Digitalising designing of prefabricated ventilation elements

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Abstract
What is traditionally understood as construction drawings are of such a low level of detail that they cannot be used for accurate construction, purchasing, scheduling, or material logistics. These deficiencies also result in the designs' poor applicability for prefabrication. The key to solving all the abovementioned problems lies in accurate material information and manufacturability of designs. Instead, traditional mechanical, electrical, and plumbing design is focused on system design, and information is transferred via PDF drawings. In this study design science research is used to determine guidelines for digital designing using accurate material information. The use of this accurate information for purchases, takt scheduling, and prefabrication is demonstrated. SolidWorks was used to re-model engineers' ventilation designs. The resulting design model was validated and improved through manufacturing and assembly tests in the factory and on the construction site. Despite previous digitalisation of designing (CAD) and extensive use of BIM, the product of designing (often 2D drawings) does not serve the construction phase. The meaningful transition towards digitalisation of design is necessary to improve the productivity of construction. Accurate location-specific material information can be used for purchasing, scheduling, and efficient construction, without modifications or recreation.

Keywords: Digitalising designing, DfMA, Lean construction, MEP

1 Introduction

Industrialising construction is necessary to improve productivity and quality. Employing a division of work in accordance with industrial manufacturing practices using prefabrication will be crucial in achieving shorter lead times and better quality (Johnsson and Mailing, 2009; Bernstein et al., 2011). Transferring tasks to off-site locations will remove interdependencies between tasks and facilitate the use of better work methods. However, designs for on-site construction do not support prefabrication and have been identified as one significant barrier preventing the adoption of prefabrication (Mao et al., 2015). Further digitalisation and higher level of design detail are needed for implementing prefabrication.

Digitalisation has been proposed to help overcome boundaries throughout the construction project by connecting disciplines and project phases to one another (Kunz and Fischer, 2020). Building information model (BIM), as a crucial part of digitalisation, is a digital representation of the building and is intended to function as a boundary object in design collaboration and construction. BIM has been promised to help in construction through straightforward visual representation of design intent. While BIM has been a significant improvement compared to 2D drawings, its limitations regarding manufacturability are obvious. It is also noteworthy that very recent research indicates that BIM has predominantly remained confined to the design phase and has not been effectively utilised in the construction or management phases (Revolti et al., 2024). Furthermore, end-to-end digitalisation in repetitive construction projects has demonstrated that the current use of MEP BIM is primarily focused on system sizing by MEP designers, as well as solving system geometry and space reservations. However, procurement by the main contractor, quantity takeoff by subcontractors, site logistics, and the actual construction still rely on the use of 2D drawings (Alhava et al., 2024). As depicted in Figure 1 below, 2D drawings are mainly used in the manufacturing phases of construction.

BIM in the context of MEP design coordination has been shown to be beneficial by improving the process of clash resolution (Tommelein and Gholami, 2012; Pärn, 2018). This clash resolution by engineers is, however, not enough to achieve buildable design. Instead, a separate detailer is needed (Tatum and Korman, 1999). As details are added, addressing tolerances becomes important, and BIM does not have the capabilities for tolerance analysis (Rausch et al., 2022).

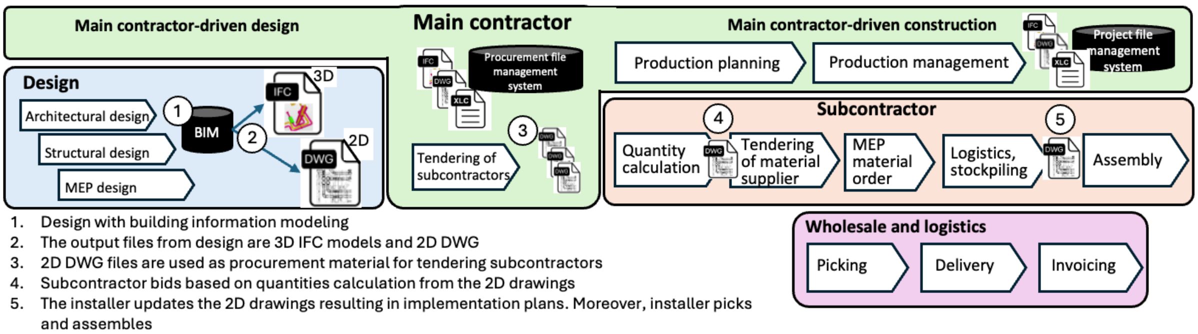

Figure 1. The design information used in different parts of the construction phases focuses on 2D drawings rather than IFc models.

Mechanical, electrical, and plumbing (MEP) systems consist of large numbers of interconnected parts, often in small spaces, making design coordination important. MEP installations have been shown to differ from designs (Valkonen and Seppänen, 2023), and installers have been shown to use significant time for designing on-site (Seppänen and Görsch, 2022). Both of these observations are linked to poor buildability of designs, meaning that designing for manufacture and assembly (DfMA) has not been done. Typically, MEP engineers BIM needs further detailing to enable efficient construction (Khanzode et al., 2008). This detailing includes selecting materials and components, designing hangers, resolving clashes, and improving buildability. In the Finnish market, and similar markets with low adoption rates of prefabrication, this detailing is often outsourced to subcontractors and designing is performed by individual installers on-site with minimal 2D documentation. Information regarding materials and parts is dispersed to multiple separate documents, hangers are not designed, and clashes are resolved as they occur. For efficient prefabrication, these issues must be solved in designing, and for this purpose, further digitalisation is needed. To determine solutions the following research questions are answered:

- RQ1 What are the requirements for a digital design model that can be used for prefabrication of ventilation installation in apartment buildings?
- RQ2 How can a digital design model support efficient material logistics?

In this study, guidelines for creating a digital design model are determined based on design science research (DSR) and literature. DSR is used for developing and validating the digital design model in three design and installation experiments. As a result, a guideline for designing for prefabrication of ventilation installations in new precast concrete apartment buildings is presented.

The rest of the paper is structured as follows: First, the research methodology is presented. Second, the research question and its theoretical background are described in detail. Third, results are reported. Finally, the results are discussed in relation to existing knowledge.

2 Methods

The design science research (DSR) approach was used to determine guidelines for designing for prefabrication. DSR consists of three phases: 1) identification of the problem, 2) empirical study to solve the problem, and 3) discussions of the implications of the results (Holmström et al., 2009). DSR is used to create an artefact as a solution to a real-life problem (Hevner et al., 2004). The DSR process is iterative by linking literature to practice and by incremental improvement of the proposed solution (Markus et al., 2002). The research design is presented in Figure 2.

In the Identification phase, the problem is described from the case company's perspective and based on the literature. As a result of this phase, descriptions of the current state and proposals for improving the future state are given.

In the solution phase the description of improved future state is transformed into guidelines for designing for prefabrication of ventilation systems. These guidelines are then tested and developed on three construction sites. The guidelines are developed after each site test based on observations of designing, manufacturing, and installation. All three construction sites represent one iteration in DSR research. These three tests were carried out by the first author in collaboration with designers and installers. The three case projects used in the solution phase are new apartment building constructions in Finland using precast concrete elements for the framework. Construction methods in the three projects are similar, while apartment layouts may vary slightly.

Finally, in the Discussion phase, the iterated solution is fine-tuned based on observations in the solution phase and knowledge in the literature. The proposed solution's implications are discussed in relation to current design and construction practices and current knowledge in the literature. The study's limitations and topics for future research are identified.

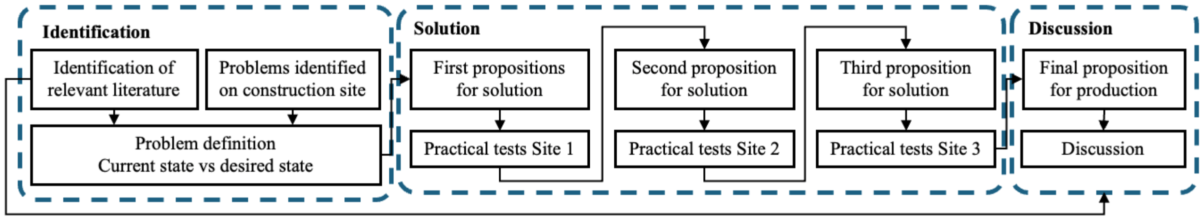

Figure 2. Research methodology.

3 Problem identification

The problem was identified as twofold. The first problem is data loss in the transfer from design to construction. The second problem is low construction productivity, which refers to inefficient on-site logistics and installation based on the transferred designs.

MEP designer creates a design model using CAD software. This model is created using imaginary (non-manufacturer-specific) parts for the purpose of system design, dimensioning, and space reservations. Typically, the design model is combined with other design models, such as architectural or structural models, for coordination and clash resolution using IFC format and BIM software. This coordination does not solve all clashes, as imaginary parts are used, and many parts or components are not modelled (such as hangers or connectors for piping). This digital design information is then transformed into 2D PDF drawings, where lines and symbols represent MEP objects. These 2D drawings with supporting documents are used for bidding and purchasing by the MEP contractor. The contractor often calculates quantities from the PDF files manually, even though the designer could deliver the engineering bill of materials. Some contractors use digitising software for processing 2D drawings, which helps identify symbols in PDFs as products (pixel recognition) and/or draw system routes over the image. This allows for the calculation of quantities of products and materials. Finally, the installer determines the needed materials based on the same 2D drawings without knowledge of the preceding calculation. This loss and recreation of data is the first problem.

Notably, BIM is used virtually in every design project, and issues manifest regardless of this. In most cases, contractors have access to the designer's BIM model but choose not to use it due to its poor buildability and low information content.

MEP installer uses the low Level of Detail (LOD) 2D drawings created by the designer as reference for installation. Even if BIM is available, in most cases it is not used. The installer first hauls materials from the site warehouse to the location of installation. Approximate locations of installations are measured from the designs, but cut lengths are measured from the site as the installation progresses, one piece at a time. This improvisation of detailed installation leads to variation and waste. Variation means that the same installer creates a new solution every time, resulting in different installations of the same exact apartment layout. This variation causes time to waste, as the installation is designed every time instead of merely assembling according to specific instructions. This improvisation due to poor quality of designs is the second problem.

The designer uses BIM for route planning and calculations, such as sound calculations, pressure loss calculations, and network balancing. BIM can be used as a reference for equipment locations but not as a detailed work plan.

The two identified problems, loss of data and low productivity of construction resulting from poor designs, have been documented in the literature as well. This is demonstrated by a time-motion study determining HVAC installers use, on average, only 15 % of their time on value-adding tasks (Seppänen and Görsch, 2022) and a study documenting deviations in installations compared to designs (Valkonen and Seppänen, 2023). These studies determined the low quality of designs as one major contributor to this variation.

In the manufacturing industry, these problems have been solved by detailed design, standardization of work, interchangeability of parts, and division of work. Interchangeability of parts and standardisation of work guarantee that a work task is performed identically every time, minimising variation (Womack et al., 1990). Furthermore, the Design for Assembly (DFA) in manufacturing reduces the number of parts while increasing the automation (Groover, 2021). Division of work means shortening lead times by removing interdependencies of tasks or even eliminating tasks. For construction, this could mean prefabricating MEP systems. In on-site construction, MEP installations are dependent on the progress of the framework and other trades. In prefabrication, assemblies can be manufactured independently

The research objective was to accomplish a one-piece flow in a standardised apartment building concept. Standardising design and construction are important steps towards industrialisation and prefabrication. The studied company's standardised apartment building concept already uses prefabricated technical rooms, bathroom modules, and roofs. Standardising ventilation installations was selected as the next development. The relative simplicity of ventilation installations compared to plumbing makes them a good choice for beginning digitalisation. The resulting designs must be accurate and specific enough to guarantee that two installers end up with interchangeable subassemblies. Digitalisation of designs is needed to improve designing, manufacturing, purchasing, and scheduling processes.

4 Solution phase, Results

4.1 First proposal

The first phase was designed to determine the requirements of digitalised designs derived from the installer's needs. The first experiment was conducted on-site in collaboration with the installer for fast implementation and instant feedback. The installer worked on a fixed contract. Designing for prefabrication was done on-site using pdf-editor and 2D drawings. An example of these designs is shown in Figure 3. The design separates make-to-stock components such as bends and silencers from ducts cut to length on site. These components were then precut and assembled into subassemblies that were attached to the ceiling. This first experiment of prefabrication shortened installation time to half in comparison to on-site installation, not accounting for the time needed for prefabricating.

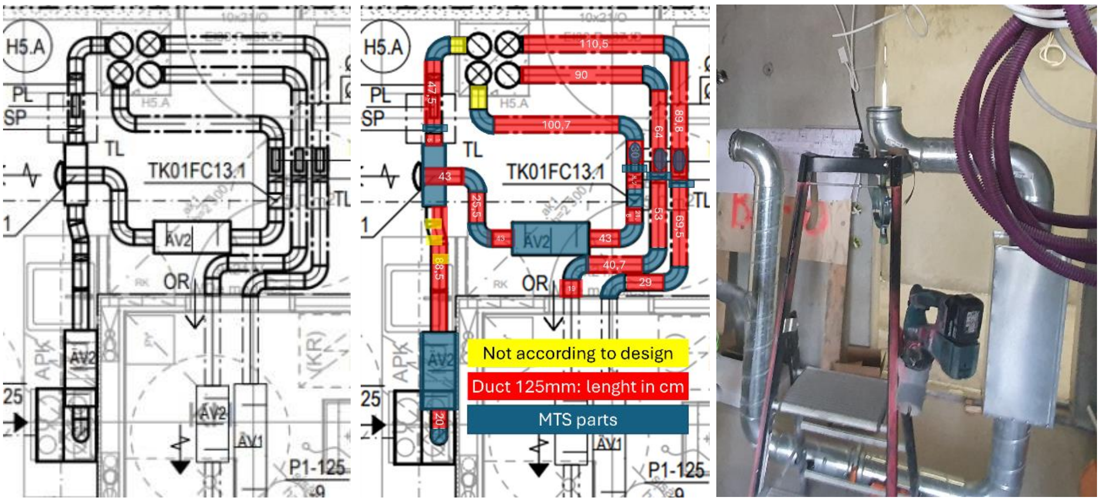

Figure 3. 2D design from Site 1 (left). The design was transformed for prefabrication by adding colour codes and cut lengths (centre). Blue represents MTS parts, red represents ducts cut to length on site, and yellow represents deviation to design after installation. Parts without colouring on the right belong to the prefabricated bathroom module. The prefabricated assembly is ready for installation (right).

The first experiment revealed problems. Clashes with domestic water pipes and electrical cables caused the need to move these installations, to fit the ducts in designed locations. The ventilation installer moved domestic water pipes by moving the locations of the hangers. The hangers were disposable for electrical cables, and the electrical installer had to install new hangers. In duct installation, the connection to the concrete element was damaged, and the duct had to be shaped. Additional bends compared to the design were needed to correctly position the duct for the cooker hood. The maximum length for subassemblies in a man installation was determined to be three hangers for straight installations and shorter for more complicated shapes. Small inaccuracies in subassemblies were observed to cumulate into large variations during longer routes.

It was also observed that the level of detail in traditional designs is not sufficient for prefabrication. The duct lengths had to be modified, and the design was missing needed bends and hangers. More detailed designs presenting measurements and accurate part types are needed for manufacturing in an off-site location.

A lack of coordination in the design phase caused clashes with water pipes and electrical conduits. This coordination is more difficult for electrical conduits since they are only presented as schematics, and routes are decided on-site. Designing for manufacture could resolve the issue of missing components.

The installer estimated that fixing these problems would shorten on-site installation time by half, resulting in 75% time savings compared to traditional on-site installation.

4.2 Second proposal

The second phase consisted of designing, manufacturing, and installation of prefabricated ventilation systems in two identical apartments on Site 2. The apartments were selected to represent the most difficult installations in terms of the problems observed on Site 1. The difficulty was favoured to enable solving problems for the next phase.

To start, identical on-site built apartments were measured for deviations in relation to designs. These deviations had to be resolved in designing for ease of assembly. Measurements showed three types of deviations: 1) elevation deviation, 2) rotation deviation, and 3) distance deviation. Elevation deviation was the difference in elevation of duct connections between the shaft element and the prefabricated bathroom module. Rotation deviation was the inaccurate installation of the concrete shaft element, causing rotation of the element around the vertical axis. Distance deviation was the difference in actual and designed distance between duct connections in the shaft element and prefabricated bathroom module. For distance deviation measurements indicated variation between ±1 cm and ±3 cm. The three types of deviations are presented in Figure 4.

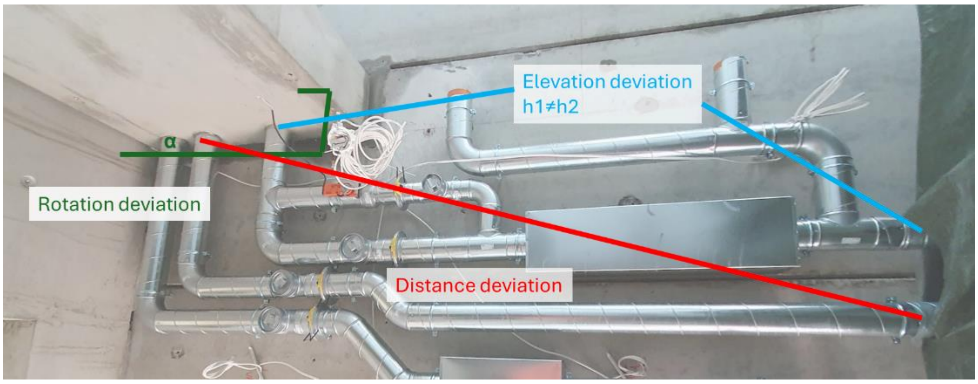

Figure 4. Elevation deviation, rotation deviation, and distance deviation measured from on-site installation.

The need for isometric drawings, accurate M-BOMs, and smooth data transfer from design model to ERP led to the discarding of traditional CAD and BIM-based design software. The main barrier to their use is that traditional CAD software does not enable using manufacturer-specific parts in designing, which effectively leads to failure in all three needed aspects. Using generic parts leads to faulty cut lengths for ducts, as the dimensions of other parts vary. Instead, SolidWorks was chosen as a design software. Initially, the designer had to create libraries of parts by modelling the chosen manufacturer-specific ventilation parts based on measurements of purchased parts. SolidWorks made it possible to export accurate M-BOM to ERP as data for purchasing. The resulting design model and isometric drawing with M-BOM are presented in Figure 5.

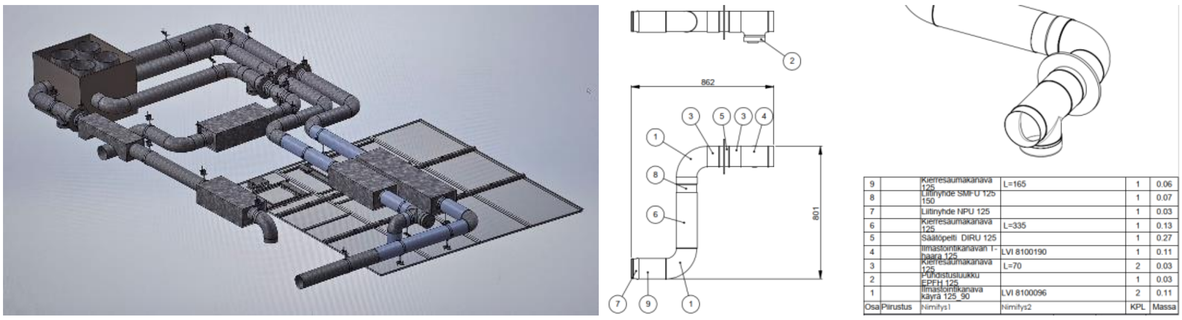

Figure 5. Model of ventilation installation in one apartment and isometric drawing with BOM of one assembly.

The deviations measured from on-site installations and issues identified in Phase 1 were addressed in the design. The first solution was increasing the level of detail by using software typically used in the manufacturing industry with high requirements for accuracy (Distance deviation and level of detail in designs). The second solution was incorporating methods for variation control. Installation was divided into smaller subassemblies to enable minor adjustments of alignment in assembly (Rotation deviation). Thirdly telescopic connectors were used in selected locations to connect assemblies, allowing for adjustment of ±50mm (Distance deviation). Connections to terminal units were left too long on purpose for cutting on-site (Distance deviation). Clashes in the design model were addressed to avoid re-installing other systems. And subassemblies were at maximum three hangers long depending on the shape.

Ventilation installations for two apartments were prefabricated in a workshop based on isometric drawings. Installation of one apartment consisted of 9 subassemblies. The installers were now contracted on an hourly rate instead of a fixed-price contract. This change of contract type was intentional to realise benefits from prefabrication. The installers were trained on the principles of installing preassembled installations. The implemented solutions for the identified deviation types were shown to work. Division to a larger number of subassemblies solved the issue of rotation deviation. Telescopic connectors solved the problem of distance deviation. The problem of elevation deviation was left unresolved in design but was solved on-site by the installer using two 45° bends instead of one 90° bend to change elevation while changing direction.

Problems with clashes were not successfully removed and new problems were identified. The problem of clashes was determined to be a result of craftsmanship, like the installation of other trades using inaccurate 2D drawings. Removing the problem of clashes would require similar accuracy in designing and installations as the prefabricated ventilation systems. The new problem was documented relating to the previously identified inaccurate connection to the prefabricated shaft element. It was noticed that to make the needed modifications and connect the duct to the shaft, the connector piece must not be attached to the following assembly. Installing a long assembly to a distorted connection was difficult or impossible.

In addition to guidelines for designing and manufacturing, the experiment gave valuable information regarding logistics, protection of assemblies, and daily management. Prefabricated components were delivered to the site on protected roll cages, from which they were unloaded on the floor at the installation location. The subassemblies were left unprotected on the site, exposed to dripping water and concrete dust, and had to be cleaned before installation. The role of daily management in documenting and solving issues based on root causes was seen as critical.

4.3 Third proposal

The third experiment was expanded to prefabrication of ventilation of one apartment building. Vertically aligned apartments have the same layout, reducing the number of unique designs. The highest and lowest apartments differ from the rest by small differences in connection to the shaft. Accurate apartment-specific design models and M-BOM enabled scheduling of location-based material deliveries to the factory and to the construction site based on the takt schedule. The assemblies were manufactured according to the takt schedule, keeping buffers of ready installation to a minimum. This lack of buffers and implementation of daily management and reactive PDCA enabled fixing the identified problems before the next installation of the same apartment type. All seven apartments on one floor were installed directly, one after the other.

While the previously identified problems were already addressed, implementing daily management and reactive PDCA revealed 64 problems in experiment 3. Problems were identified on-site by the installer and a supervisor and reported via WhatsApp messages. These reported problems were then listed on a kanban board where progress was monitored, and responsibilities allocated. People in co-operation solved these problems by designing, manufacturing, logistics, and material purchases. The main goal was not to interrupt the flow of the construction site while working towards root causes and consequent fixes of problems.

The 64 identified problems can be summarised by root causes in the following four categories. 1) Problems in designing 2) Problems in manufacturing 3) Problems in logistics 4) Problems in installation. Problems in designing related both to original architectural and MEP designs as well as remodeled ventilation designs. Original designs had unresolved clashes that caused variation as solutions to these clashes were improvised on site. The detailed model for manufacturing included unfitting parts and demonstrated the designer's lack of knowledge regarding installation practices. Not following designs was a problem in manufacturing, which ultimately led to problems in installation. Assemblies delivered to the wrong apartments, water inside silencers, and damaged ducts were logistic problems. An example of an installation problem was the difficulty of installing hangers to designed locations due to element seams.

5 Final proposal and Discussion of results

Further digitalisation must build on the existing processes of design and construction. While BIM applications are shown to be non-applicable for prefabrication design, they are necessary in the design process. MEP designers use this software for system design, dimensioning, pressure loss calculations, and space reservations, functions that CAM systems do not support now. This leads to the need to divide design tasks into engineering tasks and detailing tasks, where engineering is responsible for system design, and detailing is responsible for DfMA.

This paper has focused on the task of detailing and following processes supported by the detailing. Processes needing information from digital designing are manufacturing, installation, purchasing and scheduling. Manufacturing requires accurate design documents. These design documents must present the precise construction of assemblies and what parts must be used. This is done using isometric drawings and manufacturing BOM. Installation needs separate installation drawings describing how subassemblies are to be connected, in which order, where the assemblies are located, and tolerance management methods. Purchasing requires accurate manufacturer-specific material information and quantities, the same information used by manufacturing but in the form of structured data. Scheduling requires location-specific material information to be able to order needed materials to the correct locations just in time. The system of construction using digitalised designing for MEP prefabrication is presented in Figure 6.

Designing, manufacturing, installation, and scheduling should all use the same information produced by detailed design. This means that designing must use accurate information for specifying materials. As current MEP design software does not support this level of detail, software of the manufacturing industry must be used. As parts manufacturers do not provide geometrically accurate representations of their parts, a library of all parts must be modelled based on measurements of purchased parts. This accurate geometrical information must be enhanced by adding detailed information for purchasing, such as manufacturer, model number, dimensions etc. After creating the database, design for manufacture and assembly can be done. The used software must enable the accurate geometry of parts and include all parts of the installation in the model.

The model of ventilation in one apartment is then, partly automatically, divided into subassemblies based on the capabilities of installers and logistics. Military projection drawings are then created for manufacturing, including M-BOM. Accurate M-BOM in the form of structured data can be exported to the ERP system for purchasing and scheduling. Once generated by detailed designing, this data does not need to be modified for purchasing. Location-based M-BOMs are used for pulling materials first from suppliers to the factory, then for manufacturing, and finally to the construction site as subassemblies when they are needed.

Detailed designing is based on the original geometry created by the MEP designer. This original geometry must often be changed to resolve clashes and to make the designs manufacturable. The engineer’s design is delivered to the detailer by 2D PDF files accompanied by text documents and, in some cases, a BIM model. The text documents describe what materials and equipment the engineer has chosen for the systems. As routes and equipment must be changed in detailed design the original design model must be updated for accurate system calculations. Detailed design must address tolerance management, as the experiments showed that tolerance incompatibilities arise when accuracy is enhanced.

Based on the results an instantaneous feedback loop from construction to manufacturing must be established. This feedback loop aims to address all issues observed on site, especially those affecting assembly. All issues must be resolved in the design and manufacturing process to remove the need for modification on-site. Digital designing is improved on the construction site. For this purpose, a digital system for communication is needed. Based on the observations, this system must be easy to use, like WhatsApp, but it also must have capabilities for documenting problems, monitoring progress, assigning responsibilities, and accumulating process information from project to project. During the research, this was resolved by using a combination of software, but ideally, one software should be used.

Based on the results, it can be argued that all MEP systems should be prefabricated with the same precision to eliminate variation related to on-site installation, and in all three iterations, variation of on-site installations caused problems for installing prefabricated subassemblies. Prefabrication ventilation alone does not seem to realise all the benefits associated with prefabrication.

Detailed structured data and accurate geometry go hand in hand. Accurate data for purchasing is possible by using algorithms that predict the needed parts based on previous projects. However, this prediction does not remove the problem of inaccurate geometry and the time waste caused by it; accurate estimation does not translate into manufacturable designs without detailed design work. The installers are still left with the task of detailed designing, and the problem of variation persists.

The study is limited by characteristics of the Finish construction industry and focuses only on ventilation installations in apartment building construction using prefabricated concrete structures. To validate the findings, further research should focus on the digital designing of all MEP trades in the same building and in different types of buildings. Additionally further study should determine specific requirements for a single digital system enabling communication, resolution, ownership, and progress monitoring for problems in construction. This system should enable continuous improvement and accumulation of structured process information over projects.

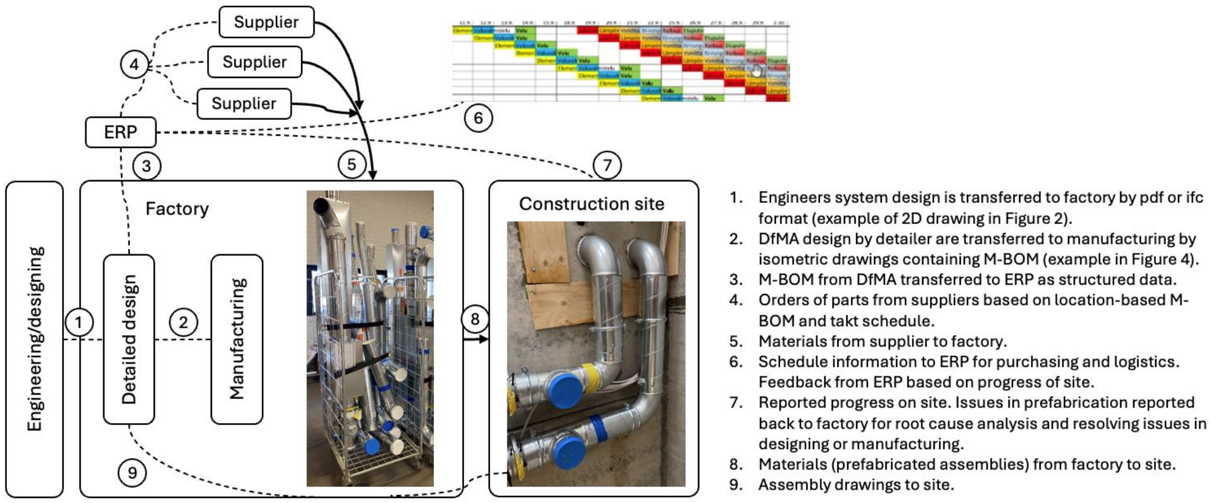

Figure 6. Proposed process for digitalised designing.

6 Conclusions

This research shows how MEP designing for prefabrication should be digitalised and what connected processes this digitalisation serves. The final reported model was developed and validated through three design, manufacturing, and installation tests. As a result, it can be stated that a special modelling software for manufacturing is needed, and the process of designing must change significantly compared to the current state. What has previously been understood as construction drawings are schematic representations that can be used as a basis for detailing but that are not accurate enough for prefabrication. Accurate manufacturing of MEP systems highlights inaccuracies in concrete element manufacturing and installation and creates the need for using tolerance management methods for absorbing the variation. This research also demonstrated the need for a rapid feedback loop and PDCA cycles from installation to design and manufacturing to solve all issues preventing installation according to design. The digitalisation of construction starts with detailed designing, from where the data is carried through the process of construction. The digitalisation of design is necessary for the industrialisation of construction.

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