Silambarasan, C., Prabaharan, R., & Devkar, G. (2026). Metrics-based process mapping for MEPF design process efficiency analysis. 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. 1419–1429). https://doi.org/10.24928/2026/0191

# METRICS-BASED PROCESS MAPPING FOR MEPF DESIGN PROCESS EFFICIENCY ANALYSIS

**Silambarasan C[1], Ragavi Prabaharan[2], & Ganesh Devkar[3]**

## ABSTRACT

Mechanical, Electrical, Plumbing and Fire Protection (MEPF) design process in Engineering, Procurement, and Construction (EPC) project delivery faces process bottlenecks and coordination issues leading to delay and cost overruns. Yet, most existing research address these qualitatively without operational-level measurement frameworks. This research adapts the Metrics-Based Process Mapping (MBPM) framework for MEPF design, using swimlane diagrams to visualize cross-disciplinary workflows and to measure activity-level metrics. The classification and analysis of waste sources is carried out with a waste identification framework . A case study of the EPC healthcare project validates this approach across Fire Protection System (FPS), Public Health Engineering (PHE), Heating, Ventilation, and Air Conditioning (HVAC), and Electrical disciplines during the schematic and detailed design phases. Through process mapping, document analysis using Document Control Index (DCI) records, and stakeholder interviews, the study identifies how MEPF design effort is diverted to non-value-adding activities, such as waiting, rework from revisions, and extra processing due to complex workflows. This work identifies significant performance gaps and the sources of waste in design processes. The framework provides a simple yet quantitative approach that helps MEPF teams and EPC contractors identify the causes of design process bottlenecks and supports structured collaboration and early stakeholder engagement to enhance Lean implementation.

## KEYWORDS

Lean design, process mapping, design management, wastes, metrics-based.

## INTRODUCTION

The potential of Lean principles can be tapped by applying them from concept through commissioning in construction projects. In particular, the Adoption of Lean principles at the design phase is significant as the design process has a major impact on project outcomes and overall efficiency (Koskela et al., 1997). Particularly, implementing Lean principles in Mechanical, Electrical, and Plumbing (MEP) design significantly impacts project outcomes, as it is highly interrelated with other departments and project stakeholders (Chauhan et al., 2022).The design workflow is often interrupted by rework, delayed approvals, and poor coordination, resulting in inefficiencies throughout the project cycle (Chauhan et al., 2022). It is essential to analyze each activity in the design process by mapping it to identify where

[1] Student, Ranbir and Chitra Gupta School of Infrastructure Design and Management, Indian Institute of Technology Kharagpur , India, silambarasanck2020@gmail.com, orcid.org/ 0009-0000-5740-7846

[2] Assistant Manager, Department of Research and Development, URC Construction (P) Ltd, India, +919788933592, ragavi.prabaharan@urcc.in, orcid.org/0000-0002-2901-7047

[3] Sr. Associate Professor, Faculty of Technology, CEPT University, Ahmedabad – 380009, India, +919099010303, ganesh.devkar@cept.ac.in, orcid.org/0000-0002-5482-1221

bottlenecks and delays occur. Process mapping tools in Lean, such as Value Stream Mapping (VSM: Rother and Shook, 1999) can potentially be used in the design stage to analyze and visualize activities, the flow of work, and information to identify non-value-added activities (Aka et al., 2017; Freire & Alarcon, 2000). While VSM has been successfully applied at the departmental level during the design stages (Pedó et al. 2022) (Aka et al. 2017 ), such studies also report the need for more comprehensive mapping due to the subjective and complex nature of design processes. Studies such as Pedó et al. (2022) reported challenges when mapping and quantifying metrics by VSM at the departmental scale, despite recognizing its benefits. They posited that VSM, being primarily a strategic and high-level tool, requires integration with operational, activity-level mapping approaches, such as swimlane diagrams, to effectively diagnose bottlenecks at the finer, process-level detail (Aka et al., 2017; Pedo et al., 2022). Department-level analyses in Lean design require an approach that stakeholders can understand, given that design is inherently subjective. There is therefore a need for a simple framework that shows results in numbers and is quantified by the department's stakeholders.

According to Martin and Osterling (2012), while VSM focuses on eliminating waste at the system level, Metrics-Based Process Mapping (MBPM ; Martin & Osterling, 2012) is a tactical, process-level mapping approach that integrates the functional view of swimlane maps with metrics, enabling frontline teams to see where time is spent and where waste occurs in their own processes. This makes Lean implementation more concrete for MEPF design teams by combining visual flow understanding with simple, stakeholder-owned metrics. This research addresses this gap by adapting the MBPM concepts specifically for MEPF design processes, integrating quantitative metrics and stakeholder input to provide actionable diagnostic insights at the department operational level.

In this study, MBPM is combined with swimlane mapping, waste classification, and interruption analysis to: visually represent the MEPF design workflow and its interdependencies across disciplines; quantify activity-level metrics that reveal where delays, waiting, and interruptions occur in each discipline and engage stakeholders in interpreting these metrics to identify practical improvement actions that are more likely to be adopted in everyday project work. These contributions make Lean design principles more concrete and decision-oriented for MEPF departments, moving from high-level awareness to specific, data-based process changes. The remainder of the paper reviews lean design management, process mapping tools, and MEPF design challenges, followed by the research method, results of the metrics-based analysis, discussion of key insights, and concluding remarks with contributions, limitations, and future research directions.

# LITERATURE REVIEW

## LEAN DESIGN MANAGEMENT

Lean construction adapts Lean principles from the manufacturing sector, resulting in improved planning and more efficient production. Construction can be considered a production system, albeit in an uncontrolled environment, and many challenges arise when applying manufacturing-based Lean principles in this sector. However, applying Lean principles and tools in construction enables better workflow, tracking, and efficient planning in projects (Koskela 1993). Lean principles and tools can be applied during the design phase of a construction project, as part of Lean design management. Koskela (1997) applied Lean construction tools such as the Design Structure Matrix (DSM) and the Last Planner System (LPS) during the design phase and improved the design flow by identifying optimal task sequences. Koskela's TFV theory provides the conceptual foundation for managing design through Transformation (T), Flow (F), and Value (V). Target Value Delivery (TVD) applies these principles specifically during the design phase to steer design decisions toward value and

cost targets. It is built on three core elements, viz., converting inputs into outputs, managing the flow of information and materials, and generating value for customers (Koskela, 1998).

Freire and Alarcon (2000) applied this concept in the design processes of construction projects by using VSM as a diagnostic tool to identify non-value-added activities and understand where time was spent in design workflows. These non-value-added activities are considered waste, as they consume resources without adding value (Koskela, 1993). However, in the construction sector, the notion of value is subjective, as it involves multiple parties, each of whom can be seen as a customer (Freire & Alarcon, 2000). This idea has also been emphasized in the context of industrialised and prefabricated housing, where value is defined both as external customer value and internal value for producers (Björnfot & Stehn, 2007). In a similar vein, Drevland and Lohne (2023) begin by asking "value for whom?" and conclude that value is driven by stakeholders' motivations and the transactions involved in the project.

## PROCESS MAPPING TOOLS

Lean principles and tools implemented in the construction sector are increasingly being used in the project's design phase, particularly to visualize and understand the processes involved. Many techniques adapted from Lean principles, such as Design Structure Matrix (DSM), and Value Stream Mapping (VSM), are being used in the design phase of a construction project for diagnosis to know the sequence and measure flow and value (Koskela, 1997; Furtmeier et al., 2010; Freire & Alarcon, 2000). VSM has become an important tool, and its use in design contexts has successfully identified sources of inefficiency at both the organizational and strategic levels by providing a broad overview, which is useful for enterprise-level decision-making (Freire & Alarcon, 2000; Pedó et al., 2022). Several studies have focused on VSM within specific departments involved in the design phase of a project and have begun to introduce qualitative metrics for assessing the design process and output. Aka et al. (2017) used VSM in the preliminary and detailed phases of the structural design process and identified non-value-added activities and process bottlenecks. By visualizing process flows using VSM, the study successfully identified bottlenecks that often go unnoticed in traditional design management. They reached an important conclusion that inherently subjective design processes need more precise and comprehensive mapping methods than the typical VSM scope to represent the complexity of knowledge work (Ko & Chung, 2014; Aka et al., 2017).

Pedo et al. (2022) provided the empirical and methodological answer to the need for a more comprehensive mapping approach by demonstrating the success of integrating multiple tools, such as swimlane diagrams, VSM, and other structured frameworks, organized by required level of detail. This integration approach provides both a strategic overview (through VSM) and operational detail (through swimlane diagrams and metrics-based tools), creating a complete picture of the design process's complexity. However, most of these applications still operate at a relatively aggregated level and do not provide discipline-wise, activity-level metrics for Design workflows, where frequent handoffs, interruptions, and dependencies are central to how waste is generated in practice. This creates a gap for approaches that can link detailed process mapping with quantitative indicators of wastes in design process.

## WASTE IDENTIFICATION AND COORDINATION CHALLENGES IN MEPF DESIGN

Mechanical, Electrical, and Plumbing (MEP) systems are among the most complex parts of a building project because they are integrated with architectural and structural designs. Mohamad et al. (2014) explained that MEP activities account for a significant share of project costs and require strong coordination among different design and construction teams. During MEP activities, waste often arises from fragmented communication, a lack of real-time visibility into design progress, and limited collaboration among stakeholders (Chauhan et al., 2022). Filho et

al. (2017) also noted that long approval times and missing information are significant causes of waiting waste in the design phase.

To reduce design waste, researchers have developed a waste classification framework grounded in Lean principles. Taiichi Ohno initially identified seven categories of waste in manufacturing. These wastes have been adapted for design processes. Aka et al. (2017) demonstrated the effectiveness of using such waste classification frameworks in discipline-specific design processes, successfully applying Value Stream Mapping to structural design and identifying wastes such as waiting time, excessive motion, excessive production iterations, and excessive inspection. In contemporary Lean practice, the DOWNTIME mnemonic is used as a practical tool for classifying design wastes. DOWNTIME represents eight categories: Defects (errors requiring rework), Overproduction (unnecessary iterations or deliverables), Waiting (idle time in approvals or information flow), Non-utilized talent (underutilized expertise and skills), Transportation (unnecessary movement of information between teams), Inventory (accumulated work-in-progress or pending tasks), Motion (excessive searching or manual effort), and Excess processing (over-detailed or redundant work beyond requirements) (Lean Construction Institute, 2026; Donarumo & Zandy, 2019).

# RESEARCH METHODOLOGY

## RESEARCH BACKGROUND AND CONTEXT

The research setting for this study was URC Construction company, a general contractor in India. This company began its Lean transformation journey in 2012. The organization implemented Lean tools, including the Last Planner System (LPS), Value Stream Mapping (VSM), 5S, and Work Sampling, across project execution phases, achieving significant efficiency improvements. Recognizing the potential of Lean principles, senior management decided to extend Lean implementation to the design phase, understanding that early application in the project lifecycle would yield greater benefits. The company's R&D division developed a strategy to introduce Lean principles in the structural, architectural, and MEPF design departments and, as a first step, conducted a Lean Design Workshop with staff from these teams. After this workshop, an action research study using VSM was done on the architectural design process, which created interest among other design departments to try Lean-based process improvement. Building on these experiences, the present study focuses on the MEPF design department and extends Lean process analysis to this discipline, with the aim of providing a simple, operational-level diagnostic framework. The research was conducted with active support from the MEPF team, who shared project data, design documents, and participated in interviews and discussions for the EPC healthcare project.

## RESEARCH APPROACH

This study adopts a case study–based research approach. At the time this research study was conducted, the URC Construction Company was undertaking various EPC projects in sectors such as healthcare and railways. The Lean Initiatives Team and MEPF Department Team in the URC Construction Company conducted a discussion and subsequently recommended Project A for inclusion in this study. Project A is a government-funded critical care project awarded under an EPC contract model. The contractor was responsible for complete design development from schematic through detailed design phases. Primary and secondary data were collected and analyzed, including project document reviews, the Document Control Index (DCI), direct observations, and interviews with project stakeholders. Simultaneously, the MEPF design team provided access to project communication emails, design documents, and Design Basis Reports. Four design managers (one from each MEPF discipline), one BIM lead coordinator, and six BIM modellers were interviewed, all of whom were involved in the project of designing and

modelling. Data triangulation was achieved by cross-checking details and validating them with stakeholders. For example, when discrepancies arose between the dates recorded in the DCI and the minutes of meetings (MoM), personnel at the site and MEP design team members were contacted to verify the information.

The methodology of this research comprised a two-step process: gaining a detailed understanding of the activities carried out in the MEPF design process and of the experience and responsibilities of the team members involved. For this, an initial meeting and interviews were conducted with the MEPF design team. This helped prepare swimlane maps and provided an overview of the complete sequence of activities within the MEPF department and their interdependencies. After completing the swimlane process mapping, a detailed metrics analysis was conducted. This study adapted the Metrics-Based Process Mapping (MBPM) framework for detailed analysis of each activity (Martin & Osterling, 2012). MBPM enables quantification of four key metrics. Lead Time (LT) represents the total calendar duration from when an activity begins to when it is completed, including all waiting periods and non-productive delays. Process Time (PT), in contrast, captures only the actual working time (value-adding activity) spent by MEP engineers on the activity, excluding any idle periods (waste). The Activity Ratio (AR) was calculated as the percentage of Process Time relative to Lead Time, indicating how much of the total lead time is spent on productive work versus waiting. Finally, Waiting Time was derived by subtracting Process Time from Lead Time and represented the idle periods that occur between or within activities. To quantify each activity's metrics, the case study of the critical care healthcare project was investigated, as it is a service-intensive project. Lead Time and process time for all activities were quantified based on the project timeline and interviews with stakeholders who worked on the project. Subsequently, a waste classification framework was applied to classify the identified wastes based on stakeholder perception.

## METHOD OF ANALYSIS

### Process Mapping Using Swimlane

At the initial meeting with the MEPF design team, information gathered through stakeholder interactions was used to gain an overall understanding about the department. All the activities were listed, from preliminary design calculations to shop drawing delivery. The activities were validated by stakeholders and mapped in swimlanes respective to the roles of those stakeholders. All activity steps, including required inputs and outputs, the responsible stakeholder or team, and dependencies between activities, were used to make the preliminary swimlane. Through this qualitative mapping process, the stakeholders gained clarity on why this study was being conducted and what its objectives were. This initial phase served as a foundation to help reduce resistance and build buy-in for the next phase of detailed metrics analysis.

### Metrics Quantification by MBPM

To provide a more detailed analysis of activities, this research study adopted MBPM metrics: Lead Time, Process Time, Waiting Time, and Activity Ratios. The DCI of the case study project provided information on the overall design timeline, the duration of each activity, and when each activity was performed. Each activity and its lead time were quantified by consolidating the deliverable timelines for the activities from the DCI. Some missing timelines, such as waiting times and approval delays, were obtained from the project's site planning team. Without digital timesheets and consistent daily logs, the process time for each activity was quantified solely from interviews with key stakeholders: one BIM lead (coordinator across disciplines), four design managers, and four senior BIM modellers (one per discipline). In these interviews, stakeholders were asked the critical question: how long would it take to finish the activity without any interruptions, such as delays for approval or waiting to receive rework files from other departments. The initial PT estimates were discussed in follow-up sessions and

triangulated with lead-time information from the DCI, planned schedule of the project, and clarifications from the site execution and project coordination teams wherever discrepancies appeared. This approach provides simple, stakeholder-agreed metrics that reflect actual operational experience in this specific project and are intended to support local improvement decisions rather than establish fixed standard times for MEPF design processes.

### Waste Identification Framework

The Waste identification framework (DOWNTIME) comprising eight waste categories: Defects, Overproduction, Waiting, Non-utilized talent, Transportation, Inventory, Motion, and Extra processing were customized for the MEPF design context through discussion with stakeholders to get operational definitions for each waste category which reflect design work rather than manufacturing. These definitions were validated through stakeholder feedback to ensure they reflected MEPF team experiences. Each identified waste was classified into one of the eight DOWNTIME categories and quantified, where possible, using project data. This stakeholder-driven customization aligned with the understanding that value and waste perceptions are shaped by how project participants experience and interpret their work.

# RESULTS

## SWIMLANE PROCESS MAPPING

Process mapping using swimlanes was conducted to provide an overview of all processes in the MEPF department for the EPC project. As shown in Figure 1, the swimlane mapping identified 9 activities common to all MEPF services. The activities are Concept Coordination, Compatibility check, Design Drawing / DBR Activities, BIM coordination with Other services, BIM Model - Creation / Correction, Clash detection & Resolution, Clash Review & Analysis, BIM sheet / Shop dwg Creation, and Client approval. The swimlanes represent the responsible stakeholders in the horizontal lanes and project phases in the vertical lanes, with activities mapped to their respective lanes.

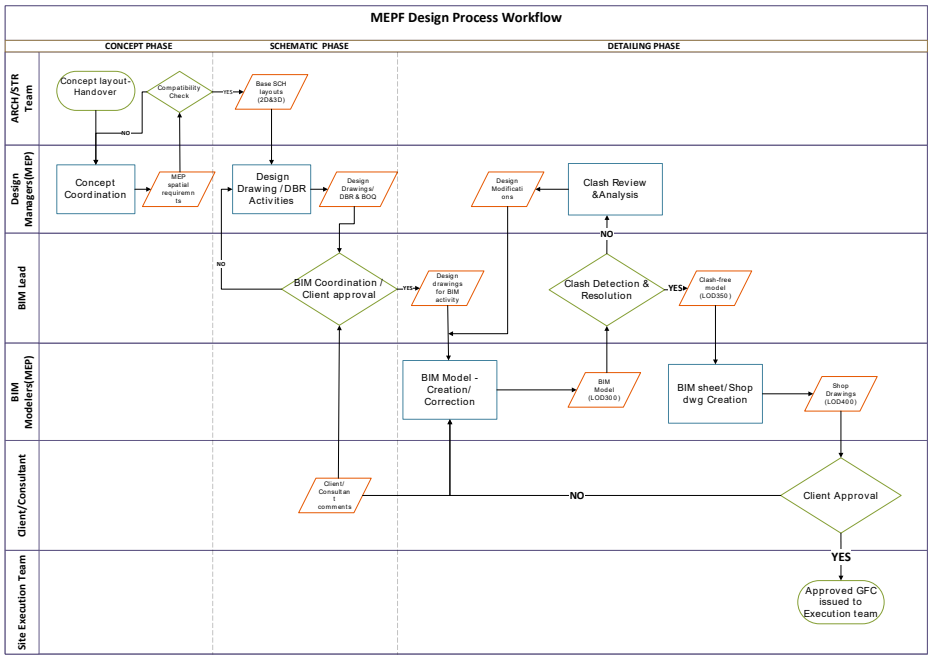


Figure 1: Preliminary Swimlane map

The responsible stakeholders involved in these activities include the architecture/structural team providing approved layouts, MEPF design managers responsible for discipline designs, a BIM lead coordinating integration and clash detection, BIM modellers developing service models, the client/consultant (CPWD) approving deliverables, and the site execution team implementing GFC drawings. The mapping captures the full sequential process flow from receiving architectural drawings, developing service-wise MEPF designs, BIM coordination and clash detection, model updates and shop drawing extraction, client reviews, design revisions if needed, and final Good for Construction (GFC) drawing issuance. It provides a clear view of each activity and its inputs and outputs. By this, sequences and dependencies were also identified, and four decision-making activities, such as Compatibility check, BIM coordination with other services, Clash detection & resolution, and Client approval, were identified, which might become bottleneck activities. Overall, the preliminary mapping provided a clear view of handoffs, approvals, and coordination points across the workflow.

## DETAILED SERVICE-SPECIFIC MAPPING WITH METRICS QUANTIFICATION

While the preliminary swimlane mapping provided an overview of the MEPF design process, it treated MEPF as a single unified workflow. It has found that all services in MEPF follow the same process sequence. When quantifying the metrics for each activity, each discipline was specified in horizontal lanes and the project phases in vertical lanes. This approach enabled examination of each discipline's workflow in parallel, revealing discipline-specific bottlenecks, waiting periods, and dependencies. A detailed metric-based mapping shown in Figure 2. All services, such as HVAC (Heating, Ventilation, and Air Conditioning), FPS (Fire Protection System), PHE (Public Health Engineering/Plumbing), and ELECTRICAL, had roles that began in the concept phase, where they coordinated with other design departments. The detailed map includes activity boxes for each discipline in their respective project phases.

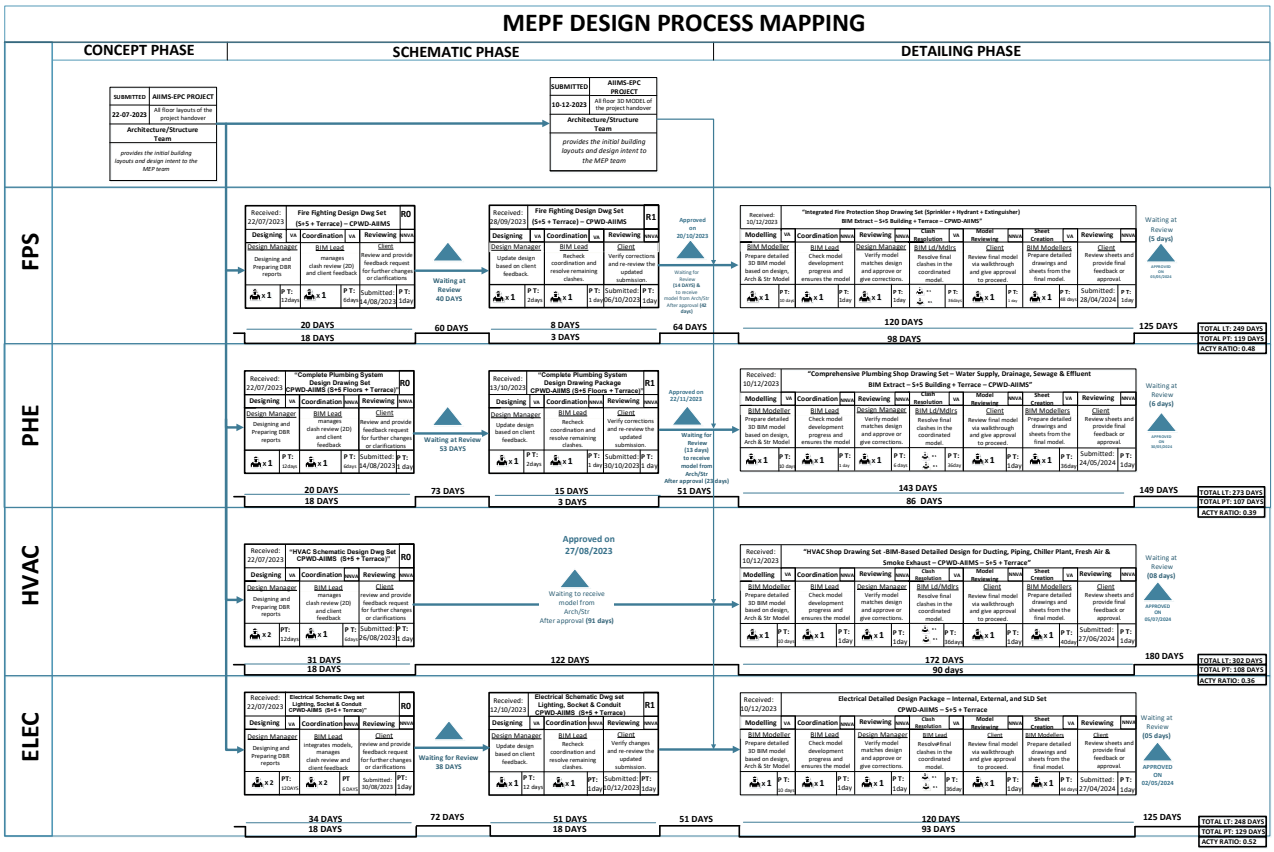


Figure 2: Detailed Swimlane map

To quantify metrics of each activity in detail, the structure enabled calculation of four key metrics (as defined earlier): process time, lead time, waiting time, and activity ratio. These metrics were calculated for each individual activity across all four disciplines, aggregated to show cumulative time for each project phase (concept, schematic, detailed design), and rolled up to determine the overall design completion period for each discipline. The analysis also captured activities involved in design revisions within each phase, enabling an understanding of rework patterns and their impact on overall timelines. Timing calculations were based on when each activity received inputs from its predecessor activities and stakeholders, ensuring that dependency delays and rework times were captured in the lead-time measurement.

The Activity Ratio, the percentage of process time relative to lead time, ranged from 36% for HVAC to 52% for Electrical, as shown in Table 1. This indicates that 48% to 64% of total time across disciplines was spent in non-value and waiting periods. These findings are significant because they quantify, at the operational level, how the duration of activities is distributed between active work and waiting in each discipline's design workflow. Rather than making general statements about MEPF design performance, the metrics reveal specifically which disciplines have higher idle ratios and where workflow interruptions occur. HVAC showed the lowest activity ratio (36%), indicating significant time is spent waiting, reviewing, and coordinating rather than doing value-added work. This suggests that discipline-specific characteristics and coordination requirements significantly impact design process efficiency.

## WASTE ANALYSIS AND CLASSIFICATION

After quantifying overall metrics such as total lead time and total process time, the difference between lead time and process time was identified as non-value-added time (NVA), which was considered a value gap. Upon further analysis, non-value-added time was classified into two main categories: rework time which occurred due to client approvals and revisions, and waiting time which which further classified into two types which because of delay in client approvals, and inter-disciplinary coordination. The time classification is detailed in Table 1.

Table 1: Metrics-based process mapping results across MEPF disciplines

| Service | Lead Time (days) | Process Time (days) | Activity Ratio(%) | NVA Time (days) | | Waiting Time(days) | |
|---|---|---|---|---|---|---|---|
| | | | | Rework Time | Waiting Time | For the model | For client review |
| FPS | 249 | 119 | 48 | 29 | 101 | 42 | 59 |
| PHE | 273 | 107 | 39 | 71 | 95 | 23 | 72 |
| HVAC | 302 | 108 | 36 | 95 | 99 | 91 | 8 |
| ELEC | 248 | 129 | 52 | 76 | 43 | 0 | 43 |

Across the four services, non-value-added time accounted for roughly half or more of the total lead time, with FPS and ELEC showing lower proportions of non-value-added time and higher activity ratios, and PHE and HVAC showing higher proportions of non-value-added time and lower activity ratios. In all disciplines, the top two waste contributors in DOWNTIME terms were Waiting and Defects (rework), but the dominant waiting cause differed by service: HVAC was most affected by waiting for the coordinated model, while FPS, PHE, and ELEC experienced more delay from client review and approval cycles.

These two main classifications were further analyzed to identify the causes of waste using the DOWNTIME waste identification framework. The analysis identified the following primary waste types: Defects (Rework), primarily caused by architectural revisions (16 major revisions

during the project) requiring MEP design updates across all disciplines; Waiting, caused by dependencies on architectural drawings, client approvals, and interdisciplinary coordination delays; Extra Processing, identified qualitatively through workflow analysis, including CAD–BIM workflow duplication and redundant reviews; and Transportation, identified when analyzing documents and communication structures, related to design file handoffs and information transfer delays between teams. Through mapping the workflow and analyzing communication patterns, these transportation and extra processing wastes were identified as contributing factors to the main critical waste of waiting time. The communication structure and dependency issues showed that information does not flow smoothly between departments, and changing client requirements compound the inefficiency. The analysis demonstrates that non-value-added time of approximately 48% to 64% across disciplines can be traced to these specific, quantifiable waste sources. A detailed examination of process interruptions is essential to understand how these wastes originated and recurred throughout the project.

### PROCESS INTERRUPTION ANALYSIS

The MEPF design process was repeatedly interrupted by major architectural revisions from the architecture department and by hierarchical communication delays that affected both the schematic and detailed design phases. The MEPF department received R16 architecture drawings from the architecture department as a baseline (an approved architectural drawing by the client) to start MEPF design process.

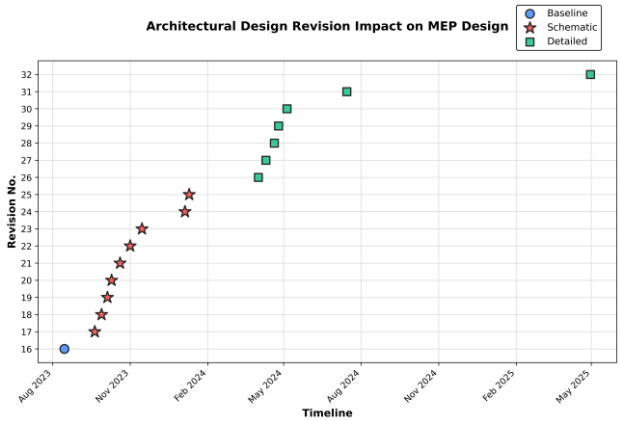


Figure 3: Architectural design revision impact on MEPF design

Figure 3 shows the timeline of subsequent architectural revisions after R16 (baseline), which impacted MEPF design at each phase of its design. During the MEPF design of the project, 16 architectural revisions (R16–R32) triggered new cycles of review, coordination, and rework. In the schematic phase, 9 revision cycles (R17–R25) forced drawing-level changes. In the detailed phase, 7 revision cycles (R26–R32) required direct BIM model modifications and substantial rework as they began detailed modelling. Root causes of interruptions caused by revisions were identified as client-driven scope changes due to evolving needs, hierarchical communication across organizational layers causing time delays, architectural dependencies in which MEPF teams rely on up-to-date models, and regulatory modifications and approvals from respective authorities. These interruptions directly contributed to the wastes identified in the Waste Classification analysis. This provides a data-driven foundation for targeted improvement interventions in future MEPF design projects.

## DISCUSSION

The analysis showed that the main bottlenecks and delays in the MEPF design process arose from late emergence of requirements and weak early coordination between stakeholders, rather

than from a lack of technical skill. When client requirements are not frozen upfront, architectural design changes later in the design process, creating a cascading effect in which MEP teams repeatedly rework their designs and extend lead times. These late requirement changes and architectural dependencies act as root causes, while fragmented communication and sequential approvals act as contributing factors that amplify waiting and rework.

To improve this situation, stronger process standardization is needed by implementing standard operating procedures (SOPs) for design handoffs, review cycles, and change-impact assessment, and by enforcing phase-freeze points for architectural and client requirements to prevent continuous interruptions to designs. Furthermore, when BIM models are created early in the schematic design phase with LOD 200 or higher, clashes between services can be detected much earlier using preliminary drawings and models; if clash detection occurs only after detailed modelling, any clashes found at that stage require significant rework to resolve, whereas early detection in schematic allows for simpler adjustments before detailed work begins and saves considerable design time and effort. It is also need to establish early, structured client coordination meetings to define scope and requirements upfront (Conditions of Satisfaction) and to conduct parallel reviews rather than sequential approvals to reduce approval delays. Finally, continuous monitoring using dashboards to track activity ratios, waiting times, and rework hours regularly, and conducting monthly lessons learned sessions for process refinements will help sustain improvements and make MEPF design processes more efficient in future EPC projects.

# CONCLUSION

This research implemented Lean design management in the MEPF department of an EPC contractor by adapting a Metrics-Based Process Mapping (MBPM) framework together with a waste classification framework. Using the critical care healthcare project as the case study, all MEPF design activities from architectural input to shop drawing delivery were mapped through swimlanes and then quantified using MBPM metrics such as lead time, process time, and activity ratio. The results showed that a significant share of MEPF design effort is lost to non-value adding activities. Most of this loss arises from waiting for architectural inputs and approvals, and rework caused by architectural and client-driven revisions. Although the four MEPF disciplines follow a similar process structure, their process performance and activity ratios differ depending on the extent of their reliance on architectural decisions and the clarity of their technical requirements. The study demonstrates that MBPM, combined with the Waste classification framework, can convert what is usually a qualitative discussion of "coordination issues" into clear, quantitative insights into where and why time is being wasted in design.

This supports EPC contractors and MEPF teams in identifying needs such as an earlier design freeze, changes in workflow, and more direct communication channels, which would serve as a collaboration platform for all stakeholders. The work is limited to a single completed project and relies partly on DCI and stakeholder recollections to estimate process times. In addition, the case organization is a contractor with several years of Lean practice and a relatively well structured digital design environment (BIM models, DCI, structured email records) which may not represent firms at an early stage of Lean adoption or with less formalized data. Future work should apply the same framework in multiple projects, including organizations with lower Lean maturity and less digitization, and should specify a minimum set of digital data sources (such as DCI, revision logs, timesheets) required to reliably quantify activity-level metrics. Even with these limitations, the study demonstrates that a simple, metrics-based mapping approach enables MEPF teams to apply Lean principles practically by identifying specific bottlenecks they can directly address in their design processes.

## REFERENCES

Freire, J. & Alarcon, L. F.. (2000). Achieving a Lean Design Process. *8th Annual Conference of the International Group for Lean Construction*.

Filho, J. B. P. D., Lima, M. M. X., Heineck, L. F. M., Tzortzopoulos, P. & Neto, J. P. B.. (2017). Waiting Times in Design Process: A Case Study. *25th Annual Conference of the International Group for Lean Construction* (pp. 483–489). https://doi.org/10.24928/2017/0294

Ballard, G. & Koskela, L.. (1998). On the Agenda of Design Management Research. *6th Annual Conference of the International Group for Lean Construction*.

Pedó, B., Nguyen, Q. A., Koskela, L., Tezel, A., Vrabie, E., Whitelock-Wainwright, A., Potter, D., Robinson, S. & Tzortzopoulos, P.. (2022). Devising and Implementing Process Models Within Infrastructure Engineering Design. Proc. *30th Annual Conference of the International Group for Lean Construction (IGLC)* (pp. 504–515). https://doi.org/10.24928/2022/0155

Aka, A., Emuze, F. & Das, D.. (2017). Mapping Waste in the Structural Design Process in South African Projects . *25th Annual Conference of the International Group for Lean Constructio*n (pp. 475–482). https://doi.org/10.24928/2017/0053

Chauhan, K., Peltokorpi, A., Abou-Ibrahim, H. & Seppänen, O.. (2022). Mechanical, Electrical and Plumbing Coordination Practices: Case Finnish Construction Market. *Proc. 30th Annual Conference of the International Group for Lean Construction (IGLC)* (pp. 635–644). https://doi.org/10.24928/2022/0169

Koskela, L., Ballard, G. & Tanhuanpää, V.. (1997). Towards Lean Design Management. In Tucker, S. N. (Eds.), *5th Annual Conference of the International Group for Lean Construction*.

Ko, C. & Chung, N.. (2014). Making Design Process Lean . In Kalsaas, B. T., Koskela, L., & Saurin, T. A. (Eds.), *22nd Annual Conference of the International Group for Lean Construction* (pp. 463–474).

Furtmeier, F. A. & Tommelein, I. D.. (2010). Explorative Application of the Multi-Domain Matrix Methodology in Lean Design. In Walsh, K., & Alves, T. (Eds.), *18th Annual Conference of the International Group for Lean Construction* (pp. 151–160).

Drevland, F. & Tillmann, P. A.. (2018). Value for Whom?. *26th Annual Conference of the International Group for Lean Construction* (pp. 261–270). https://doi.org/10.24928/2018/0533

Mohamad, A., Gehbauer, F. & Haghsheno, S.. (2014). Improving the Implementation of Modularization and Standardization of MEP Systems in Design. In Kalsaas, B. T., Koskela, L., & Saurin, T. A. (Eds.), *22nd Annual Conference of the International Group for Lean Construction* (pp. 509–518).

Osterling, M., & Martin, K. (2012). Metrics-Based Process Mapping: Identifying and Eliminating Waste in Office and Service Processes.

Koskela, L. (1993, May 26). *Lean Production in Construction*. 10th International Symposium on Automation and Robotics in Construction, Houston, TX, USA. https://doi.org/10.22260/ISARC1993/0007

Björnfot, A. & Stehn, L. (2007). Value Delivery through Product Offers: A Lean Leap in Multi-Storey Timber Housing Construction. *Lean Construction Journal*, 3(1), (pp. 33-45). https://www.leanconstructionjournal.org

Lean Construction Institute. (n.d.). The 8 wastes of Lean construction. https://leanconstruction.org/lean-topics/8-wastes-of-lean/

Donarumo, J., & Zandy, K. (2019). Managing the Eight Wastes of Lean - D.O.W.N.T.I.M.E.

Rother, M., & Shook, J. (1999). Learning to See: Value Stream Mapping to Add Value and Eliminate Muda. Brookline, MA: *The Lean Enterprise Institute.*