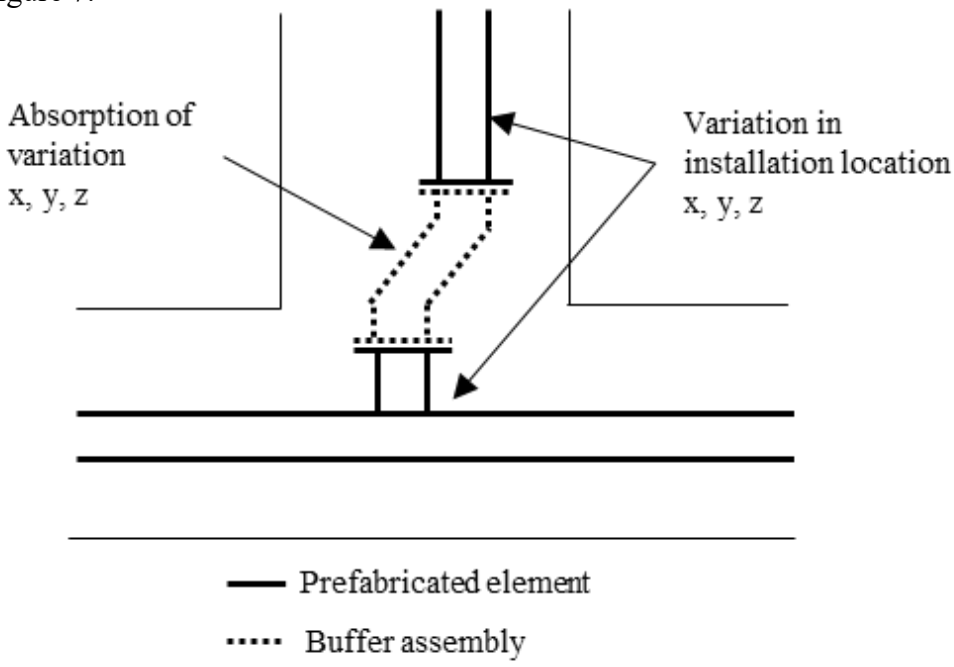
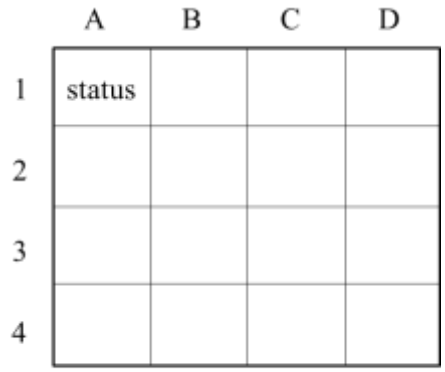

Absorption of variation x, y, z
Variation in installation location x, y, z
Prefabricated element
Buffer assembly

Figure 8.



Floor plan, Trade 1

Figure 9.

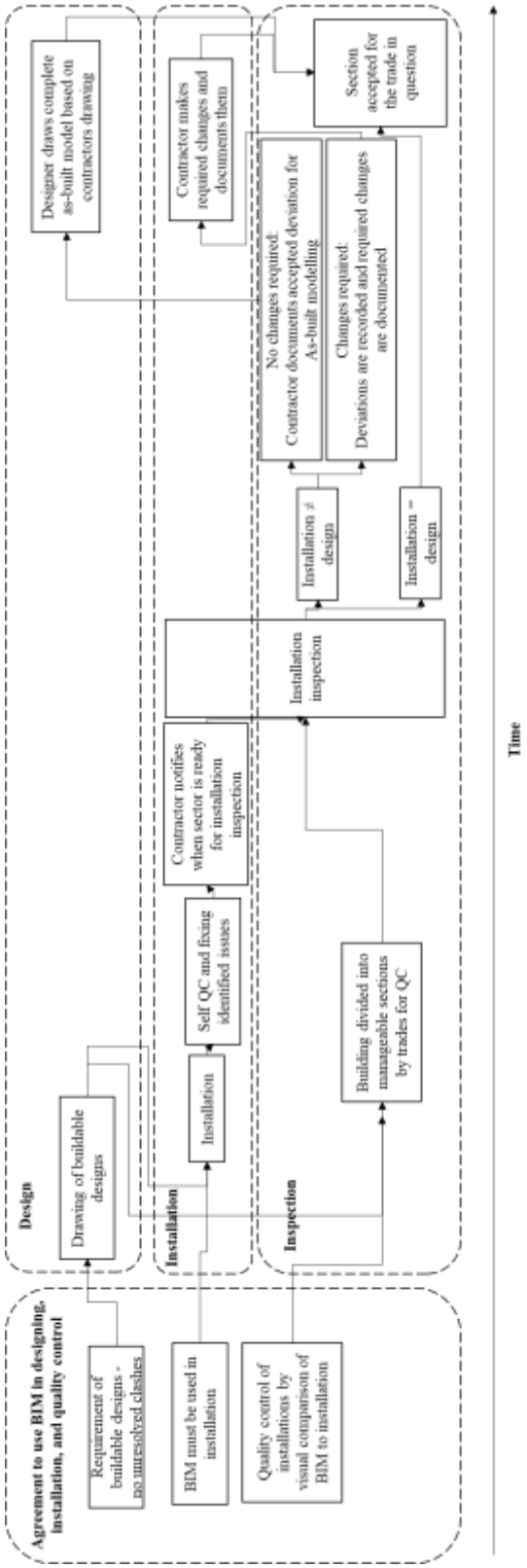

Agreement to use BIM in designing, installation, and quality control
Requirement of buildable designs - no unresolved clashes
BIM must be used in installation
Quality control of installations by visual comparison of BIM to installation
Design
Drawing of buildable designs
Designer draws complete as-built model based on contractors drawing
Installation
Installation
Self QC and fixing identified issues
Contractor notifies when sector is ready for installation inspection
Contractor makes required changes and documents them
Inspection
Building divided into manageable sections by trades for QC
Installation inspection
Installation ≠ design
Installation = design
No changes required: Contractor documents accepted deviation for As-built modelling
Changes required: Deviations are recorded and required changes are documented
Section accepted for the trade in question
Time

Figure captions

Figure 1. Relative position of case project across two axes. Position relative to x axis indicates the degree of prefabrication adoption and position on the y axis indicates the comprehensiveness of quality control.

Figure 2. Interview themes and subthemes questioned in the semi structured interviews.

Figure 3. Duct crossing installed using a special crossing part enabling crossing in smaller height. 1. Unplanned change in duct height. 2. Unplanned crossing part. 3. and 4. Unplanned change of route to align with crossing part.

Figure 4. Conduit pipe in the same location as a silencer. Locations of conduit pipes were not shown in design models, and resolving positional clashes was impossible. 1. Conduit pipes. 2. Silencer. 3. Duct height dependent on silencer height. 4. Water pipe height dependent on duct (3) height.

Figures 5a and 5b. Designers' solution where all ducts and parts are in the bathroom (3a, left). Installers' solution where the extract air duct and silencer were rerouted to adjacent space to allow for installation space in bathroom (3b, right).

Figure 6. Sources of variation and respective tolerance management methods used in case project 3 for prefabricated ventilation assemblies.

Figure 7. Schematic of a buffer assembly used in Case 4. Assemblies were measured and fabricated after element installation and used in selected locations to absorb cumulated variation.

Figure 8: Visualisation of the matrix used for recording status for each trade and section. The letters and numbers are used for coding the individual work areas.

Figure 9. Quality control process in Case 5.