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IMPROVING PRODUCTIVITY IN VENTILATION AND PLUMBING INSTALLATIONS BY DEVELOPING DESIGNS

Tuomas Valkonen[1] and Olli Seppänen[2]

ABSTRACT

Quality of designs is one of the most important factors impacting the productivity of mechanical, electrical, and plumbing work. Previous research does not investigate problems with design in detail. This research aimed to identify design aspects where additional investments in design would increase productivity in installation. For this purpose, we selected three construction sites to identify deviations from designs, and interview installers on identified deviations and buildability in general. Observed deviations were divided into three main categories based on the cause of deviation: insufficient space reservations, missing model components, and buildability. Based on our findings we suggest five methods for developing designing: 1. BIM should be used in designing. 2. BIM coordination should include the assessment of buildability. 3. Better use of BIM requires high level of detail and high accuracy in all design models. 4. Contractors knowledge on buildability, schedule, and order of installation should be utilized in designing. 5. Optimizing material cost should be part of designing.

KEYWORDS

BIM, collaboration, assembly, HVAC, design

INTRODUCTION

The main purpose of designs is to convey the designers' intent to construction and enable fabrication of functioning buildings. Ideal designs for construction would contain everything that needs to be installed and they could be executed precisely, meaning that there would be no need for improvisation on site. Unclear designs lead to improvisation and improvisation leads to low productivity (Johnston and Brennan, 1996). Design quality and coordination was identified as the second most important issue affecting productivity concerning mechanical, electrical, and plumbing (MEP) installations in a study by Seppänen & Görsch (2022). The study estimated the potential production improvement to be 20 % by improving design quality and coordination. Similarly Wu et al. (2022) specified clash detection, network optimization, and construction simulation as methods to improve MEP installation productivity.

Prefabrication requires accurate designs that can be executed exactly and utilised as part of assemblies; designs for prefabrication can be considered examples of ideal designs. A study by Poirier et al. (2015) suggested that using high level of detail in BIM and designing for prefabrication might have significant potential for increasing productivity in MEP work. High level of detail enables effective work planning and is a precursor to using prefabrication (Song et al., 2017; Lavikka et al., 2021). High level of detail also refers to geometric representation

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and model accuracy. Lavikka et al. (2021) also found that current design quality in Finland is not sufficient for prefabrication. This is one key reason why prefabrication of MEP has not been widely adopted in the Finnish construction market.

Designing for prefabrication is characterised by buildability of designs. Buildability can be considered as tool or methodology throughout the project. In this study we focus on design and construction phases and define buildability as designers using construction knowledge to draft designs that facilitate efficient building of systems or parts of them (Wimalaratne et al., 2021). Designs where buildability is not considered, such as models with clashes, cause waste and rework in construction.

Building information modelling (BIM) and coordination of design models can be used for ensuring buildability across disciplines. Clashes in MEP design models have been studied to identify their root causes and frameworks for resolving them (Tommelein & Gholami, 2012; Wang & Leite, 2016; Chauhan et al., 2022). Tommelein and Gholami (2012) suggested classifications for three different types of clashes, investigated their root causes, and ultimately concluded that clashes highly relate to buildability of designs. Effective coordination of BIM and using virtual design and construction technologies have been shown to increase productivity significantly (Khanzode et al., 2008). Past studies have been covering widely different frameworks and their productivity in BIM coordination (Lee & Kim, 2014; Seo et al., 2012; Korman et al., 2008; Korman & Tatum, 2006; Korman et al., 2003), but are limited to solving clashes that are visible in the models. Wang et al (2016) suggested a framework for MEP clash detection and resolution, their study reported 51 identified design errors from construction site but did not specify the types of errors or how they could have been avoided in designing.

While studies show that BIM coordination increases productivity (Wu et al., 2022; Khanzode et al., 2008), and BIM is widely used, there are also studies showing that current practices cause waste, and problems in coordination process remain (Seppänen & Görsch, 2022; Chauhan et al., 2022). This raises the question of what causes the need for improvisation and rework in MEP installations regardless of BIM use, clash detection, and coordination. To our knowledge there are no studies documenting reasons for deviating from designs and how these deviations relate to designing. The aim of this study is to identify these remaining problems and to suggest improvements to design process for eliminating these problems. Our aim is related to the key lean principle of minimizing waste, with focus on construction and improving designs. For this purpose we conducted three case studies on construction sites to document problems installers are dealing with.

METHODS

Based on the previous research we know that installers use significant amount of time for designing installations on site. The aim of this study was to document deviations from designs, determine causes for these deviations, and discuss possible solutions for removing these issues. To document issues in MEP designing we studied deviations in installation on three construction sites. The sites were selected to represent different project and building types. Key aspects of studied projects are shown in Table 1. All three projects had different designers, MEP contractors and main contractors. Installations of MEP systems were ongoing and observable in all selected sites.

The research was carried out in spring 2022. The first author was on-site observing installations and interviewing installers. A deviation was defined as any installation that was not identical to designs. Examples of deviations included using different parts or installing in different locations. Deviation in this context does not mean that the systems would not work as intended. Some of the deviations can result in non-functioning systems and others do not. The first author compared installations to designs and reported differences between as-designed and as-built. The identified deviations were documented by photographing the installation and writing notes about the reasons leading to the changes. The reasons were determined by interviewing installers and observing conditions affecting the installation. The installers were also interviewed regarding design issues in general and suggestions for improving designs.

All three case sites were different from one another. Cases 1 and 2 were new constructions where the first case was a school building and the second case was an apartment building. Case 3 was a renovation project in a school building where only the old structure was left untouched. All cases used BIM but there was significant variation in the utility and quality of the models. BIM was best used in Case 2 where design models were most detailed and coordinated to eliminate collisions. Lowest use of BIM was in Case 3 where a design model existed only for ventilation systems and BIM was not used in installation. Case 1 had design models of all disciplines and models were partially coordinated however there were obvious issues left unresolved. Installers of Case 1 used 2D drawings while they had seen the BIM model in meetings. Latest BIM models and 2D designs were used for evaluating installations on site. Prefabrication was not used in any of the studied installations.

Table 1: Characteristics of studied projects.

	Building type	Construction type	BIM used in designing	BIM used in construction
Case 1	Residential building	New Construction	Yes	Partially
Case 2	Educational building	New Construction	Yes	Yes
Case 3	Educational building	Renovation	Partially	No

RESULTS

Differences between design and installation were frequent on the studied construction sites. All studied spaces showed some examples of improvisation by installers. However, there were distinct differences of observed issue types between building and project types. Overall, the use of BIM in designing and installation changed problem types and higher utilisation of BIM decreased the number and severity of problems. Based on the results, BIM practices in case projects were not sufficient to remove all the problems and many issues were still left for installers to solve.

The identified problems can be divided into three main categories: insufficient space reservations, missing model components, and buildability. All these problem types could be found on all three cases. Insufficient space reservations were predominant in Case 3 which can be attributed to renovation project type. Missing model components, such as hangers or structural elements, caused issues in all cases but were most prominent in Case 1. While buildability issues are caused by the two problem types, it can be reviewed as separate aspect of designs. Buildability issues were especially observed in cases 1 and 2.

INSUFFICIENT SPACE RESERVATIONS

Insufficient space reservations can be caused by two mechanisms: built spaces are smaller compared to designs or used equipment are larger compared to designs. These problems can lead to equipment not fitting in their designated places or significantly hindering the maintenance of equipment. Insufficient space reservations were mostly observed in Case 3. Existing structures and accuracy of architectural and structural models are key differences in renovation projects compared to new constructions. In Case 3 most of the documented space reservation issues were related to faulty or non-existent measurements of existing structures.

Due to the lack of measurements, heating, ventilation, and air conditioning (HVAC) designer had to use architectural drawings as a starting point and was forced to rely on their accuracy.

In Case 3 there were many situations where corridor was narrower than assumed in designs and installers had to improvise. Figure 1 shows an example of this, where narrow corridor meant that all the ducts could not fit in the corridor and installer had re-routed one duct to be visible in classrooms which do not have suspended ceilings.

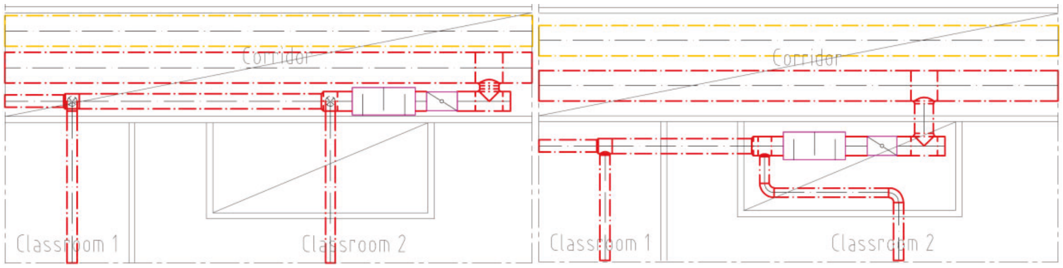

Figure 1: Left (1a) shows designers solution and right (1b) shows the installers solution. Installer had routed the supply air duct visibly in classrooms due to insufficient space in corridor suspended ceiling.

Another deviation was in technical room for ventilation where air handling units (AHU) had been arranged differently to designs, shown in Figure 2. The reason was smaller room compared to designs and as the result one AHU did not fit into its designed location. The installed solution is problematic for maintenance as AHU: s should have free space in front, equalling their depth, for replacing filters and other parts.

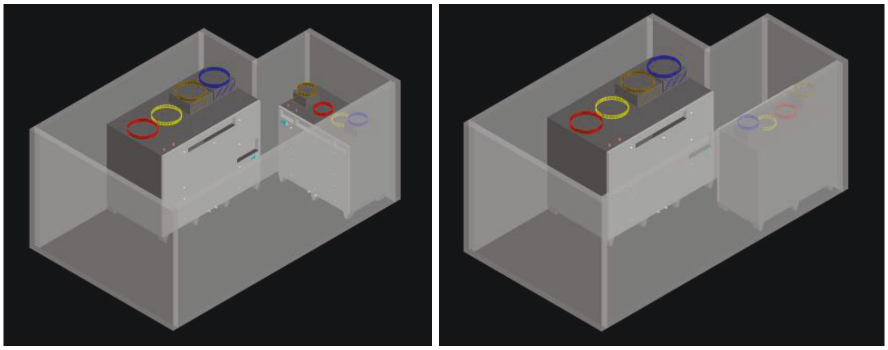

Figure 2: Designed arrangement of air handling units on the left (2a) and installed arrangement on the right (2b).

MISSING MODEL COMPONENTS

BIM coordination is not able to solve issues which cannot be seen in the model. There are many things that affect installation but are not necessarily included in the BIM. These missing model components often include, for example, hangers for MEP systems, small structural elements, and electrical cables. All these objects occupy space and can cause unforeseen problems in installation if not modelled.

In Case 2 there were several examples of walls being modelled to the elevation of suspended ceiling while they should have been modelled and were built to slab height. This leads to penetrations in suspended ceiling space which cannot be seen from the model. According to installers this caused some changes in pipe routing to avoid penetrations of concrete or brick walls. Figure 3 shows an example of re-routing pipes and its effects on the number of penetrations in a toilet group. Blue, red, and magenta lines represent the routes of domestic cold, hot, and circulation pipes. Red dots mark voids that need to be drilled on site. Figure 3a is the design solution for both pipes and walls. Figure 3b illustrates how the walls were built and how the solution affected the number of voids. Figure 3c shows the installers solution with real wall heights. The numbers of voids in the three solutions were 11 for 3a, 23 for 3b, and 18 for 3c. The difference between 3a and 3b shows the number of voids that the designer did not see from the model due to walls not being modelled high enough. The installer was able to eliminate 5 voids compared to the designer's solution.

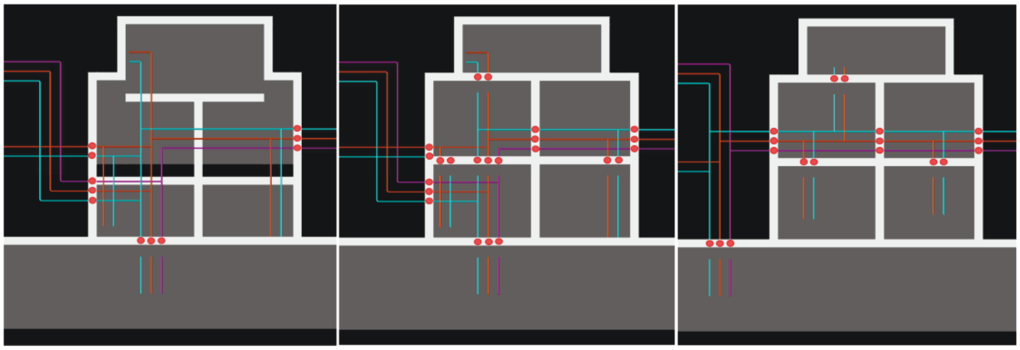

Figure 3: Pipes penetrating wall marked by red dots in three different cases. 3a, situation in BIM model. 3b, designed solution in reality. 3c, installers solution. The cases respectively have 11, 23 and 18 penetrations.

Supporting structures for interior walls and suspended ceilings can similarly cause collisions on site as these structures are not modelled. Figures 4a and 4b show how a supporting structure for suspended ceiling caused the need to lower the ceiling height. Figure 4a shows the design solution where ventilation duct penetrates the vertical surface of suspended ceiling and Figure 4b shows the supporting structure of suspended ceiling as it was built. The designed duct did not fit between the horizontal structures and the ceiling height had to be changed.

Third example of deviation caused by supporting structure can be seen in Figures 5a and 5b. The design model is missing a structure for movable partition wall where the wall can be stacked. Figure 5a shows the designed situation and 5b shows the installers solution. As a result of this structure, the installer had moved the silencers of two ducts away from the wall and re-routed the yellow extract duct to avoid collision with the supporting structure. The larger duct was installed higher compared to design which made it impossible to install the smaller ducts above the larger one. Installed solution is more difficult to install as it requires going through the supporting structure and using more parts for re-routing ducts, and it may result in worse acoustic properties when silencers are not installed beside structures.

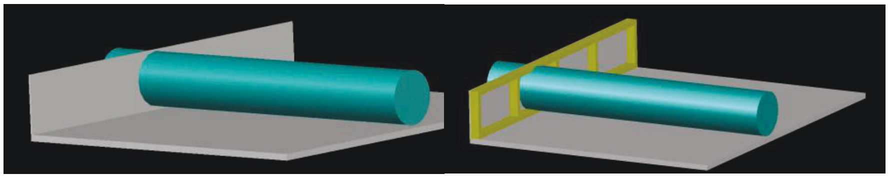

Figure 4: Duct penetrating the vertical wall of a suspended ceiling. 4a shows as-designed solution. 4b shows the supporting structures needed for installing the ceiling. In 4b the duct does not fit between the horizontal structures.

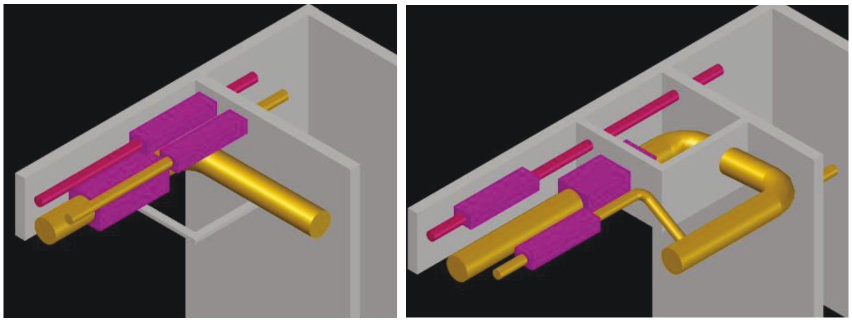

Figure 5: Ventilation ducts and structures as designed (5a, left) and as built (5b, right).

BUILDABILITY

Considering buildability is an important part of BIM coordination and neglecting it can result in clash free models that are impossible to construct. Of all the studied cases, the highest level of coordination was in Case 2 and the lowest in Case 3. In these cases, coordination was focused on eliminating clashes which is reflected in the following examples. Buildability is highly connected to missing model components and insufficient space reservations but it can be considered as individual dimension as well. In this case buildability means for example that there is enough space to make the installations, there is space to use scaffolding for ceiling installations, there is room for using tools, or the order of installation is reflected in designing.

In apartment buildings with decentralized ventilation, bathrooms are typically used for placing the AHU and the suspended ceiling of bathrooms have many ducts in a small space. This can result in difficulties considering buildability. In Case 1 the ventilation installers had made changes to one bathroom type to make more space for installation by re-routing one duct, as seen in Figure 6. The re-routing was possible without changes to other designs as the adjacent room had similar suspended ceiling to bathroom which enabled re-routing the duct. This solution gave more space to the bathroom as the number of ducts decreased and the silencer was installed to the adjacent space.

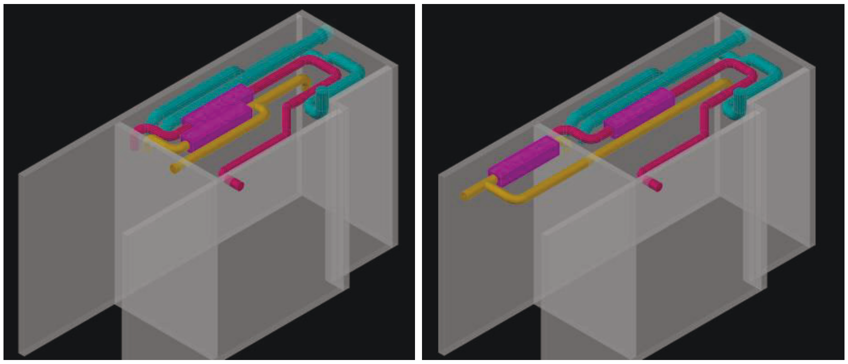

Figure 6: Ventilation ducts in suspended ceiling of bathroom and adjacent hall. Designers solution 6a on the left and installers solution 6b on the right.

Installation sequence should be reflected in designs as changing the sequence in construction phase will lead to clashes that could not be solved in designs. The coordinated models work only if they are followed. Schedule issues can affect the sequence of installations as had happened in Case 3 where plumbing works were changed to be made first. The reason was that the plumbing installations can be made during other dusty stages while ventilation installations require a dust free environment. This resulted in many deviations where pipes were installed above ducts even though ducts were designed to be installed as highest.

Duct crossing takes a significant amount of height and should be avoided or designed to fit into the installation space. In Case 1, there were duct crossings in suspended ceilings that could not fit the reserved space as designed. Figure 7 shows the crossing of two 125 mm ducts with insulation. Left side version is the designed solution and right side version is the installed version. Left hand version does not fit in the space above suspended ceiling. This is clearly shown in the BIM. However, the issue was not solved by either HVAC designer or architect. HVAC designer could have solved the issue by using the same part as the installer had used or a rectangular duct and the architect could have lowered the suspended ceiling or raised the story height. Installer had solved the issue by using a factory made crossing part that enables making the installation in the reserved space. Similar case in Case 3 is shown in Figure 8 where a crossing of two 400 mm diameter round ducts was designed to be done with rectangular duct in the size of 400mm x 200mm, as shown on the left side. Installers solution, where the crossing was made using round duct of 250 mm in diameter, can be seen on the right side. The reason for the change was given by the installer as 250 mm round duct requires the same height as 200 mm rectangular duct with flanges and using a round duct is significantly cheaper and easier to install. Using the round duct causes similar pressure loss compared to the rectangular solution so there is no impact to the functionality of the system.

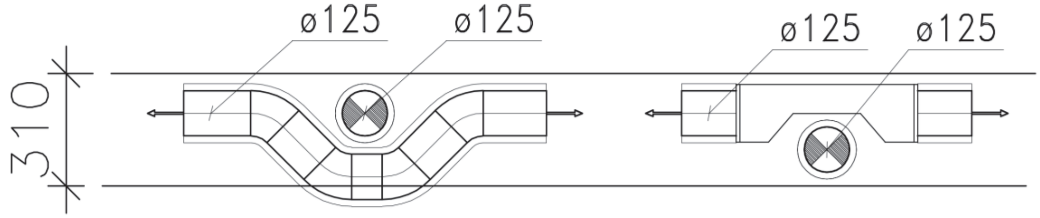

Figure 7: Using special crossing part to fit ducts into suspended ceiling without changing room height.

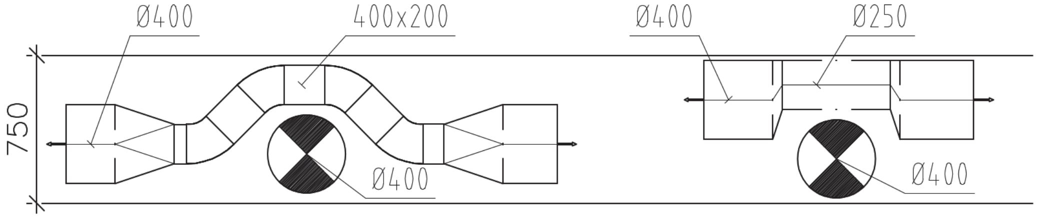

Figure 8: Changing rectangular crossing into round duct for a cheaper and faster installation.

Figure 9 shows a different case of installer changing parts for easier installation. The designer had used 90° elbow in turning a duct from vertical to horizontal under a concrete slab as seen on the left. The installer had changed the bend to a T-branch. This change enabled combining cleaning cover to the T-branch and continuing the horizontal duct in correct elevation and using fewer parts compared to designers solution.

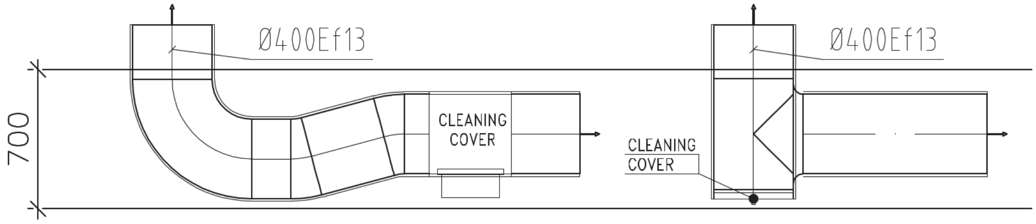

Figure 9: Changing of 90° bend into T-branch to minimize part and space usage.

INTERVIEW OF INSTALLERS

The reasons for deviating from designs are not always obvious and the feedback loop from installation to designing is minimal. For bridging this gap, installers were interviewed on site regarding specific deviations and in general about improving designs to better consider buildability. In addition to the issues described previously the installers identified areas for improvement, these are listed in Table 2.

Table 2: Suggested improvements for MEP designing from installers.

1	Assessment of buildability should be part of BIM coordination.
2	Scheduled order of installation should be reflected in designs.
3	Systems need to be considered on building level as opposed to story level.
4	Unnecessary on-site penetrations of concrete or brick walls should be avoided.
5	Architectural and structural models should be more accurate, especially in renovation projects, to consider existing structures.
6	Unmodelled components such as hangers should be further considered in designing.
7	When defining voids for concrete elements, space for insulation and hangers should be considered.

Many installers mentioned buildability in some form. Their experience was that BIM models always have clashes and buildability is not considered in designing. In addition to the examples given earlier in this paper installers mentioned considering room for using scaffolding. Toilets in Figure 3 were one location where working in the ceiling according to safety requirements using a scaffolding is difficult due to constrained space and the installers were forced to using ladders which is not permitted officially due to safety reasons. In this example they had also minimized the difficult tasks by re-routing pipes.

Scheduled order of installation should be reflected in designs. Systems that will be installed first should be designed as highest since installing will advance from top to bottom. To enable efficient installation constant elevations for systems make installation easier. Frequent changes in installation height means that installers cannot complete their own systems but instead need to wait other systems to be built to continue their own installation.

Especially in large buildings, design tasks can be divided by floors to reduce design time by adding designers. Sometimes this leads to suboptimal solutions which one installer had noticed on site. He suggested that designers should consider systems more on building level and to make sure that the systems are functioning and efficient as a whole.

Penetrations made on site are not desired as the MEP installers often have to drill them by themselves or wait for the main contractor to do it and this decreases the time they can spend making actual installations. These should be avoided if possible by routing pipes and ducts differently.

Existing structures caused many deviations in Case 2. Ventilation installer suggested that available spaces and load bearing structures should be measured in designing to solve problems better in design phase.

Many installers mentioned hangers as an area of development. Hangers were not modelled in any of the studied cases, and it is not customary in Finland. This means that space reservations for hangers are not considered and installers need to coordinate all the clashes caused by hangers. Changing locations of already installed hangers to accommodate other trades is common.

Voids in elements need to be placed so that the pipes or ducts can be installed into them. In some cases, the voids are too close to the ceiling and installing hangers above the parts becomes difficult. Ceilings can also have sound absorbing materials that are not modelled but affect the free space between voids and ceiling.

DISCUSSION AND CONCLUSIONS

The objective to convey designers' intent into installation via designs is not realized fully by using current design practices, even when BIM is used for coordination. In many cases it is not possible to execute the designs exactly as intended. In some cases, it could be said that the designs are used as schematics and routing between two points can be changed as long as the points are connected in correct sequence. The study also showed that improvisation leads to more improvisation and unclear designs lead to waste, as predicted.

Installers have a good understanding regarding buildability and in most cases had good reasons for deviating from designs. In some cases, their changes improved the engineer's solution and in some cases the changes resulted in decreased functionality. Based on the observations and interviews, having contractor comment on design and suggest changes could remove many of the documented deviations and increase productivity in installation phase. Contractors could contribute to solving possible issues in designs phase and optimizing designs based on their experience and typical construction practices. Knowing the building schedule and planned order of installation by early contractor involvement would enable designing for the installers needs.

BIM coordination does not guarantee collision free installation even if models are clash free, as was in Case 2. BIM coordination can only resolve clashes which are visible in the model. Many of the documented deviations were caused by unmodelled objects. These problems could be solved by increasing the LOD of all models. Potential of using BIM was not realized to fullest in any studied case, assessment of buildability was left undone in all cases. Increasing the LOD is a requirement for effective assessment of buildability as only visible issues can be resolved.

Observed deviations from case sites were divided into three categories: insufficient space reservations, missing model components, and buildability. All the problem types could have been solved before installation by more accurate designing. Based on our observations to improve productivity in installation we suggest the following changes to designing. 1. Designing must be done using BIM. 2. Shift from collision free models to buildable models. BIM coordination must be part of designing and it must include resolving clashes and assessment of buildability. 3. Increasing the LOD and accuracy of designs to better enable steps 1 and 2. 4. Contractor should be involved in designing and giving feedback especially on buildability, schedule, and order of installation. 5. Cost optimization based on components should be part of designing.

While positive effects of BIM use in designing have been documented extensively and coordination practices have improved continuously (Tommelein and Gholami, 2012; Jang and Lee, 2018; Khanzode et al., 2008), we found that these practices are not followed in projects in Finland, and likely other countries, where prefabrication of MEP is not yet commonplace. Therefore, we primarily suggest adopting already proven BIM practices in all types of projects. Secondly, we suggest a move from clash free models to buildable models. Projects using modelling and BIM coordination are focused on achieving clash free models but currently neglect assessing buildability in many cases. This is partly due to low level of detail in design models and designers' lack of installation knowledge. Increasing the level of detail in all design models will benefit BIM coordination as more issues can be resolved in designing. Modelling of hangers for example is common practice in markets that use prefabrication and having these additional details will help solving issues in design phase. More research is needed to determine a reasonable level of information need to guarantee that further modelling effort supports assessment of buildability.

We presented prefabrication designs as closest existing example of ideal designs. When studying barriers in adopting prefabrication in the Finnish market Lavikka et al (2021) found designers are lacking capabilities for detailed level design. Our results support this finding with many examples where buildability could have been better considered, while we recognize that contractual issues and tight deadlines may also be factors. Our proposition to solve this issue is involving contractor and installers in design phase and letting them affect designing by analyzing buildability based on their experience. One proven method for incorporating scheduling into designing is 4D BIM (Koo and Fischer, 2000; Buchmann-Slorup and Andersson, 2010), which is not widely used in the Finnish market. Using contractor knowledge in designing and having contractors designing detailed models is commonplace in markets where prefabrication is widely used (Khanzode et al., 2008). Having a feedback loop from construction to designing is critical for identifying and removing problems (Tommelein and Gholami, 2012). Contractors could also help on optimizing designs to decrease material costs. Our results showed that installers are already doing optimization on site to reduce work time and material cost.

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