Valkonen, T., & Seppänen, O. (2026). Variation management in prefabricated MEP installations: challenges and opportunities. In F. Hamzeh, M. Poshdar, N. P. Garcia-Lopez, & V. Gan (Eds.), *Proceedings of the 34th Annual Conference of the International Group for Lean Construction* (IGLC34) (pp. 727–738). https://doi.org/10.24928/2026/0129

VARIATION MANAGEMENT IN PREFABRICATED MEP INSTALLATIONS: CHALLENGES AND OPPORTUNITIES

Tuomas Valkonen[1] & Olli Seppänen[2]

ABSTRACT

Managing variation is an essential lean principle. Tolerance management remains marginal in construction and focuses on architectural and structural trades. Especially mechanical, electrical and plumbing systems have largely been neglected in tolerance management research, despite their critical role in project delivery.

This research studies variation management, its challenges and opportunities for improvement in a plumbing renovation project through semi structured interviews and thematic analysis. The interview questions addressed prefabrication practices, planning processes, production and control activities, tolerance management, accuracy, and sources of variation. Three aggregate themes emerged as key results: (1) detection and management of deviations, (2) design information and tolerance management, and (3) management of change and personnel. Together these themes highlight the multifaceted nature and difficulty of variation management.

The results emphasize that both technical and human factors must be addressed simultaneously while maintaining constancy of purpose. Improving installation guidelines and accelerating issue resolution were identified as key development areas. Stabilizing the production system provides an opportunity to further enhance productivity and shorten cycle times.

KEYWORDS

Tolerance management, variability, variation, prefabrication, MEP.

INTRODUCTION

Achieving a steady flow in construction is a fundamental lean idea. This idea is founded on controlling and minimizing variation. Typically referring to variation in task durations, and it has been shown that variation in task durations is detrimental to project performance (Tommelein et al., 1999). The eight wastes reported by Ohno (1988) and Koskela (2004) are all related to variation and its management. As Hopp and Spearman (2011) state, variation in the product, like dimensional variation, affects directly task durations through rework and disruptions of the production system. Managing dimensional variation should therefore be a key priority in managing the flow of a construction project.

Tolerance management is an established and researched practice that addresses dimensional variation. Studies show that some projects adopt tolerance management practices, but these are often limited to structural and architectural trades (Talebi et al., 2020). Regardless, dimensional

[1] Doctoral Researcher, Department of Civil Engineering, Aalto University, Espoo, Finland, tuomas.valkonen@aalto.fi, orcid.org/0000-0002-2710-5190

[2] Associate Professor, Department of Civil Engineering, Aalto University, Espoo, Finland, olli.seppanen@aalto.fi, orcid.org/0000-0002-2008-5924

deviations occur (Talebi et al., 2021; Milberg and Tomelein, 2019) and evidence indicates significant deviations in Mechanical, Electrical and Plumbing (MEP) installation (Valkonen and Seppänen, 2023; Görsch et al., 2024).

Mechanical, electrical and plumbing (MEP) construction is a significant part of construction. It can attribute to up to 40 % of project costs and is a complicated interconnected multi contractor and designer entity (Khanzode et al., 2008). Research regarding variation reduction in MEP construction is scarce. Especially when adopting prefabrication, minimizing dimensional variation and controlling it is crucial. Prefabrication changes the nature of variation management as traditionally variation is managed on installer level on craft-basis. For these reasons the objective of this research is to study the challenges of variation management in a MEP prefabrication project. Specifically, we answer the question: What are the major challenges in managing variation in MEP prefabrication and how could these be overcome?

This study examines one prefabricating MEP renovation project through semi structured interviews to identify challenges and opportunities in variation management. The paper contributes theoretically by showing that instead of eliminating variation prefabrication transforms it from a craft-based installation issue into a challenge of information quality, deviation handling, and organizational capacity. Practically, the study highlights that establishing systems for prefabrication, deviation reporting, and tolerance management is not sufficient without sustained managerial follow-up, timely resolution of issues, and adequate resources to support new production methods.

LITERATURE REVIEW

Manging variation is a manufacturing originated practice. The first academic quality themed publications were related to statistical process control in manufacturing (Shewhart, 1931). Since then, variation and its management through measurements have been the subject of fundamental textbooks of manufacturing (Deming, 2000; Hopp and Spearman, 2011). In construction, variation management has been implemented as part of lean construction philosophy. Koskela's (2000) foundational thesis discusses variation and its management in detail. Variation management can be related to schedules and task durations or properties of the products like geometric dimensions (Hopp and Spearman, 2011). More recent studies deal with tolerances and tolerance management in construction as a practice of managing variation (Milberg, 2006; Talebi, 2019). Tolerance management in construction is motivated through improvement of quality and its corollaries in safety and function as well as the improvement of flow in construction. Variation in task durations cascades into project delays (Tommelein et al., 1999) and geometric variation directly affects variation in task durations (Hopp and Spearman, 2011).

Construction is a heavily craft-based industry and therefore prone to variation. As industrialisation of construction has progressed the need for variation management has also increased. Ensuring fit of prefabricated components on site is crucial for smooth flow of construction and quality of the completed assembly. Variation is managed through setting of tolerances for both manufacturing and installation (Ballast, 2007). In on-site construction the variation of previous assemblies or phases can be absorbed in the following installations, but in prefabrication it is counterproductive to modify all subsequent installations on-site.

MEP systems are especially prone to variation and may cause significant deviations and delays for following trades (Seppänen, 2009). Some of the sources of variation are identified as poor quality of designs, improvisation of installers without reason or due to improvisation of previous trades, and lack of requirements for accuracy (Valkonen and Seppänen, 2023; Alhava et al., 2024; Görsch et al., 2024). Therefore, it can be said that prefabrication reduces dimensional variation through necessitating higher accuracy. However, it is not known how this need for accuracy is managed in projects or what its key difficulties and opportunities for improvements are.

Introducing prefabrication requires coordinated change in organization and process, as new workflows alter responsibilities, information needs, and interdependencies. Construction projects often struggle with such transitions because established ways of working and fragmented contracting limit learning and adaptation (Fischer et al., 2017). Insufficient change management can intensify coordination problems, contribute to rework, and weaken the ability to manage variation (Love et al., 2014). Effective change management is therefore essential for ensuring that project teams can adapt to new production methods and maintain flow.

Research on takt planning shows that tightly paced operations demand reliable handovers, predictable task durations, and rapid resolution of disturbances (Frandson et al., 2015). Similarly, in MEP prefabrication detailed design data, timely logistics, and accurate installations are required to prevent on-site adjustments slowing the process. Managing fast-paced operations requires strong coordination and systematic variation-control mechanisms to maintain stability.

Taken together, the literature suggests that while variation is widely recognized as detrimental to production systems and tolerance management is an established response to controlling dimensional variation, existing tolerance management approaches are largely framed as technical solutions and their application to MEP systems remains underexplored, particularly in the context of fast-paced and takt-based operations.

METHODS

To answer the research question, we studied one plumbing renovation project which utilized prefabrication. Data were collected with semi structured interviews. The studied project was chosen during an industry workshop regarding tolerance management and prefabrication by asking for willing participants into interview research about prefabrication and tolerance management. The studied project was the only available project including MEP prefabrication and a systematic way of documenting deviations and was therefore selected for investigation.

The project consisted of 8 multi-family residential buildings. The scope of a plumbing renovation is to renew all technical systems of the building. Typically, these include sewers, water pipes, ventilation, electrical systems, and heating pipes. The project used prefabricated installations, and the project team had experience in multiple identical or very similar projects. The prefabrication scope included water pipes in the ceiling and on the walls, ventilation, underfloor heating, risers in the stairwell, and the frame for the suspended ceiling.

Data were collected through six semi-structured in person interviews. The interviewed people and durations of the interviews are presented in table 1. All the interviews were conducted during one day and the interviews were recorded and transcribed. All key personnel related to prefabrication and project management were selected for interview and they were asked to identify potential new interviewees, none were recommended. While all interviewees contributed role-specific insights, the data overall reached saturation by the final interviews.

Semi-structured interviews were conducted using a predefined thematic guide to ensure consistent coverage across respondents. The interview protocol consisted of five broad themes. First, interviewees were asked to describe their role, responsibilities, experience, and familiarity with prefabrication. Second, general project background was discussed, including project type, scale, use of prefabrication, and its role in the production system. Third, participants reflected on prefabrication implementation, goals, logistical arrangements, types and sizes of prefabricated assemblies, and the perceived effects on schedule, quality, and overall project performance. The fourth theme focused on the prefabrication planning process, including the methods and tools used, the roles of project participants, the strengths and weaknesses of the planning approach, and the key drivers and barriers encountered. Finally, the interviews explored the production and production control process, with particular attention to tolerance management, expected accuracy, process capabilities, sources of variation, quality control

practices, communication between design, manufacturing, and site, reporting and resolution of issues, and recurrence of problems. Most emphasis was put on this fifth theme. Together, these themes enabled a comprehensive examination of variation management in prefabricated MEP installations within the project.

Table 1: Interviewees and interview durations.

	Role on the project	Interview duration
1	Head of estimating, financial matters	50 min
2	Project manager	46 min
3	Site manager, apartments	36 min
4	MEP installer	20 min
5	Site manager, general spaces	37 min
6	Production designer	47 min

Data analysis was based on the Gioia framework presented by Gioia et al. (2012). The interviews were transcribed by an outsourced professional. The first author analyzed the transcribed interviews by first reading all interviews thoroughly and then inductively coding meaningful text segments line by line, resulting in 307 initial codes. These codes were subsequently refined by grouping and merging similar codes into higher-order concepts and aggregate themes. Analysis of the interviews was divided into four phases according to the Gioia framework as presented in figure 1. The identified classifications and their aggregation into higher level themes and aggregates is presented in the results section.

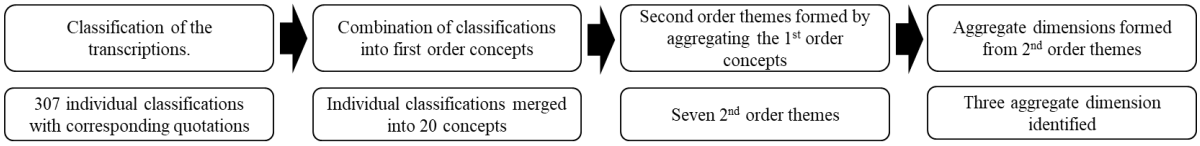

Figure 1: Data analysis procedure used in the study.

The method is subject to potential bias in both case selection and the coding and classification of interview transcripts. The case company may have been more willing to participate due to production challenges; however, few comparable MEP prefabrication companies exist in Finland, and the selected company is known for systematic development efforts, which mitigates this risk. Researcher bias was reduced through predefined interview themes, diverse interviewee roles, and by interviewing all individuals identified by the company as having relevant knowledge rather than selectively choosing participants.

RESULTS

The analysis revealed three overarching dimensions that shape the accuracy, stability, and predictability of MEP prefabrication and installation performance. The dimensions were: 1) detection and management of deviations, 2) design information and tolerance management, and 3) management of change and personnel. These dimensions represent interconnected mechanisms through which variation emerges, accumulates, or is mitigated during installation, describing how technical, informational, and organizational factors interact to shape installation accuracy and the practical management of deviations. The 20 combined classifications along with corresponding sample quotations are presented in Table 2. The Gioia table is presented in Table 3.

Table 2: Quotes for each first order concept.

Deviation management	”Even if we have been able to identify a huge number of deviations, even on a daily basis. Our operation is so fast paced, we haven’t been able to process them”
Documenting deviations	”This is a key question. Not enough (quality control) … solution is to make systematic inspections and identify potential issues early.”
Material buffers and deviations	”The assembly does not fit. And we have already eight apartments built (prefabricated assemblies).”
Material shortages	”We had material deliveries in the apartments. They were not exactly correct. Sometimes we were missing parts and sometimes all the parts were not needed.”
Rework	”Many times when you attach it to the ceiling and take it down and remove a pipe section from the middle, it would be the same to do it on-site altogether.”
Schedule related items	”We have buffer wagons and loosely stacked wagons, that we use for keeping up with the schedule. Overtime is still required occasionally.”
Problems in designs and updating them	”When water, sewer, and ventilation intersect in one point, you can already guess that BIM has not been used nor designs coordinated and clashes exist.”
Installation instructions	“Its not the installers fault, that they don’t do as we want. We should be able to better tell them.” ”…installation instructions must be improved.”
Inadequate starting data	”Renovation projects differ significantly from new constructions… We face, undocumented renovations, original designs are not valid, varying structures.”
Variation management	”In pipe assemblies, there are multiple branches and valves. Nine out of ten parts are standardized and the last one is oversized. We don’t need zero tolerance.”
Accuracy in installation	”Sometimes we have deviations of some millimetres. …the manufacturing accuracy is good. The largest problem is the accuracy of installation on site…”
Lack of personnel resources	”…if we have a list of 200 items, 50 of those are assigned for one key individual who does not have the time to begin with ” ”… it is a resource issue also”
Staff retention and continuity	”We are constantly going through ambitious changes causing exhaustion. Managing change on an individual and psychological level is challenging.”
Prefabrication and technical challenges	”But in the pipe installation, installers have been happy with prefabrication” ”In designing it is easy to draw thin lines without insulation, not reflecting reality.”
Prefab. and production process	“Then if necessary, I think about transportation, how to get the assemblies undamaged to the site. Do we have elevators or stairs on the site.”
Frustration for slow improvement	”…when we have a lot of feedback from the field they expect that the issues would not happen in the next line. And when they do its frustrating and discouraging for everybody.”
Deficiencies in process control and flow	”…we developed prefabrication much more compared to everything else in the project, it made the management more difficult.” “When we can sell projects with solutions that support our production system. (management will be easier)”
Collaboration: site and factory	”In my opinion we should have the factory here on site. Management could supervise better, and communication with on-site installers would be easier.”
Cultural change	“One project went quite well and based on that we doubled the prefabrication and halved the takt times. It was too big a step, we started to get tangled up.”
Lack of expertise	”…one problem is that I don’t simply have the knowledge to accurately report and identify possible problems on-site.”

Table 3: The resulting Gioia table showing the sequential aggregation of the 307 codes into three aggregate dimensions.

First order codes (307)	Categories	Second order themes	Aggregate dimensions
57	Deviation management, Documenting deviations, Material buffers and delays in deviation handling	Deviation reporting and control	Detection and management of deviations
28	Material shortages, Rework, Schedule related items	Material shortages, rework, and schedule disruptions	
70	Problems in designs and updating them, Installation instructions, Inadequate starting data	Design quality and installation instructions	Design information and tolerance management
47	Variation management, Installation accuracy and manufacturing precision	Prefabrication and installation accuracy and variation management	
42	Lack of personnel resources, Staff retention and continuity of competence	Human resources, workforce stability, and workload	Management of change and personnel
41	Prefabrication and technical challenges, Integration of prefabrication into the production process	Execution of prefabrication and integration into the production process	
22	Frustration for slow improvement, Deficiencies in process control and flow, Collaboration between site and factory, Cultural change, Lack of expertise in design, installation, or management	Process management challenges	

DETECTION AND MANAGEMENT OF DEVIATIONS

The interviews revealed that there were significant shortcomings in reporting deviations. Many of the interviewees reported that daily management and WhatsApp groups were used for reporting deviations and that these fora had worked for some time in a previous project. However, the responses also reflected a reality where reporting deviations did not lead to identification or resolution of the root causes. Ultimately this led to people not reporting issues and frustration in the design and management team.

Personnel resources were identified as a problem in the resolution of identified issues by multiple interviewees. Production planning and design management was under resourced in relation to the number of tasks. Resolution of reported deviations was further slowed by material inventories of prefabricated elements. These elements had already been assembled and contained the reported issues. Thus, rework would have been needed. Reporting of deviations did not always enable effective resolution of issues. For example, some material problems were in fact caused by deviating from designs for an unknown reason. These types of deviations are impossible to fix in future installations as the root cause is not known and therefore cannot be resolved.

DESIGN INFORMATION AND TOLERANCE MANAGEMENT

The interviews revealed the extensive design effort required in prefabrication and efficient production planning. The detailer used the bidding material as starting data for their design for manufacturing and assembling. Traditionally in on-site construction, the bidding material is used as construction drawings. In prefabrication however, the manufacturing, installation, and logistics are carefully considered (detailed designs for manufacturing, takt schedules, takt logistics). The quality of the starting data causes problems such as incomplete coordination of designs, unfeasible technical solutions, and unknown site conditions. The interviews revealed that there are issues in installation instructions on site even with detailed design. Sewer installers did not use the designs at all and instructions on how to install the prefabricated elements were lacking. The material deliveries based on the detailed designs were not always accurate as the existing condition did not always enable the designed solution. Furthermore, when issues were reported on site, it took a long time to fix the issues in subsequent installations. Installation instructions and onboarding of new employees were seen as development areas by the designer also.

Manufacturing accuracy was seen as good, deviations in relation to designs were small, in the range of millimetres. On-site installation accuracy was seen as the most significant source of variation. One interviewee highlighted the need for the prefabrication assembler to have knowledge about the site and to be in communication with the site installers to make better fitting installations. On the other hand, it was seen that the manufacturing accuracy was high since the prefabrication assembler did not know exactly where or how the assemblies would be installed and was therefore motivated to follow the designs to the letter. The on-site variation was addressed through making the assemblies such that it would be clear where possible modifications such as cutting or bending should be done. This was done for example by over dimensioning the buffer parts or by insulating all the parts that should not be modified on site.

MANAGEMENT OF CHANGE AND PERSONNEL

One key bottleneck in many of the issues of the production system was that the people with the knowledge and authority to solve these issues did not have the time to do so. In many of the responses it was indicated that a significant number of key tasks were the responsibility of one person. Keeping the management organization small has its benefits in lowered costs and maximizing resource efficiency but it risks the occurrence of under resourcing that compromises the success of the operation. Prefabricating removes the need for highly skilled installers who can improvise and make the installation design on site. This means that the process is not as dependent on skilled workforce, and it was stated that educating new persons for tasks is very simple and no experience is required. On the other hand, it was implied that onboarding had been neglected and the following example was given. One interviewee described a previous project where summer holidays had left only inexperienced installers on site, while most planning and supervisory staff were absent. In the absence of adequate guidance and managerial support, prefabrication practices quickly collapsed, even though assemblies had already been manufactured and design work for prefabrication was complete. Furthermore, the continuous development efforts along with the accompanied problems in managing deviations caused frustration and exhaustion in the worker and manager roles, and this was seen as a potential risk as people might not stay in their positions.

The rapid pace of development and variation between projects means that the process is difficult to stabilize. Problems even if successfully reported and resolved are not beneficial to the continuous process if the next project faces completely different challenges. Managing the process from sales on was highlighted. For stabilization, it would be important to develop a specific standardized solution and sell projects where the solution is applicable, to avoid project specific non repetitive challenges.

Prefabrication is a cultural change from traditional methods. While installers may require less traditional craft skills, management requirements increase, and it was reported as an issue that the site managers do not have the required technical MEP expertise to identify and accurately describe the occurring problems to the designer thus preventing efficient resolution.

INTERACTION OF THE AGGREGATE THEMES

The mutual hierarchy and interaction of the aggregate themes are illustrated in figure 2. Management of change and personnel forms the foundational level spanning multiple projects. At this level, working methods are established, the purpose of operations is defined and maintained, and the social structure of the company and work is shaped. Design information and tolerance management operate at the project level, influencing design quality, tolerance management, and the accuracy of manufacturing and installation. Detection and management of deviations operate at the individual installation level, focusing on the identification, reporting, and resolution of issues. Although a hierarchical structure is evident, the mechanisms through which problems emerge are not strictly linear, and challenges may originate at any level while propagating across the others as the following examples show.

Deviations detected during installation may be reported, but if their resolution is slow, similar errors may recur, leading to repeated rework. Over time, this may reduce willingness to report issues, further increasing unmanaged variation.

Insufficient installation instructions may lead to inaccurate installations, leading to need for rework in subsequent stages and may result in design-related problems being misclassified as assembly defects or material shortages.

At the organizational level, multiple consecutive changes to the production system may overburden an already under-resourced organization, causing workers to prioritize immediate survival over process discipline. In such cases, design and manufacturing may focus on reacting to site pressures, leaving more issues to be resolved during installation.

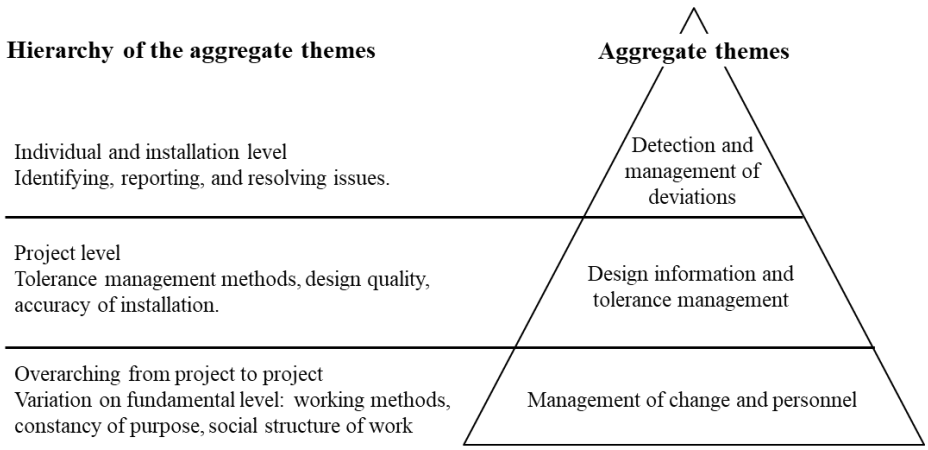

Figure 2: Conceptual illustration of the three themes, their hierarchical relationships, and the associated challenges in managing variation.

DISCUSSION

Research on MEP prefabrication has predominantly emphasized its potential benefits or, conversely, the challenges (Eastmann & Sacks, 2008; Poirier et al., 2015; Jang and Lee, 2018; Lavikka et al., 2018). However, prefabrication is typically evaluated at the level of isolated tasks or components, while offering limited insight into how prefabrication interacts with the broader production system and the management of installation processes. The results of this study indicate that successful implementation of MEP prefabrication is fundamentally a production system management challenge. Variation cannot be reduced solely through

technical solutions or shifts in production location; rather, improvement hinges on practices such as deviation detection and rapid feedback loops, standardization, tolerance management solutions, and stable workflows, mechanisms long emphasised in quality management and Lean Construction (Deming, 2000; Koskela, 1999; Koskela, 2000; Gibb, 2001; Hopp & Spearman, 2011). Our findings therefore contribute to knowledge by demonstrating that the performance of prefabricated MEP systems depends on the construction organisations management of information quality, coordination of trades, and maintaining control over variation during installation.

Research on tolerance management has highlighted the importance of identifying and resolving tolerance issues or deviations (Talebi et al., 2020). However, these discussions typically remain at a high level and do not address the practical difficulty of managing such issues within a hectic and time-pressured project organization. The results of this study enrich this general understanding by emphasizing the need for both timely identification of deviations and rich, technically precise descriptions of the observed problem. Effective interpretation of deviations often requires specialized technical expertise that site managers may not possess, creating a need for continuous training or the presence of knowledgeable technical personnel on site. Moreover, once a deviation is detected, its resolution must be expedient, not only to limit downstream impacts, but also to sustain motivation for systematic reporting. When corrective actions are delayed or inconsistent, reporting deteriorates, creating a self-reinforcing cycle of under-detection and unmanaged variation.

The example of collapsing back into on-site construction during the summer holidays highlights that the success of prefabrication is contingent not merely on technical preparation but on the stability and competence of the project organization responsible for implementing it. The lack of onboarding and the simultaneous absence of the key management and design personnel meant that prefabricated assemblies could not be used even if they were already manufactured.

Although prefabrication is often associated with improved dimensional accuracy, the findings indicate that variation is not eliminated but transformed. In craft-based on-site construction, design and coordination deficiencies are solved by installers, whereas in prefabrication these tasks are transferred upstream to detailed design, production planning, and managerial coordination. Thus, changing not only the production logic, but also where variation is generated and how it must be managed.

Three propositions along with the aggregate themes are presented. First, sustained deviation reporting depends on timely managerial response, as missing or delayed responses reduce the willingness to continue reporting problems. Second, the success of design and production planning depends on how design intent and requirements are communicated as instructions. Third, variation management in prefabricated MEP work is not solely a technical coordination problem but a socio-technical challenge shaped by work practices, training, and managerial capacity. Accordingly, managers should establish systems for prefabrication, deviation reporting, and tolerance management, and sustain them through rapid issue resolution, clear instructions, adequate training and work prerequisites, and pacing of organizational change.

This study is limited by its small sample of six interviews conducted within a single renovation project. Such a narrow empirical base creates the risk of over-emphasizing project- or company-specific practices that may not hold more broadly. This risk is partly mitigated by the interviewees' extensive references to previous projects, many of which exhibited similar coordination challenges, tolerance-related issues, and difficulties in managing change. Several of the identified themes such as limited resources, insufficient systematic quality control, and constraints arising from rapid development cycles, are well-known in traditional construction contexts and are therefore unlikely to be unique to this specific project type. The renovation project context limits the broader applicability of the findings, as new construction projects are

not affected to the same extent by uncertainty in starting conditions and external sources of variation.

Future research should aim to verify the findings through larger dataset. The role of project type should also be studied by comparing the results from a renovation project to new construction, renovation project type has naturally more uncertainty.

Despite the limited sample, the generalizability of the findings is supported by the recurrence of the identified challenges across the interviewees past project experiences and by the fact that many issues reflect broader management shortcomings rather than characteristics specific to MEP prefabrication. The contribution of this study lies not in identifying entirely new categories of problems, but in demonstrating how these well-known challenges manifest in the context of MEP prefabrication, where the consequences of variation and weak change control can escalate rapidly. While it is reasonable to anticipate that insufficient quality management and fast-paced development may create difficulties, the specific forms these took in this project could not have been fully predicted. This provides the basis for the study's novelty and practical relevance. As discussed by Valkonen et al. (2025), prefabrication is promised to offer clear benefits, yet its successful implementation still requires significant system-level transformations. This study advances that discussion by revealing variation-related challenges and opportunities that extend beyond technical solutions and into project governance and management practices.

CONCLUSIONS

This study examined the challenges in management of variation in MEP prefabrication projects and identified three aggregated themes: (1) detection and management of deviations, (2) design information and tolerance management, and (3) management of change and personnel.

First, effective detection and management of deviations remains a central challenge. Accurate reporting with sufficient detail is essential for enabling root cause analysis and resolution of issues, yet reporting practices deteriorate when corrective actions are slow or inconsistent. The findings highlight the need for rapid, systematic deviation handling aligning with the pace of production.

Second, design information and tolerance management were found to be critical enablers of variation control. High-quality starting data and clear installation instructions are necessary to support accurate prefabrication and on-site installation. Pre-emptive mechanisms such as design features that absorb variation are needed to support the standardisation of most parts.

Third, managing system-level change and ensuring workforce continuity are fundamental in evolving and fast-paced production environments such as prefabrication. The results show that resource sufficiency, competence development, and coordinated change management are prerequisites for realising the benefits of prefabrication and avoiding variation-induced disruptions.

Together, the three themes suggest that variation management in MEP prefabrication is not primarily a technical challenge, but a managerial and socio-technical one. Improving accuracy requires not only systems for prefabrication, deviation reporting, and tolerance management, but also sustained managerial follow-up and organizational capacity to support new ways of working. Accordingly, prefabrication should be understood not as an isolated technical solution, but as a broader production system change requiring coordination, supervision, and managerial competence.

AKNOWLEDGEMENTS

This work has been supported by "Talotekniikan esivalmistus ja toleranssit" (MEP prefabrication and tolerances) project, funded by Building 2030 consortium.

REFERENCES

Alhava, O., O'Loughlin, M., Haapasalo, H., Viitanen, J. & Pitkäranta, T.. (2024). Rigorous 2-Hour Takt Reveals Upstream Underperformance. *IGLC32*. https://doi.org/10.24928/2024/0219

Ballast, D. K. (2007). *Handbook of construction tolerances* (2nd ed.). John Wiley & Sons.

Deming, W. E. (2000). Out of the crisis. *MIT Press*.

Eastman, C., & Sacks, R. (2008). Relative productivity in the AEC industries in the United States for on-site and off-site activities. *Journal of Construction Engineering and Management, 134*(7), 517–526.

Fischer, M., Ashcraft, H. W., Reed, D., & Khanzode, A. (2017). *Integrating project delivery*. Wiley.

Frandson, A. G., Seppänen, O. & Tommelein, I. D.. (2015). Comparison Between Location Based Management and Takt Time Planning. *IGLC23*.

Gibb, A. G. F. (2001). Standardization and pre-assembly: Distinguishing myth from reality using case study research. *Construction Management and Economics, 19*(3), 307–315. https://doi.org/10.1080/01446190010020435

Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2012). Seeking qualitative rigor in inductive research: Notes on the Gioia methodology. *Organizational Research Methods, 16*(1), 15–31. https://doi.org/10.1177/1094428112452151

Görsch, C., Seppänen, O., Peltokorpi, A., & Lavikka, R. (2024). Unlocking productivity: Revealing waste and hidden disturbances impacting MEP workers. *Journal of Construction Engineering and Management, 150*(9), 04024108. https://doi.org/10.1061/JCEMD4.COENG-14204

Hopp, W. J., & Spearman, M. L. (2011). *Factory physics* (3rd ed.). Waveland Press.

Jang, S., & Lee, G. (2018). Process, productivity, and economic analyses of BIM-based multi-trade prefabrication: A case study. *Automation in Construction, 89*, 86–98. https://doi.org/10.1016/j.autcon.2017.12.035

Khanzode, A., Fischer, M., & Reed, D. (2008). Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project. *Electronic Journal of Information Technology in Construction, 13*, 324–342.

Koskela, L.. (1999). Management of Production in Construction: A Theoretical View. *IGLC7*.

Koskela, L. (2000). *An exploration towards a production theory and its application to construction* (VTT Publications 408). VTT Technical Research Centre of Finland.

Koskela, L.. (2004). Making-Do — the Eighth Category of Waste. *IGLC12*.

Lavikka, R., Chauhan, K., Peltokorpi, A., & Seppänen, O. (2021). Value creation and capture in systemic innovation implementation: Case of mechanical, electrical and plumbing prefabrication in the Finnish construction sector. *Construction Innovation, 21*(4), 837–856. https://doi.org/10.1108/CI-05-2020-0070

Love, P. E. D., Smith, J., Ackermann, F., Irani, Z., & Canas, R. (2014). Making sense of rework and its unintended consequence in projects: The emergence of uncomfortable knowledge. *International Journal of Project Management, 32*(7), 1137–1150. https://doi.org/10.1016/j.ijproman.2013.12.005

Milberg, C. (2006). *Application of tolerance management to civil systems* [Doctoral dissertation, University of California, Berkeley].

Milberg, C. T., & Tommelein, I. D. (2019). Methods for managing tolerance compatibility: Windows in cast-in-place concrete. *Journal of Construction Engineering and Management, 146*(2), 04019105. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001728

Ohno, T. (1988). *Toyota production system: Beyond large-scale production*. Productivity Press.

Poirier, E. A., Staub-French, S., & Forgues, D. (2015). Measuring the impact of BIM on labor productivity in a small specialty contracting enterprise through action research. *Automation in Construction, 58*, 74–84. https://doi.org/10.1016/j.autcon.2015.07.002

Seppänen, O. (2009). *Empirical research on the success of production control in building construction projects* [Doctoral dissertation, Helsinki University of Technology].

Shewhart, W. A. (1931). *Economic control of quality of manufactured product*. Van Nostrand.

Talebi, S. (2019). *Improvement of dimensional tolerance management in construction* [Doctoral dissertation, University of Huddersfield].

Talebi, S., Koskela, L., Tzortzopoulos, P., & Kagioglou, M. (2020). Tolerance management in construction: A conceptual framework. *Sustainability, 12*(3), 1039. https://doi.org/10.3390/su12031039

Talebi, S., Koskela, L., Tzortzopoulos, P., Kagioglou, M., Rausch, C., Elghaish, F., & Poshdar, M. (2021). Causes of defects associated with tolerances in construction: A case study. *Journal of Management in Engineering, 37*(4), https://doi.org/10.1061/(ASCE)ME.1943-5479.0000914

Tommelein, I. D., Riley, D. R., & Howell, G. A. (1999). Parade game: Impact of workflow variability on trade performance. *Journal of Construction Engineering and Management, 125*(5), 304–310. https://doi.org/10.1061/(ASCE)0733-9364(1999)125:5(304)

Valkonen, T. & Seppänen, O.. (2023). Improving Productivity in Ventilation and Plumbing Installations by Developing Designs. *IGLC31*. https://doi.org/10.24928/2023/0151

Valkonen, T., Alhava, O., Viitanen, J., & Seppänen, O. (2025). Why do some projects prefabricate MEP while others do not? *Lean Construction Journal, 2025*, 96–124. https://doi.org/10.60164/2a4ktfnel