Valkonen, T. Alhava, O. Viitanen, J. Seppänen, O. (2024). Why do some prefabricate MEP while others do not In D. B. Costa, F. Drevland & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction* (IGLC32) (pp. 857–868). doi.org/10.24928/2024/0145

WHY DO SOME PREFABRICATE MEP WHILE OTHERS DO NOT?

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ABSTRACT

Prefabrication of mechanical, electrical, and plumbing (MEP) systems seems to be an obvious choice to some, while others are struggling to reach the same conclusions. Most of the literature is focused on benefits, implying prefabrication is an obvious choice. To understand reasons why different conclusions are reached, we studied two cases where one decided against, and one decided to use MEP prefabrication. While some reasons can be contributed to differences in project type, there are general conclusions to be drawn. Reluctancy to use prefabrication seems to correlate to first time experience of prefabrication, namely overestimation of direct costs, and underestimation of indirect benefits (obstacles). Moreover, in the second case, prefabrication was used as a tool to enable lean practices such as short takt time, low amount of waste, levelled production, and efficient flow of materials. The key difference between the two cases is, Case 2 uses prefabrication to reach a valued goal while Case 1 evaluated its utility without a real problem that could be solved by prefabricating. Based on the two studied cases prefabrication becomes a more attractive alternative when it is used as part of a systemic change to achieve a valued goal.

KEYWORDS

Prefabrication, Choosing by Advantages (CBA), Lean construction.

INTRODUCTION

The construction industry is far from other industries if measured by industrial revolutions (Lasi, 2014; Sharma and Singh, 2020). If compared to factory environment, construction industry has passed Mechanisation (Industry 1.0) and has entered to Electrification (Industry 2.0). As an example of current state, the workstation lighting is an essential part of electrification but is often not a normal part of the site's working conditions. For construction, Automation (Industry 3.0), Digitalisation (Industry 4.0) and Personalisation (Industry 5.0) are still waiting for realisation. Construction is done on-site by craftsmen as opposed to work being divided into manufacturing and assembly operations as in Industry 3.0. Womack et al. (2007) describe craft production of 1890's as follows: workforce was highly skilled in machine operations and fitting, organisations were extremely decentralised, although concentrated within a single city, general purpose machine tools were used, and production volume was very low. Same applies to on-site production in construction industry. Lean methods towards industrialisation are applied as isolated solutions, and the need for systemic change is often overlooked or not understood.

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Prefabrication of mechanical, electrical, and plumbing (MEP) systems is an example of such an isolated Lean method. It has been suggested to solve the problem of low productivity and poor quality in construction. The term prefabrication does not have a clear-cut definition, but in general, it means moving work from construction site to factory environment, thereby reducing installation time on site. Documented benefits associated with prefabrication include lower time and material waste, better ergonomics, shorter lead time, fewer accidents, improved productivity, and better quality (Easmann & Sacks, 2008; Poirier et al., 2015; Lavikka et al., 2018). In addition to these non-monetary benefits, direct cost savings have also been reported, although evidence is contradictory (Khanzode et al., 2008; Jang and Lee, 2018). Decision-making frameworks have been developed to make non-monetary benefits visible for project members, as direct costs are easier to evaluate. Based on these previous results, adoption of MEP prefabrication seems like an obvious choice. However, the adoption rate in Finland and other countries remains low.

Studies have documented multiple obstacles hindering or preventing the adoption of MEP prefabrication. The following obstacles in adoption of MEP prefabrication have been reported by Lavikka et al. (2021) and Lopez et al. (2022):

- Prefabrication requires detailed designs earlier in the process, necessitating early design freezes. In traditional procurement, designs are not detailed enough for bidding prefabrication accurately.
- Lack of prefabrication procurement knowledge and resistance to change.
- Direct costs are the main bidding criteria.
- Lack of detailed modular designs due to lack of capabilities and the custom of designing one-of-a-kind buildings.
- Contract and union agreement boundaries.
- Lack of flexibility (design revisions).

Obstacles of prefabrication are making its adoption difficult but not impossible. Objectively balancing benefits and obstacles to decide whether to prefabricate is not simple, hence various evaluations methods have been introduced. Based on previous research Chauhan et al. (2019) proposed a Choosing by Advantages (CBA) based method for evaluating MEP prefabrication. Their proposed model answered to the need for transparency in evaluating non-monetary benefits in addition to direct costs. The need for such a framework was derived from the overemphasis on direct costs and the difficulty in translating other benefits to monetary benefits reliably. In CBA method, these non-monetary benefits are ranked between on-site and prefabrication alternatives to determine their relative advantage over each other. Finally, prefabrication is compared to on-site construction by combining the direct costs and relative advantage in one figure(Suhr, 1999; Arroyo, 2012).

Research literature lacks an explanation of why some companies choose to implement MEP prefabrication, and succeed in it, while others deem it unprofitable or impossible. In this research, two cases are evaluated. One decided to construct on-site and another decided to prefabricate. Differences in reasons contributing to these decisions are evaluated. The following research question is answered:

RQ: What are the differences in decision-making processes and motives resulting in the adoption and rejection of MEP prefabrication?

Prefabrication has the potential of being a more interesting alternative to a more significant number of projects by demonstrating why some choose to prefabricate. Broad adoption of prefabrication has the potential to significantly increase the quality and productivity of construction industry by enabling adoption of other Lean methods like takt production.

METHODS

Two case studies were conducted to determine differences in decision-making leading to different outcomes related to MEP prefabrication. Workshops, interviews, document reviews, and site visits were used as part of case study research. Case study research was selected to study differences in decision-making processes retrospectively.

New construction of an educational building was studied as Case 1, where the main contractor was interested in studying possibilities of cost savings by using MEP prefabrication. The main contractor had started the project using traditional on-site construction. They were interested in studying the possibility of MEP prefabrication for the current project and with future projects in mind. The phase of the current project would have enabled utilisation of some prefabrication. The company decided against prefabrication due to higher cost.

Renovation of residential buildings was studied as Case 2, where the main contractor had chosen to implement MEP prefabrication. The case company uses prefabrication for competitive advantage. They had decided to prefabricate before the study.

CASE 1

Three workshops were arranged to evaluate potential applications for MEP prefabrication and related benefits. The workshops were organised by the first author on initiative of the main contractor, having interest in studying possible advantages of MEP prefabrication.

In the first workshop, the project was introduced to all participants and a prefabrication programme was drafted listing all possible use cases for the project. Then positive and negative effects for project were listed for all alternatives, including effects on designing, schedule, additional responsibilities, and purchasing.

The second workshop focused on choosing two most attractive options for further assessment and determining of non-monetary benefits for both on-site and prefabricated solutions. This evaluation was done by utilising choosing by advantages method.

The third workshop was focused on determining costs for two application comparisons and comparing the combined effects of monetary and non-monetary factors in parallel. Possible implementation of prefabrication and reasons for these decisions were discussed.

The case project was a large new construction of an educational building with various use purposes. None of the participants had any significant previous experience in prefabrication, and they were all experienced professionals. Table 1 lists the participants. During the workshops construction was ongoing while designing and customer requirements were still developing.

Table 1: Workshop participants and their roles in Case 1.

Workshop participants	Role in project
MEP foreman 1	Electrical
MEP foreman 2	HVAC
Project manager 1, GC	
MEP designer	Design project manager
MEP expert, GC	Initial design
Construction manager, GC	
Project Manager 2, GC	

CASE 2

Case 2 was a renovation of an apartment building where the general contractor had chosen to implement MEP prefabrication. To study the prefabrication process and to document the reasons for adopting prefabrication, interviews, site visits, and document reviews were conducted. The interviewed people are presented in Table 2. The interviews were semi structured interviews focusing on reasons for adopting prefabrication and specific methos of implementation of prefabrication. Document review and site visits were used to study the process of designing and manufacturing prefabricated assemblies.

Table 2: Interviewed people and their roles in Case 2.

Interviewees	Role in project
Construction worker	MEP (on-site)
Construction worker	Prefabrication
Designer	MEP (prefabrication and site installations)
Team Leader	Foreman on-site (workers)
Group Leader	Foreman on-site (team leaders)
Development Manager	Development

RESULTS

CASE 1, COST IS KING

In the first workshop, a prefabrication programme was drafted recognising 15 possible use cases of MEP prefabrication in the case project. This included discussions of design scope, requirement for special prefabrication contractor, site and design schedule, material acquisition, site logistics, safety, and contractor capabilities. At this point, none of the alternatives were deemed impossible, while schedule of designing and construction was seen problematic in many cases. This was due to planned element installation during frame erection, which was not possible due to the project and design schedule.

In the second workshop, two most potential alternatives, a ventilation shaft with HVAC systems and a fully equipped door frame with Electrical systems, were selected for detailed CBA analysis. The ventilation shaft would consist of a supporting structure containing all ductwork within the shaft and be either one or two floors high. These elements would be installed during frame erection and manufactured in a separate location by the selected contractor. The door frame would include electrical installation in the panel adjacent to the door, including lighting switches, sensors, displays, and indicators. Both installations are typically made on-site.

The CBA compared onsite construction to prefabrication separately for both alternatives. For both evaluations, the prefabricated alternative was decisively preferred over on-site construction in the case of non-monetary factors. In the case of the ventilation shaft, 5 out of 7 benefits were assigned for prefabrication alternative. In CBA analysis, prefabrication had 270 importance points against 90 for on-site. For the doorframe, all benefits were assigned to prefabrication alternative, the total importance points being 320. The three most important factors in both evaluations were assessed to be safety, ergonomics, and material waste. The detailed evaluation is presented in Tables 3 and 4 for ventilation shaft and door frame respectively.

Table 3: CBA analysis of ventilation shaft, prefabrication versus on-site construction.

Factors	Prefabricated ventilation shaft	Imp.	On-site ventilation shaft	Imp.
Material waste	Attribute: Causes less waste. Better utilisation of cut pieces. Cleaner storage and handling. Adv: Causes less waste.	40	Attribute: Causes waste due to unused cut pieces and damaged ducts. Waste in insulation also.	-
Safety of workers and environment	Attribute: Risks in lifting of the elements. Decreases working in areas with a risk of falling. Adv: Smaller safety risks overall.	100	Attribute: More work in open shafts, risk of falling or dropping tools and materials.	-
Ergonomics	Attribute: Possibility to work in positions of better ergonomics and horizontal installation of ducts. Adv: Better working positions.	60	Attribute: Working in high and cramped spaces. Especially insulation is challenging, very small spaces.	-
Quality	Attribute: Supports and insulation are easier to install in steel frames. Adv: Fewer quality issues.	50	Attribute: Support of ducts need to be designed on site to fit the local conditions, variation to installation.	-
Flexibility of designing	Attribute: Design changes are more expensive or impossible.	-	Attribute: Design solution can be changed for as long as the installation is made, installation later compared to prefabrication. Adv: More flexible solution.	50
Logistics	Attribute: Lifted immediately to the right location and installed. Less site storage. Adv: Ready installation quickly from delivery.	20	Attribute: Hauling large ducts from site storage to shafts is challenging.	-
Design schedule	Attribute: Designing must be completed significantly earlier and takes more time due to increased LOD.	-	Attribute: Later installation and lower LOD, more available design time. Adv: More time for designing and, therefore, more flexibility for designing.	40
Total		**270**		**90**

Table 4: CBA analysis of door frame, prefabrication versus on-site construction.

Factors	Prefabricated door frame	Imp.	On-site equipped door frame	Imp.
Material waste	Attribute: Smaller risk for damage, affects waste, a significant factor. Adv: Elimination of broken equipment during installation.	90	Attribute: More waste caused by equipment broken during installation.	-
Safety of workers and environment	Attribute: Fewer accidents. No working in high places. Cleaner site. Adv: Fewer accidents.	80	Attribute: Many openings drilled on site to high locations. Causes debris to surroundings.	-
Ergonomics	Attribute: Possibility to work in an ergonomic position and use industrial methods. Adv: Better working ergonomics.	50	Attribute: Working in high places. Unergonomic working positions.	-
Maintenance and flexibility for changes	Attribute: Door frames equipped with extra conduit pipes, allowing for easy addition later. Adv: Better flexibility during the life cycle.	60	Attribute: Only what is needed will be installed; changes later are more difficult.	-
Logistics	Attribute: No need to store or transfer equipment on site. Adv: Less logistics and storage on site.	40	Attribute: Need to store equipment on site close to doors when door frames are opened.	-
Total		**320**		**0**

The third workshop focused on determining direct cost differences and adding the cost component of CBA. For the ventilation shaft, the direct cost of prefabrication was estimated to be 6% more expensive. Respectively for the door frame the prefabricated version was estimated to be 11% more expensive. Costs related to factors evaluated in CBA were not calculated due to the lack of an objective method for determining costs. The resulting CBA analysis is presented in Figure 1. In both cases, the prefabricated alternative scored significantly higher and was only slightly more expensive.

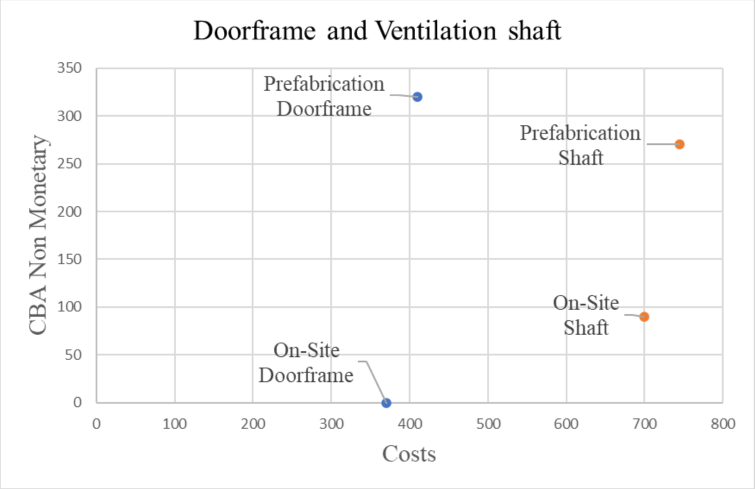


Figure 1: Effects of monetary and non-monetary factors of prefabricated and on site manufactured for ventilation shaft and doorframe with electrical installations.

All participants agreed that based on these results, on-site would be favoured in both cases. Competition for contracts being solely based on total cost was given as the reason for this choice. Participants acknowledged that quality and safety affect costs. They had ranked these as important factors. However, they did not trust the cost savings to be sufficient in comparison to direct cost without calculations. Without experience in prefabrication, they found it difficult to estimate the magnitude of cost saving. While there were no barriers preventing prefabrication, some aspects were found to hinder its adoption. These were designer capability (detailed modelling and schedule), construction schedule (designing concurrent to construction), and difficulty in evaluating possible savings from CBA factors in advance.

CASE 2, PREFABRICATION ENABLES INDUSTRIAL CONSTRUCTION

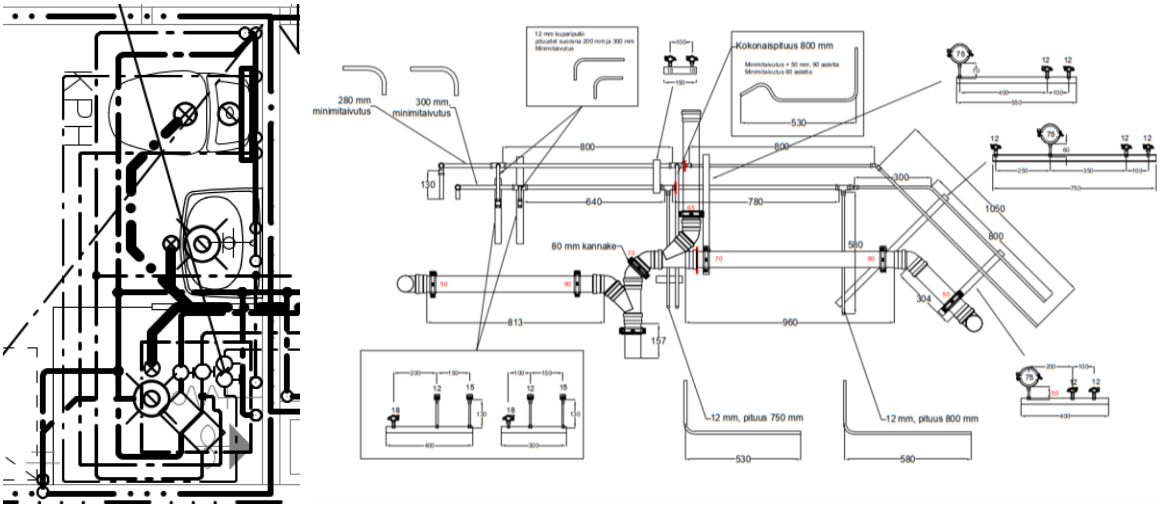
The case company prefabricated MEP systems for apartment building renovation. Prefabricated products included water, sewer, ventilation, electrical cables, heating, and suspended ceilings. The company had a goal of achieving competitive advantage by shortening lead times and improving quality by introducing practices of industrial construction. The company is considered a pioneer in the application of flow and takt production in Finland.

The business unit in question first adopted the Theory of Constraints (ToC) and Alliance business model but, in 2019, switched the production system to using Constant Work in Progress (CONWIP). This transformation was based on large amount of variability and difficulty of creating an efficient flow by using outsourced processes with multiple subcontractors. Additionally, the project team implemented a business model change by separating materials from work and using standard partners for work instead of per-project bidding. These standard partners were contracted on an hourly base as opposed to traditional contract work and quotas. The interviewees reported adopting these methods in stages during 2020-2022 in accordance with the Toyota organisation model (Liker, 2020) and Deming principles 11-14 (Deming, 1991).

Applying CONWIP enabled examining workflows in a high level of detail. Used parts, materials, work methods, and work sequences were documented at a minute level. As a result, traditional construction drawings and their low level of detail were abandoned. Instead, the company aimed at a standardised product by standardising work and materials using Manufacturing Bill of Materials (M-BOM). Knowing the exact M-BOM at each location made it possible to implement four-hour takt and move to precise takt logistics by utilising the Plan for Every Part concept described by Harris et al. (2011).

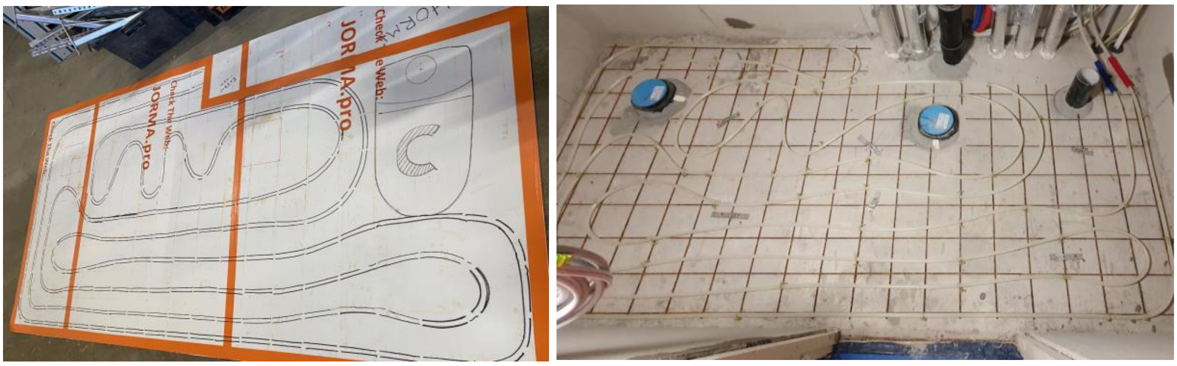
After standardizing work and drafting accurate M-BOM, increasing flow and shortening takt times require moving work from construction site to a separate workshop. Prefabrication was first adopted 2021. This separation of manufacturing from assembly was a transition towards industrialisation. Tests by the case company indicated a 23-46% time saving in total installation time by using prefabrication. Large-scale adoption of prefabrication with advanced on-site logistics further led to the shortening of takt times from four hours to two hours to realise shortened lead times. The effect on lead times was significant as the company reported having increased their yearly production rate from 150 to 320 apartments/year, while number of personnel has grown by 20%.

In the prevailing construction mode contractors bid both materials and work as fixed price (black box purchasing), based on construction drawings. These construction drawings, however, are not buildable, and as a result installers are responsible for installation designing. This undocumented designing by installers leads to significant variation in installations of identical apartments. The following installer, wagon in takt production, must take this variation into account and adapt, leading to ever increasing variation. Examples of traditional construction drawings and designs for manufacturing are presented in Figures 2 and 3.



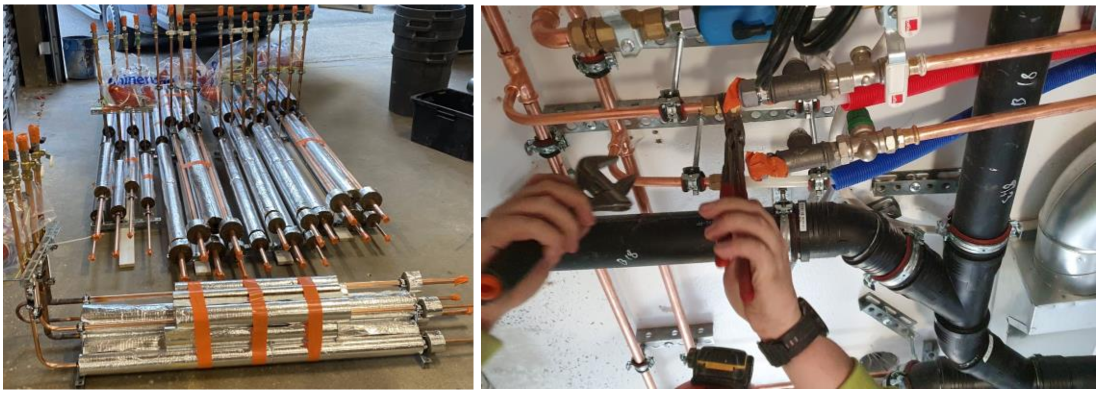
Figures 2 and 3: Figure 2 (left) is a traditional construction drawing for water and sewer installation (LOD below 200). Figure 3 (right) is a design for prefabrication (LOD 400) containing three sub-assemblies (separated by red lines in drawing).

As traditional construction drawings do not enable the creation of M-BOM due to their low level of detail, separate designs for manufacture and assembly are needed. A detailer drafted high LOD designs using AutoCAD and their own library of manufacturer-specific parts. All support systems were also designed, and possible clashes were resolved. These assembly drawings contained millimetre-level cut lengths. Reuse of designs from project to project reduced design time as the number of projects increased. Figures 4 and 5 show the manufacturing and installation of underfloor heating.



Figures 4 and 5: Cardboard template (1:1, prototype design) for laying underfloor heating pipes in one bathroom type and later installed prefabricated module (white pipes on steel net).

Fabrication was scheduled according to a takt schedule, and work was divided into packages per takt area for one day. Team leader presented the fabrication schedule on a white board for workers in daily huddle. Team leader also either solved with the construction workers the arisen problems or escalated them to group leader in team leader’s daily huddle. The logistical takt was based on on-demand deliveries of materials and parts with a two-day buffer. Figures 6 and 7 show subassemblies of pipes ready for transportation and installation itself. Four different consolidation points (wholesale, factory, site warehouse, and workstation) were in use, and logistics were carried out by specialised personnel.



Figures 6 and 7: Prefabricated pipe elements for vertical ascent in shaft ready for transportation (left) and connecting horizontal pipe elements with shaft elements (right).

DISCUSSION

Prefabrication was evaluated in Case 1 to win in almost all non-monetary factors and to be slightly more expensive. While most of the non-monetary criteria have a cost reducing effect, reliably evaluating their magnitude is difficult. As a result, the case decided against prefabrication. Since cost was the deciding factor, companies would benefit from an objective tool for assessing monetary benefits in case of non-monetary criteria. For Case 1, even relatively small cost savings could have favoured prefabrication over on-site construction. When determining direct costs for Case 1, the participants were able to assign additional costs to prefabrication (e.g., higher design cost or higher cost of manufacturing) but were unable to see monetary benefits from shortened lead time or fewer quality issues.

For Case 2 prefabrication allowed shortening lead times, improving quality, and profitability. Case 2 was focused on adopting Lean practices, one piece flow, takt production, and industrial construction where prefabrication was eventually used as a mean to achieve these targets. Case 2 shows all the obstacles identified by Lavikka et al. (2021) and Lopez et al. (2022) can be overcome. When construction drawings were not suitable for prefabrication, M-BOM was created, and a detailer was employed to draft construction drawings. It was also shown that the detailer does not need to have formal training in MEP engineering, but understanding of installation methods is required.

The decision-making processes for the two studied projects were very different. For Case 1 the process started with the question “Can prefabrication save us money?”. This question was eventually answered by difference in estimated direct cost compared to on-site construction. For Case 2 the process had started years ago with the goal of improving flow and shortening lead times, eventually resulting in competitive edge by being able to bid at a lower cost and complete more projects during the same time. Eventually through gradual lean implementation the company was in a position where transition to prefabrication was the natural next step to further improve, and they had gained the necessary knowledge for smooth implementation. Conversely, in Case 1 adoption of prefabrication would have been the first step towards industrialisation and would have caused the need for rapid development of culture, logistics, schedule, and designing, all at the same time.

While the projects in cases 1 and 2 were of different type, both companies operate in the same Finnish market and compete for projects in a market where contracts are won or lost based on cost. The two cases have differences in design schedules. Apartment renovations are bid on ready construction drawings. In larger projects designing is more concurrent with construction. This difference becomes less significant with the observation that construction drawings for bidding must be completely redesigned for prefabrication (Case 2) causing eventually similar concurrency as in larger projects.

The studied cases also differ in contracting. In case 1 the main contractor uses a separate MEP contractor. In Case 2 the company had previously used similar subcontracting business model but had observed that change to industrial construction necessitated removing subcontracts. This allows the case company 2 to control material acquisitions and logistics and efficiently lead the work of installers contracted on hourly basis, as opposed to fixed price contracts. Keeping prefabrication in-house drives costs down and prevents partial optimization by minimizing the cost of every subcontract. For example, in Case 1 the main contractor would certainly get higher bids for MEP contracts if asking for prefabrication since they would have to invest in capability. This gives the impression of saving money by choosing the cheapest non prefabricating bidder. When prefabrication is implemented by an experienced main contractor, keeping costs down and developing the process are more important compared to an independent subcontractor.

Bidding based on construction drawings is not necessary for prefabrication to be possible. Both customer and prefabrication will benefit from bidding with more schematic designs. This removes rework as detailer does not have to redraw all systems. As a result, customer saves money by reduced design costs for bidding phase and lower overall cost as the detailer does not spend time fixing original designs.

Based on our findings, similarly to O'Gorman et al. (2023), we suggest that only considering MEP prefabrication and direct costs related to it is not recommended. Contrary to O'Gorman et al. (2023), we however argue, that this is not due to lack of cost savings from prefabrication, but the incomplete question framing where prefabrication is considered alone without all other necessary transformations towards industrial construction. The only way for prefabrication to succeed is to implement and improve it over time as part of other methods of industrial construction. For example, a study by Chauhan et al. (2018) demonstrated that takt production and prefabrication benefit from each other. Simply suggesting to only consider non-monetary aspects is not feasible when contracts are won or lost based on the cost only.

This study is limited by low number of cases, which limits the reliability of drawn conclusions. Further investigations to a larger number of cases is needed to confirm the results and determine how project type affects the decision-making process. Additionally, these cases represent the situation in a predominantly non prefabricating market, and differences could be found from countries of advanced application.

CONCLUSIONS

The two studied cases highlighted fundamental differences in reasons motivating the use of MEP prefabrication. To answer our RQ about differences in decision making processes the following can be concluded. Participants of Case 1 were keen to study if prefabrication can be used to obtain cost benefits and Case 2 decided to use prefabrication to enable short takt time, short lead time, and increased quality, eventually translating to increased profitability. The main difference being instrumental use of prefabrication for immediate realisation of cost savings (Case 1) as opposed to a far-reaching cultural change towards industrial construction with prefabrication as part of it (Case 2).

Based on the observations of advanced lean adoption in Case 2 it is necessary to acknowledge the need for large cultural changes in moving towards prefabrication. Gradual transformation towards prefabrication through other lean adoptions increases the likelihood of success.

ACKNOWLEDGMENTS

This work has been supported by Talotekniikan esivalmistussuunnittelu (Designing for MEP prefabrication) project funded by Building 2030 Consortium. The Building 2030 consortium includes Aalto University and 21 companies from the Finnish construction sector.

REFERENCES

Arroyo, P. , Tommelein, I. D. & Ballard, G. 2012. Deciding a Sustainable Alternative by Choosing by Advantages' in the AEC industry, 20th Annual Conference of the International Group for Lean Construction

Chauhan, K., Peltokorpi, A., Seppänen, O and Berghede, K. (2018). “Combining Takt Planning with Prefabrication for Industrialized Construction.” In: Proc. 26th Annual Conference of the International. Group for Lean Construction (IGLC), 848–857. DOI: doi.org/10.24928/2018/0542.

Chauhan, K., Peltokorpi, A., Lavikka, R. & Seppänen, O. 2019. Deciding Between Prefabrication and On-Site Construction: A Choosing-by-Advantage Approach, Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC), 749-758. doi.org/10.24928/2019/0158

Deming, W. E. (1991). Out of the crisis. Cambridge, MA: 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.

Harris, R. Harris, C. Wilson, E. (2011). Making Materials Flow: A Lean Material-Handling Guide for Operations, Production-Control, and Engineering Professionals. Lean Enterprise Institute Cambridge, MA, USA, ISBN 0-9741824-9-4

Jang, S., & Lee, G. (2018). Process, productivity, and economic analyses of BIM–based multi-trade prefabrication—A case study. Automation in Construction, Volume 89, ISSN 0926-5805, 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.

Lasi, H., Fettke, P., Kemper, HG. (2014). Industry 4.0. Bus Inf Syst. Eng **6**, 239–242. https://doi.org/10.1007/s12599-014-0334-4

Lavikka, R., Chauhan, K., Peltokorpi, A. and Seppänen, O. (2018) Fostering prefabrication in construction projects – case MEP in Finland, eWork and eBusiness in Architecture, Engineering and Construction, Proceedings of the 12th European Conference on Product and Process Modelling (ECPPM 2018), Copenhagen, Denmark, 12-14 September 2018.

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

Liker, J. (2020). The Toyota Way. US: McGraw-Hill.

Lopez R, Chong H-Y, Pereira C. Obstacles Preventing the Off-Site Prefabrication of Timber and MEP Services: Qualitative Analyses from Builders and Suppliers in Australia. Buildings. 2022; 12(7):1044. https://doi.org/10.3390/buildings12071044

O'Gorman, T. C., Daniel, E. I. & Chinyio, E. (2023). The impact of an offsite production approach on mechanical and electrical projects: evidence from the UK. Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31), 767–777. doi.org/10.24928/2023/0165

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, Volume 58, 74-84, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2015.07.002.

Sharma, A. & Singh, D. (2020). Evolution of Industrial Revolutions: A Review. International Journal of Innovative Technology and Exploring Engineering. 9. 66-73. 10.35940/ijitee.I7144.0991120.

Suhr, J. (1999). The Choosing By Advantages Decisionmaking System. Quorum,
Westport, CT, 293 pp.

Womack, J. P., Jones, D. T., & Roos, D. (2007). The machine that changed the world. Simon & Schuster.