Seppänen, Olli; Görsch, Christopher

Decreasing Waste in Mechanical, Electrical and Plumbing Work

Published in:
Proceedings 30th Annual Conference of the International Group for Lean Construction (IGLC). Edmonton, Canada, 27-29 Jul 2022

DOI:
10.24928/2022/0111

Published: 01/01/2022

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Seppänen, O., & Görsch, C. (2022). Decreasing Waste in Mechanical, Electrical and Plumbing Work. In *Proceedings 30th Annual Conference of the International Group for Lean Construction (IGLC). Edmonton, Canada, 27-29 Jul 2022* (pp. 84-94). (Annual Conference of the International Group for Lean Construction). International Group for Lean Construction (IGLC). https://doi.org/10.24928/2022/0111

Seppänen O. & Görsch, C. (2022). Decreasing Waste in Mechanical, Electrical and Plumbing Work . *Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC30),* 84–94. doi.org/10.24928/2022/0111

DECREASING WASTE IN MECHANICAL, ELECTRICAL AND PLUMBING WORK

Olli Seppänen[1], and Christopher Görsch[2]

ABSTRACT

Eliminating wasted effort is an important part of lean philosophy. Waste has typically been measured with time sampling or time motion studies, where the share of direct work is estimated. However, few studies have taken the next step and investigated the root causes of wasted effort. This paper reports the results of an extensive time and motion study and focuses on qualitative evidence on the root causes of wasted effort. 15 MEP workers and foremen on four projects carried a helmet camera for one calendar week and quantitative time-motion analysis was done based on these videos. All participants were interviewed, and video footage was reviewed together with the participants to evaluate root causes of waste.

The root causes of wasted effort were poor communication, issues with production planning and control, uncoordinated design, poorly organized material flow and a high share of preparatory work steps. The best direct work share was achieved in the only project which implemented takt production even though it was also the project with least repetitive work and largest distances due to large floor area. The biggest impact could be achieved with better constructability of design which would also enable just in time logistics and greater share of prefabrication. The results could be used to convince practitioners to adopt lean principles.

KEYWORDS

Lean construction, waste, workflow, time-motion study

INTRODUCTION

Eliminating wasted effort is a critical part of lean philosophy (Koskela 2000). Seven waste types have been introduced in lean literature (Santos et al. 2006) and lean construction researchers have proposed new ones such as Making-Do (Koskela 2004) and unutilized talent (Ansah et al. 2016). Waste can be eliminated by making sure that tasks have sufficient preconditions (Koskela 1999).

Waste and productivity have been often researched with the use of work sampling methods. Work sampling evaluates quantitatively the share of direct work and other types of work (Neve et al. 2020). Although time sampling can estimate the share of time spent on non-value adding activities, significantly less effort has been spent on studying the root causes of wasted effort. Time and motion studies have been used as an alternative approach and can also identify wasted effort and investigate root causes (Demirkesen et

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

[2] Doctoral Candidate, Department of Civil Engineering, Aalto University, Espoo, Finland, christopher.0.gorsch@aalto.fi, https://orcid.org/0000-0001-9632-4031

al. 2020). However, most reported time and motion studies have not approached the classification of time using lean concepts, such as waste categories and preconditions.

In this paper, our aim is to present findings on root causes of non-value adding work and the potential impact of lean interventions. These findings could convince more practitioners to adopt lean methods. The research is based on an extensive time and motion study, and focuses on mechanical, electrical, and plumbing (MEP) trades which have often been regarded as complex and have shown low share of direct work. The study aims to answer two research questions: 1) What are the root causes of wasted effort in MEP work in building projects and 2) What is the estimated productivity impact of lean interventions which target the identified root causes?

WASTE IN CONSTRUCTION

Transformation-Flow-Value (TFV) theory provides theoretical foundation to lean construction (Koskela 2000). In addition to looking at the efficiency of transformation, the theory recognizes the need to have better flow and increased value to the customer. Traditional ways to improve productivity have mostly focussed on increasing the efficiency of transformation, e.g., by developing means and methods or investing in automation to remove human labour. The flow view to productivity seeks to decrease the share of wasted effort which typically happens at the interfaces of transformation activities (Bertelsen et al. 2006).

Typically, transformation activities have been labelled as direct work (DW) in work sampling and time-motion studies. Higher share of direct work has been shown to correlate with productivity both on project level (Thomas et al. 1984) and on industry level (Neve et al. 2020). Although direct work is rather consistently measured across studies (Gong et al. 2011) research about waste is focused on analysis of categories which are not direct work.

Waste has been categorized by Ohno (1998) to seven different categories: overproduction, waiting, unnecessary transportation, unnecessary movements, over-processing, inventory, and defects. In construction context, Koskela (2004) added the waste of "making-do" – starting work without prerequisites. Although waste categories are often cited by researchers of lean construction, to our best knowledge they have not been used in work sampling or time motion studies. This is probably because waste can only be seen in context and work sampling classifies actions based on snapshots, taken for example every 5 or 15 minutes (Jenkins & Orth, 2004; Kalsaas 2011).

Another thing missing from previous time sampling studies is the analysis of prerequisites which is required to identify some forms of waste. It is understandable, that time sampling studies would not be able to identify missing prerequisites because they focus on snapshots. To know what the worker is missing when he cannot perform direct work, a longer sequence of events needs to be followed – i.e. what does the worker do next when direct work stops. Our interest in this research is to fill these gaps by not just classifying time into categories, but also observing longer sequences of work, allowing us to categorize missing prerequisites and the eight wastes. By doing that, we can estimate the impact of lean interventions, which typically attempt to increase the probability that certain prerequisites will be present at the right time when the worker is about to start a task.

METHODS

To get a broad understanding of wasted effort, several methods were utilized to get both quantitative and qualitative data. The main method was a time-motion study of 15 MEP workers and foremen, and a continuous survey of constraints and challenges experienced by the workers. The helmet camera study was conducted on four different projects with different characteristics. The research was carried out in spring 2021 and observation period was one calendar week per worker. Afterwards, each participant was interviewed. Clips of helmet camera footage were shown and the workers explained in their own words what happened in the footage, validating classified data from a workers perspective as well as developing a deeper understanding of connections between activities, waste and prerequisites. They were also asked whether their experience from the researched project and week differed from what they would consider a normal project and normal week, and for their opinions how to improve MEP productivity and key challenges related to their work.

At the time of this study, 170 hours of helmet camera footage have been analyzed in detail out of the total of 411 hours of collected video material. Time-motion data from helmet cameras was analyzed quantitatively by categorizing worker actions. In addition to classifying the time into categories, missing prerequisites and waste types were also identified from video footage. They could only be identified by looking at a longer sequence of events. For example, a typical issue was stopping work and moving away from the workplace. Video footage made it possible to see why the worker left the location and what was missing. Sometimes he went to look for materials, or tools or help from a supervisor. With longitudinal analysis of videos, it was possible to determine the missing prerequisites and determine why the work stopped.

In addition to video analysis, interviews were used to find out root causes for low productivity and propose recommendations. Root causes were identified by observing reasons why workers were engaged in non-value adding activities or why they wasted effort when doing direct work. This was determined mainly by reviewing the time-motion study classifications and by qualitative analysis of video material, confirmed with discussions with the workers. Quantitative evaluation of the impact of each cause was estimated by the share of time workers spent on a wasteful activity. Based on identified root causes, the potential impact of lean interventions were evaluated.

Projects available for study were limited due to the COVID-19 pandemic. Several candidate projects could not be studied due to COVID exposures on the project. Even though labor unions supported the study, finding consenting participants was challenging, especially due to additional stress caused by COVID-19 and need to catch up schedules on several projects. Therefore, the studied projects and workers had to be selected based on availability. The projects were all new construction. Two of them were residential construction, one was a hybrid hotel/office building and one was a large retail mall. Table 1 shows the key aspects of studied projects.

Table 1: Features of studied projects

	Residential 1	Residential 2	Hotel/office	Mall
No. of buildings	2 stairwells	1	2	1
Floors	6	5+1 underground	8+2 underground	5+2 underground
Size	7 023 m2 (79 units)	4 023 m2 (70 units)	12 000+ 10 000 m2	135 000 m2
Repeatability	High	High	High	Low
Lean implementation	No	No	No	Yes
Special notes	Normal residential	Design changes, modular bathroom	Major COVID-19 schedule delays	Takt production, minor COVID-19 delays

RESULTS

CLASSIFICATION OF TIME, PREREQUISITES AND WASTE TYPES

The quantitative analysis of time classification revealed that actual installation work was rare and fragmented. The electricians had slightly higher share of direct work (24%) while the plumbers and HVAC installers had just 15% share of direct work. The largest differences between trades were in discussions (electricians 7%, plumbers 16%) and in logistics related activities – namely hauling and searching (electricians 11%, plumbers 17%). The overall results for electricians and plumbers are shown in figure 1. When looking at project differences, the projects with delays (hotel/office) had a significantly higher share of discussions than other projects for both electricians and plumbers.

Most of the missing prerequisites were related to missing materials or parts. Residential 1 had well organized logistics, with materials on wheels, which can be seen in smaller share of missing materials and equipment in that project. All projects except the retail mall suffered from many interruptions caused by preceding work. This gives an indication about the benefits of takt production which was used in the retail mall but not in the other projects. Figure 2 shows the missing prerequisites per project.

90% of the wasted effort identified in the study could be explained by missing prerequisites. For example, movement represented 53% of the waste observed, and 83% of movement could be explained by missing prerequisites. Waiting was 20% of wasted effort and missing prerequisites were identified for 83% of cases related to waiting. Also waste types transportation (9%), defects (9%) and inventory (5%) were often associated with missing prerequisites. Delays in predecessor tasks led more often than other prerequisites to waiting, making-do and defects. Missing material very rarely led to waiting but was seen mainly as movement, transportation and searching from storage areas. Missing design information led more often than other prerequisites to overprocessing (additional work steps), movement and defects.

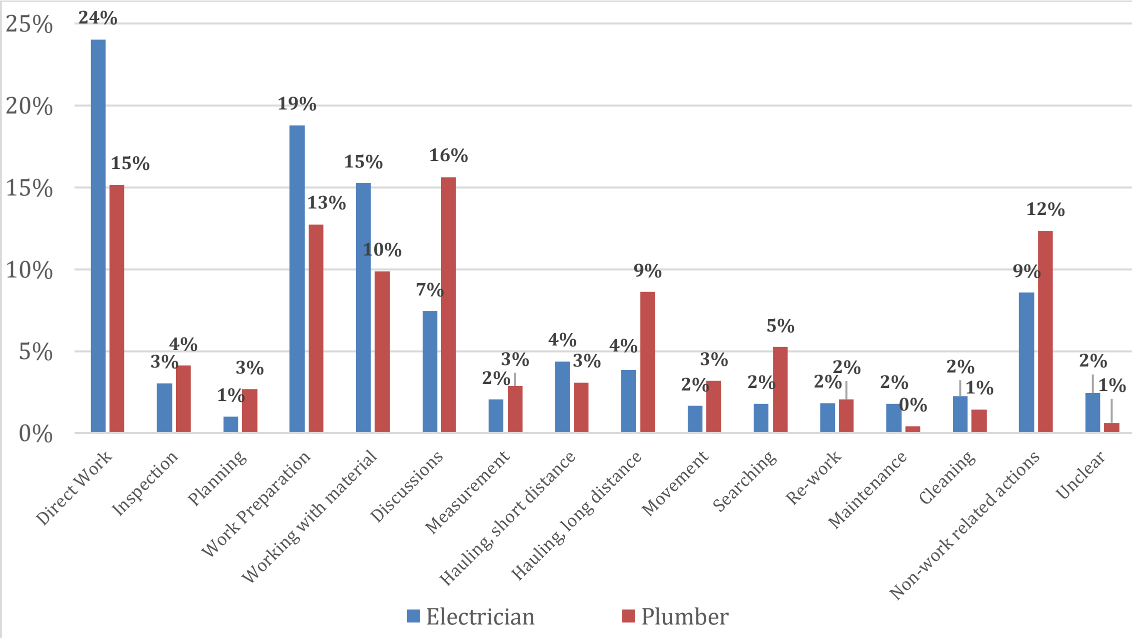

Figure 1: The share of time in different activities for electricians (blue) and plumbers (red)

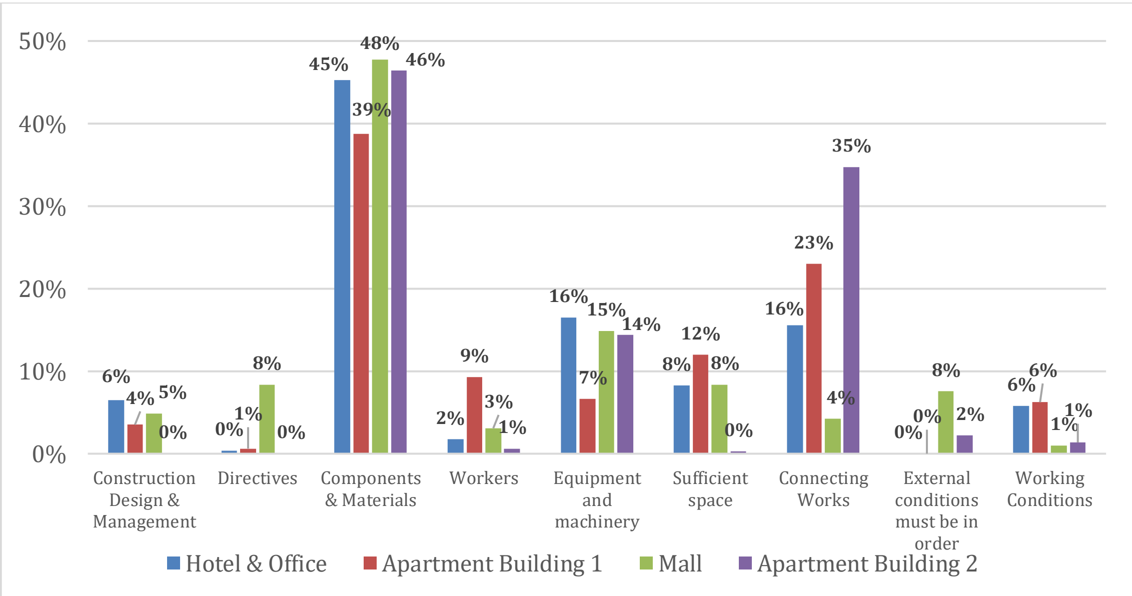

Figure 2: Share of missing prerequisites per project

ROOT CAUSES OF WASTED EFFORT

Based on quantitative data, interview results and qualitative observation of videos, five main root causes of wasted effort were identified. Generic root causes were related to communication, production planning and control, material logistics, design and the share of preparation work on site. In addition, several task-specific root causes were identified but due to space constraints, only the generic root causes are discussed here.

Communication

Much of the discussion happening on site was because the installers did not have enough information about their tasks. The overall understanding of the process was missing. The participating installers did not know what their part in the bigger picture was, and they did not know the impacts of their work. This led to hurried installations where another contractor needed quickly some work because they were closing a wall or pouring a floor. Missing information about dependencies was frustrating to installers and clearly led to wasted effort (especially discussions) in helmet camera data.

Interviews highlighted long and complicated command chains. For example, it was often faster for an electrician to make penetrations themselves rather than figure out how to get someone else to do the work. The installers did not know who to contact when encountering different types of problems. Problem solving took a long time or did not happen at all.

The importance of communication is shown by the large share of time spent on discussions. Because the sound was not recorded due to privacy concerns, interviews were used to get an understanding of the content of discussions. Although most of the discussions are within the own crew to coordinate tasks and materials or social discussion, significant share of discussions was coordinating work sequences and design with other trades. The share of discussions increased in the delayed project (hotel/office) because it was not clear how to catch up delays and the General Contractor's schedule did not help in coordination. The share of discussion was high in the other residential project because there were a lot of design changes due to modular bathroom pods of which the project team had no prior experience.

Production planning and control

The success with production planning and control had a significant impact on productivity. A large part of missing prerequisites was related to preceding works not being ready. The participants were frustrated about the deficiencies in production planning and control. The schedules used by General Contractor were not detailed enough and were not updated when there were delays. This led to the finding that installers are unable to use the official schedules. This was not a big problem for electricians who always had some other work to do if they could not do the scheduled work. Plumbers were struggling because they need very different materials for different tasks and locations, and they were unable to predict upcoming work and order required materials. Many installers were not aware of any schedule goals or deadlines, especially in projects with delays.

The difference of the shopping mall project which used takt production to other projects was very clear. Even though the project was less repeatable than others and installations were more complex, there were less delays caused be preceding tasks. The video footage showed a much more systematic process. Although the installers still thought that there was room for improvement, the differences to other projects were clear. The results also impacted the share of wasted effort. The largest and most complex project had the highest share of direct work, even though the distances were much longer than in other projects. Although the share of material hauling was larger in the project, the share of discussions was the lowest and explained best the increase in direct work.

Projects that did not use takt did not experience productivity losses dues to trade stacking. However, out of sequence work was constantly happening. Workers were jumping from task to task and had a lot of emergency work which led to disruptions of work.

Logistics and material management

Missing materials and equipment were the most common missing prerequisite. Material storages were far away from the work location in all projects. Interviews of plumbers revealed that material management is one of the biggest waste causing factors from their point of view. It should be noted that although the COVID-19 pandemic has caused increased material prices, none of the workers experienced lack of materials due to unavailability. Missing material was typically stored elsewhere or had not been ordered.

Plumbers were struggling with material management because if designs are not constructible, each improvised installation requires different materials (e.g. different angles of pipes). Material storages were not organized according to 5S principles and it was difficult to find the right material. There was one notable exception, in a residential project where an HVAC foreman spent working time to organize the storage. That crew had lower material hauling and searching times than other workers in the research.

Electricians had slightly different types of problems. Their material needs most often happened due to surprising and urgent assignments, which happened often based on the helmet camera footage and interviews. Electricians are often last in sequence and they are struggling with the materials of other trades which are blocking their scissor lifts and ladders. Much of the hauling time of electricians was used to move materials of other trades out of the way.

Design quality

Design quality and coordination was the second biggest concern of participants. All participants agreed that designs on Finnish projects do not consider constructability. There were often clashes in delivered BIM models. More common were problems where the designers had not used the actual parts available to installers. Hangers were missing from design, and often cable trays were designed right below large HVAC ducts, which is either impossible or very time consuming.

These deficiencies caused a lot of design discussions and improvisation on site. Detailing happened on site in collaboration with other crews. Deficiencies in design rarely prevented work but led to discussions, inspections (getting shared understanding) and improvised installations increasing the fragmentation of direct work. Design problems had cascading effects because improvisation also caused material-related problems.

Work preparation on site

Preparing for work and organizing materials took more time than the actual work in all projects. Productivity could be increased by decreasing the share of preparation work. Preparation included all material movements and organizing in the workplace (less than five meter distance). This took a long time and was inefficient. Several preparation tasks observed from videos could be done centrally and before the workers come to site. Short, less than five meter movements related to preparation took a large share of the installation time.

POTENTIAL IMPACT OF LEAN INTERVENTIONS

Several basic lean interventions from past lean research could be used to tackle the root causes. The proposed interventions to tackle the root causes are quite familiar to attendees of IGLC, so they are presented briefly, focusing on the estimated impact. The benefit of quantitative analysis is to estimate the impact of different interventions, and present data that can convince companies to make systemic changes.

Detailed MEP design and improved coordination

Design tasks have been successfully moved away from site in all construction markets where MEP is prefabricated (e.g. the USA, the UK, Australia). Typically, this has been done by giving more design and coordination responsibility to the supply chain so that they can prefabricate. Detailing and coordination on detailed level is done by workers from the trades. In Finland, there has been less interest in prefabrication because the workers work on a piece rate system, and negotiations about prefabrication with labor unions have been difficult. However, the study revealed that investing more in design could have significant benefits in addition to prefabrication.

Based on the study results, it can be estimated that proper detailing and coordination of MEP systems could increase installation time by four percentage points. Resolving most of design issues before on-site work could halve the discussions, decrease searching for material and decrease waiting. Productivity benefit for on-site work could be thus around 20%. Part of the saved hours must be invested up front in detailed design and coordination but naturally resolving problems virtually before going on site would take fewer hours than improvisation on site.

The role of improved logistics

The time spent on searching and hauling materials was a large part of the worktime (electricians 10%, plumbers 17%). Several interventions have been previously proposed in lean literature. They range from simple ("everything on wheels") to slightly more complex (5S principles) to complex (logistics service, kitting, just in time deliveries). Based on the quantitative results, some estimates can be given of potential productivity gains.

Easily movable material storage ("Everything on wheels") was shown to be beneficial in one of the case studies where workers had improvised such a storage – there the time spent on getting materials was notably smaller than in other comparable projects. Workers on other projects had also suggested similar innovations to their employers but their concerns were not heard. Based on the analysis of video footage, it can be estimated that hauling time would be reduced to 75% of current time, which would result in a 10% productivity improvement for plumbing and 5% productivity gain for electricians.

5S principles would eliminate a lot of searching through better organization of storage areas. It could be estimated that searching could reduce to 25% of current time. This would help the plumbers a lot due to their varied materials and could add 1 percentage point to their direct work.

If kitting and just in time deliveries could be implemented, at least half of the hauling performed by workers could be eliminated. This could add 3 percentage points to the direct work share of plumbers and 2 percentage points to electricians, and therefore major productivity gains. However, to be able to estimate exactly the materials needed in each work area, the design should be better coordinated first, and also the schedules need to be better controlled. For JIT deliveries, the process needs to be more stable.

Increased prefabrication

MEP elements are being prefabricated in several construction markets. Previous reports about the US market have shown that productivity benefits of prefabrication have been large (Khanzode et al. 2008) but companies have needed to invest in prefabrication capacity. Currently, the Finnish contractors are not ready to invest in capacity but in the short-term prefabrication could happen in a centralized location on site where all the required materials and tools are in the work site. Especially preparing ceiling installations on ground level could improve productivity significantly. However, before any increase in prefabrication becomes possible, the issues with detailed design and coordination must be solved first.

Production planning and control

The workers could not use the schedules of the project to understand what to do next. The schedules were not up-to-date and were not followed. On one of the sites, COVID delays had led to a major schedule update which had lasted for seven weeks – during that time there was no usable schedule on the project. This led to major improvisation and coordination among the trades. For most workers, this was acceptable and normal but there was a lot of stress on crew foremen who had to coordinate material deliveries and orders without being able to plan ahead sufficiently.

The impact of good planning and control becomes clear when the retail project with takt production is compared with the other projects. The project had very few issues caused by missing predecessor tasks. The qualitative analysis of video material showed a clear difference, and a systematic process while other projects seemed chaotic. Interviewed installers on the shopping mall project said that the biggest issues on that site were logistics due to the large size of the project and fragmented storage area but did not emphasize schedule related problems. The share of direct work was 25% in the shopping mall and just 14% on the hotel/office project which did not have a functional schedule at the time of the research. The largest differences were in the amount of discussions required (mall 5%, office/hotel 17%). Some productivity was lost due to larger amount of hauling on the shopping mall project.

However, there is still a lot of room for improvement. Although the Last Planner System is widely used in Finland and even in participating companies, there was no evidence of involving the crews in production planning on any of the projects. All interviewed workers were eager to participate and provide their expertise, but the schedules were still planned top-down and often missed the details required by workers.

Communications

Based on qualitative analysis of the videos, communication was not structured with continuous meetings (such as daily huddles) but happened when required through WhatsApp, phone or face-to-face meetings. All participating workers agreed that crews should have daily or weekly meetings where work is coordinated rather than interrupting work to do coordination every time there was an issue. It is difficult to provide a quantitative estimate of the benefits, but it is clear that a short daily meeting where all tasks of the day are reviewed would prevent many surprises and decrease the share of discussions. Surprising needs for coordination often interrupted the work and there were often hurried needs for work elsewhere which could have been prevented with better coordination.

DISCUSSION

Although there are hundreds of studies reporting shares of direct work in the literature, few researchers have combined qualitative and quantitative methods using time-motion study as a major source of evidence. The early results reported in this paper show that it is possible to get quantitative estimates of productivity gains resulting from lean interventions by comparative time-motion studies of different projects. Although the amount of data is small and the results cannot be generalized, this kind of data is beneficial in convincing practitioners about the magnitude of productivity problem and what kind of role lean methods could play in solving the issues faced by workers in their everyday life.

The share of direct work was just 25% for electricians and 15% for plumbers. This is much lower than the shares reported in work sampling studies, where the average seems to be 30-40% (Neve et al. 2021). This is not necessarily because of less direct work but could be explained by different granularity of methods. It can be hypothesized that work sampling exaggerates the share of direct work because if an observer checks the activity periodically, they do not have a longitudinal view of what is going on. It could take a few minutes to understand what is going on and the worker can transition between non value-adding and direct work tasks while the determination is taking place. This hypothesis should be evaluated in future research..

The proposed interventions themselves are not new. Better communication, involving crews in planning, improved logistics and implementation of 5S principles and takt production have been proposed and implemented by practitioners for a long time. It is more important to ask whether this kind of research is helpful in convincing more practitioners to adopt lean methods.

There is initial evidence that the research achieved its aims. New research has been funded which aims to solve the design constructability problem and involves the trade unions, MEP engineers and several major main contractors. The results about takt production have alleviated the concerns of trade contractors that prioritizing "work waiting on workers" would negatively affect their bottom lines. Trade unions have taken a positive view on resource tracking on construction sites to decrease the waste and representatives of workers are actively participating in coming up with solutions. Longer term impacts will be investigated in future research.

CONCLUSIONS

Root causes of wasted effort in MEP work (RQ1) were poor communication, poor production planning and control, deficiencies in logistics, lack of constructible and coordinated design and a large share of preparation work on site due to work spaces moving. The root causes are familiar and have been previously tackled by several proposed lean-based interventions.

It was possible to evaluate the productivity potential of different interventions by detailed comparison of missing prerequisites, project characteristics and patterns of used time (RQ2). The largest potential is associated with improving constructability and coordination of design (plumbers 20%, electricians 10%). Significant opportunities were found also with material logistics where just having everything on wheels (plumber 10%, electricians 5%) and organizing storages with 5S principles could result in substantial benefits (1 percentage point). More comprehensive industrial just-in-time logistics solutions could improve the productivity even more but would also require installation-level design to evaluate the right amount of materials. Installation level design would also give opportunities for prefabrication or at least more efficient work preparation on site. The study also indicates that takt production can substantially increase the direct work share of MEP workers, alleviating the concerns of trade contractors that capacity buffering would result in increased labor costs.

ACKNOWLEDGMENTS

This work has been supported by "Hukka LVI- ja sähkötöissä" (Waste in plumbing and electrical work) project funded by STUL (electrical contractor association), LVI-TU (HVAC contractor association) and STTA (electrical employers union) from Finland.

REFERENCES

Ansah, R. H., Sorooshian, S., & Mustafa, S. B. (2016). Lean construction: an effective approach for project management. *ARPN Journal of Engineering and Applied Sciences, 11(3),* 1607-1612.

Bertelsen, S., Koskela, L., Henrich, G., & Rooke, J. (2006). Critical flow–towards a construction flow theory. *14th Annual Conference of the International Group for Lean Construction*. Santiago, Chile.

Demirkesen, S., Sadikoglu, E & Jayamanne J. (2020). Investigating effectiveness of time studies in lean construction projects: case of Transbay Block 8. Production Planning & Control, DOI: 10.1080/09537287.2020.1859151

Gong, J., Borcherding, J. D., & Caldas, C. H. (2011). Effectiveness of craft time utilization in construction projects. *Construction management and economics, 29(7)*, 737-751.

Jenkins, J.L. and Orth, D.L. (2004), "Productivity improvement through work sampling", *Cost Engineering, Vol. 46 No. 3*, pp. 27-32.

Kalsaas, B.T. (2011). On the Discourse of Measuring Work Flow Efficiency in Construction. A Detailed Work Sampling Method. *19th Annual Conference of the International Group for Lean Construction 2011*.

Khanzode, A., Fischer, M.A. and Reed, D.A. (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. *Journal of Information Technology in Construction, Vol. 13*, pp. 324-342.

Koskela, L. (1999). Management of Production in Construction: A Theoretical View In:, *7th Annual Conference of the International Group for Lean Construction.* Berkeley, California, USA, 26-28 Jul 1999. pp 241-252.

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

Koskela, L. (2004). Making-Do — the Eighth Category of Waste. In:, Bertelsen, S. & Formoso, C. T., *12th Annual Conference of the International Group for Lean Construction*. Helsingør, Denmark, 3-5 Aug 2004.

Neve, H. H., Wandahl, S., Lindhard, S., Teizer, J., & Lerche, J. (2020). Determining the relationship between direct work and construction labor productivity in North America: four decades of insights. *Journal of Construction Engineering and Management, 146(9),* 04020110.

Santos, J., Wysk, R.A., Torres, J.M. (2006). *Improving Production with Lean Thinking.* Hoboken, NJ, USA. John Wiley & Sons, Inc. pp.1-165 ISBN 978-0471-75486-2 (cloth)

Thomas, H. R., J. M. Guevara, and C. T. Gustenhoven. (1984). Improving productivity estimates by work sampling. *Journal of Construction Engineering and Management 110 (2):* 178–188. https://doi.org/10.1061/(ASCE)0733-9364(1984) 110:2(178).