Rethinking Automation in Construction: An Exploratory Study of Lean for Robotics in Mobile Factories

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Abstract -

Lean principles have long supported digital transformation in manufacturing. The architecture, engineering, construction and operations (AECO) sector has increasingly adopted them for off-site fabrication. Yet, AECO projects usually involve bespoke designs, unique site conditions and project-specific processes; and the role of lean in advancing emerging robotic fabrication remains under-investigated. This is particularly the case for mobile factory setups, which offer flexibility across varying site conditions. This study explores how lean can facilitate robotic fabrication in mobile factories in current practice. The research combines an industry survey on lean concepts for mobile factory robotics with a comparative case study of three recent digital fabrication projects, including robotic bending of standing seams and two 3D-printing applications. The findings identify *just in time*, *just right in amount*, *5S*, *autonomation*, *pull planning*, *waste*, *andon* and *takt time* as the lean concepts most relevant to mobile factory applications. This study further proposes candidate key performance indicators (KPIs) across four dimensions: efficiency, standardisation, synchronisation, and waste reduction. Modularity, virtual commissioning, reliability and adaptability to site conditions emerged as recurring technical parameters across cases. The study contributes to both construction automation and lean construction, offering a foundation for interdisciplinary research on robotic fabrication management.

Keywords -

On-site and off-site construction; digital fabrication; lean construction; mobile factory; construction robotics; 3D printing

1 Introduction

1.1 Robotisation in Construction:

The architecture, engineering, construction, and operations (AECO) sector ranks amongst the lowest in digitalisation and innovation [1]. The sector faces pressing global challenges, including climate change, resource scarcity, labour shortages and persistently low productivity, that demand systemic responses. Industry professionals and researchers have been looking at robotisation as an effective approach in digital transformation to boost productivity and sustainability [2]. The use of robotics enables precise digital fabrication based on digital design information, such as 3D BIM models, and helps avoid design and construction misalignments [3]. Robotisation, applied to both construction and deconstruction across the entire lifecycle of a building, can facilitate circular construction practices. This includes promoting the reuse of building materials or components through robot-oriented design. [4, 5].

1.2 Robotics in Mobile Factories:

Recently, researchers have looked at off-site and on-site robotics in construction. Within the topics of on-site robotics in construction, researchers and industry practitioners have been looking into robotics in a mobile factory scenario due to its mobility and flexibility to adapt to different site conditions. Bock [6] proposed a modular mobile robot unit for on-site interior work, demonstrating that up to 80% of drilling, mounting, and assembly tasks could be automated. Cao et al. [7] applied reinforcement learning to optimise mobile factory scheduling in infrastructure projects. Ng et al. [8] presents a constructed project of using a bending robot installed in two mobile containers to automatically fabricate standing seams based on 3D BIM models and point-cloud data from 3D scanning.

1.3 Lean for on-site and off-site Construction:

To assist in robotisation for on-site and off-site applications in construction, recent studies look into industrialisation for robotics implementation in construction [4]. Unlike manufacturing of products, architectural designs for buildings are typically bespoke. Furthermore, each project is defined by the unique site conditions. The requirements in design and construction processes could be challenging. In construction management, lean construction has been recognised as appropriate for managing robotics in construction [9, 10]. For example, lean approaches can reduce the costs of digital fabrication because they help integrate information between upstream design and downstream construction [11].

On one hand, off-site processes can be industrialised in a controlled factory setup. Mass customisation using digital or computational design tools enables parametric design for digital fabrication that takes constraints from machinery and produces customised building components such as custom column structures [12, 13]. This factory setup incorporates manufacturing knowledge and innovations such as lean production, which is originated from the Toyota Production System in Japan. Lean concepts such as *just in time*, *pull planning* and *kanban* have been researched and adopted in robotics in construction in practice to different extents to facilitate robotisation in construction through design for off-site fabrication [9].

On the other hand, lean concepts have been studied to assist robotic work on-site. For example, researchers conducted cost-benefit analyses, which is a key tool in Lean Six Sigma, to analyse key financial indicators of automation and robotic systems in the construction industry [14, 15]. Rauch et al. [16] presents *just in time* in mobile factories to address the requirements for scalable and reconfigurable on-site production, which could be applicable for the AECO sector. Linner et al. [17] uses a customised four-step management method for continuous improvement of processes, products or services (Deming Cycle) to facilitate the development of on-site construction robots. Hu et al. [10] further demonstrates through a case study of two on-site construction robots that lean concepts, such as *5S*, *early stakeholder involvement*, *Last Planner System*, *Gemba Walk* and *kaizen* (*continuous improvement*), have the potential to improve the deployment of on-site construction robots. Beyond the studies cited above, a growing body of work addresses the integration of lean principles with robotic and automated systems. Innella et al. [18] reviewed lean methodologies for modular construction and found that, despite lean's suitability for this hybrid sector, its full productivity potential remains unrealised. Gusmão Brissi and Debs [19] mapped the intersections of lean, automation and modularisation across 31 papers, revealing significant untapped research potential. A scientometric analysis by Cardenas et al. [20] confirmed that the lean-robotics intersection remains significantly under-researched, with only 18 of 842 articles addressing both fields. Feldmann [21] identified seven barrier dimensions to automation in prefabrication, including robot-oriented design. Fu et al. [22] noted that human–robot collaboration and lean production can synergistically unlock the potential of modular construction. Skalli et al. [23] established transferable frameworks for measuring operational efficiency in automated production. These perspectives inform the present study and position its research questions within the broader lean–robotics landscape.

1.4 Research Questions

Despite some industry applications and recent research, the application of robots in mobile factories is still confined to laboratory settings [24]; how lean can benefit these applications has not yet been studied to the authors' knowledge.

This study aims to answer the following overarching research question: How can lean principles facilitate the adoption and management of mobile factories for digital robotic fabrication in current construction practice? To address this question, three sub-questions are investigated:

SQ1 What are the industry needs and barriers to using a mobile factory in current practice?

SQ2 What are the potential parameters related to lean in a mobile factory application?

SQ3 What are the potential key lean performance indicators (KPIs) for mobile factories in the construction sector?

The remainder of this article presents the research methodology (Section 2), industry survey findings (Section 3), comparative case study results (Section 4), a discussion of potential KPIs (Section 5), and conclusions with future research directions.

2 Research Methodology

This exploratory study presents the research conducted with a mixed method of industry survey via two rounds of workshops to answer SQ1 and SQ2, followed by a comparative case study of two existing mobile factory cases and one off-site robotic case to draw cross-case patterns for validation. This elaborates on the potential KPIs and answers SQ3.

It should be noted that established analytical methods in management science, such as Exploratory Factor Analysis (EFA) for identifying latent constructs from survey data and Porter's Five Forces for analysing competitive dynamics, offer robust approaches to the types of questions investigated here. However, the present study is exploratory in nature with a purposive sample of 16 participants, which is insufficient for factor-analytic methods that typically require substantially larger sample sizes. The workshop-and-survey design is therefore intended to generate preliminary insights and hypotheses that can be tested with more rigorous methods in future research.

2.1 Industry Workshops

The authors of this study conducted two rounds of a two-hour workshop titled "Lean or not? Match-making of

Figure 1. The *Microfactory* system presented at the workshop by Digital Building Technologies (dbt), ETH Zurich.

lean concepts in automation in construction" at two international conferences in 2025 respectively. Each workshop comprised three sessions: (1) a lean concepts quiz from [25] and a presentation on lean for on-site robotics [10]; (2) a presentation on the *Tor Alva* 3DCP tower project [26]; and (3) a group discussion on the ETH Zurich's *Microfactory* (Figure 1), where participants proposed lean-based implementation strategies for mobile factories in practice.

The first workshop was held at IGLC 2025 (World Expo Osaka, Japan) with ten participants; the second at ISARC 2025 (Montreal, Canada) with over twenty participants. Participants included industry practitioners, government professionals and academic researchers with robotics knowledge. Results from the first workshop informed the survey distributed at the second. The post-workshop questionnaire survey was completed by sixteen participants, comprising twelve academic researchers, two professional architects, one professional engineer and one robotic engineer. Amongst all, eight reported having practical experience in lean management and six had experience with on-site construction robotics.

2.2 Comparative Case Study

To validate the parameters of the survey research, the authors conducted a comparative case study based on Yin [27] of three polar cases of robotics in construction [28] based on the project's process studies of the first author. They possess maximum variations, as shown in Table 1. Case 1 in Project Q used a two-container-size bending robot to digitally fabricate standing seams for the free-form roof construction of a theatre building constructed in 2016. This case remains anonymous in this article due to the agreed confidentiality. Details of this case and its process studies can be found in Ng et al. [8]. Case 2 from Digital Building Technologies (dbt) [29] comprises a binder-jet 3D printing of stone waste from the Ticino quarries. Within Case 3 from dbt [26], Case 3a refers to the 3D printing process of the structural columns of the tower [12]; Case 3b is the 3D printing process of the plastic form work to pre-cast column base. For each level of the tower, a column set from Case 3a was pre-assembled with a base from Case 3b to form a column-base unit. Then each unit was transported to the site for assembly. Case 3 is a control case of off-site robotic construction.

3 Findings on implementing Lean for Robotics in Mobile Factories

3.1 Focus-group Workshops

From the two workshops at IGLC and ISARC respectively, *just in time* and *pull planning* were identified as important lean concepts for the *Microfactory* case. For example, with the scenario of bathroom pod production, the participants proposed using one or multiple *Microfactory* containers with robot arms to configure an on-site factory to produce volumetric bathroom pods on site in a one-piece flow manner, instead of producing pods in batches in an off-site factory and transporting them to the site, which can cause waste and inefficiency. Moreover, in the highway construction scenario, the participants proposed redesigning the logistics infrastructure associated with the implementation of mobile factories according to the relevant lean concepts. To further elaborate, the authors compiled the following six questions raised at the workshops for a post-workshop questionnaire survey.

3.2 Questionnaire Survey

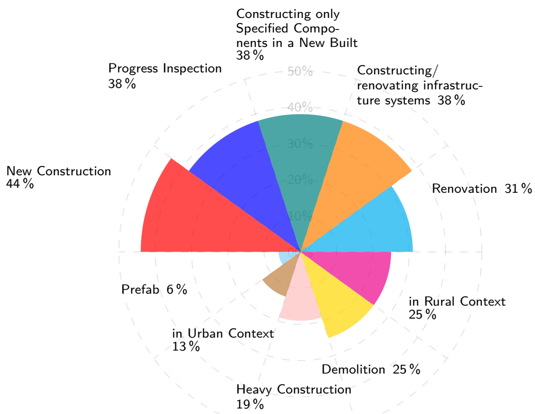

Figure 2. Most needed applications for a mobile factory in construction.

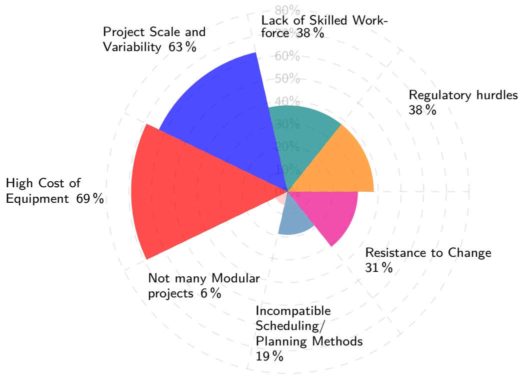

Figure 3. Most perceived barriers to integrating robotics in lean construction.

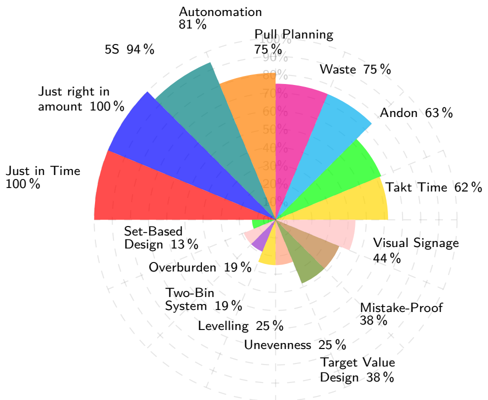

Figure 4. The relevency between each of the 16 lean concepts from Ng and Chen [25] and a mobile factory case in construction.

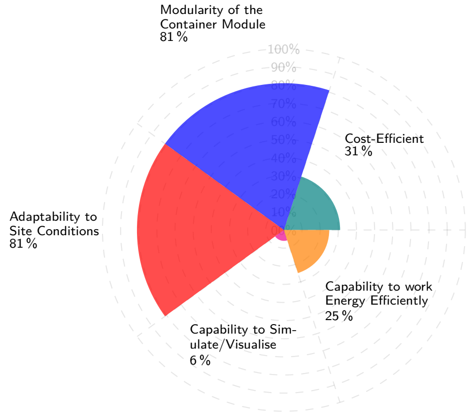

Figure 5. Five most-perceived influential technical parameters of a mobile factory's container in relation to lean concepts.

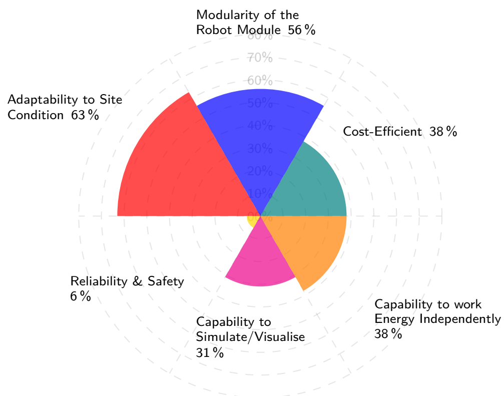

Figure 6. Six most-perceived influential technical parameters of the robot in a mobile factory in relation to lean concepts.

Given the small sample size (N=16), the following results should be interpreted as indicative rather than generalisable. Figure 2 suggests that participants perceived mobile factories as most needed in new construction, followed by progress inspection, construction of specified components in a newly constructed building and construction or renovation of infrastructure systems such as roads. The following figures show the results from the participants, who could choose more than one option. Figure 3 indicates that, amongst the respondents, the high cost of equipment was perceived as the most significant barrier to integrating robotics in lean construction, followed by the scale and variability of the project, as well as the lack of skilled workforce and regulatory hurdles, respectively.

Figure 4 shows how each of the 16 lean concepts introduced by the short quiz from Ng and Chen (2025) at the beginning of the workshops could be relevant to the applications of a mobile factory case. The results suggest that *just in time*, *just in right amount* and *5S* may have particular potential to be applied when planning an application with mobile factories. *Autonomation*, the lean concepts about *waste*, *pull planning*, *andon* and *takt time* also show their relevancy to mobile factories. Further investigations are presented in the next section of the comparative case study.

To investigate influential parameters related to lean in a mobile factory application and answer SQ2, Figure 5, Figure 6 and Figure 7 present the initial survey results of five technical parameters, related to the container, the robot/machine and the site, respectively, in a mobile factory application with regard to their relations to lean. These parameters were derived at the workshops. For

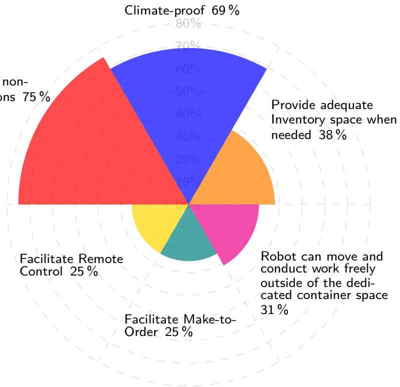

Figure 7. Six most-perceived influential operations site parameters for mobile factory implementation in relation to lean concepts.

both the container and the robot in a mobile factory, the two most-perceived technical parameters are *adaptability to site conditions* and *modularity of the container/robot module*. *Cost-efficiency* is also significant. *Reliability and safety* are also mentioned as influential factors for the robot in a mobile factory.

Regarding operational parameters, participants considered it influential to enable 24/7 non-stop operation with or without human involvement, followed by climate-proof. These align with the general advantage of off-site fabrication, where the construction work is not obstructed by changing site conditions.

4 Comparative Case Study

To further investigate and validate the parameters for the implementation of mobile factories in current practice, this study also presents a comparative case study of three existing mobile factory cases to answer SQ2. As shown in Table 1, the cases exhibit a number of shared similarities and distinct differences. Crucially, each project represents an example of bespoke architectural design, meaning that elements, such as the geometry of building systems, are entirely unique to that specific case.

Case 1 and Case 3 are both digital fabrication cases for the construction of theatre buildings. Case 2 and Case 3 both involved 3D printing but with different printing technologies and techniques.

4.1 Within-Case Analysis

In Case 1, the site refers to where the final theatre building is located. The source materials for the aluminium profiles, provided off-site, and transported to the site for on-site fabrication in the mobile factory on-site in batches based on the analysis of the 3D point cloud data from on-site scanning. They were assembled on-site piece by piece. This ensured a reliable fabrication of bespoke standing seam profiles without delay [8].

Case 2 uses a container-based mobile factory with a binder-jet printer, set up directly in marble quarries to obtain raw material and immediately manufacture modules for a discrete funicular floor system on site (Figure 8). A key aspect is the use of recycled rock dust from the quarries as a sustainable alternative to virgin construction materials. Case 2 involves a funicular floor slab system in which the geometry directly determines structural performance. These structural applications entail additional challenges, including material testing, quality assurance protocols and regulatory approval [29, 30].

Case 3a involves off-site 3D Concrete Printing (3DCP) of structural columns with robotically integrated rebar (Figure 9). Case 3a involves 3D-printed concrete columns that form the primary load-bearing structure of a 30-metre tower, requiring rebar integration during printing and compliance with structural certification standards. Case 3b involves off-site 3D printing of plastic formwork for pre-cast concrete slabs. Columns and slabs were pre-assembled in modules off-site, then on-site assembly (Figure 10).

4.2 Cross-case Analysis

To better understand and validate the results of the industry workshop survey, this study investigates the parameters presented in Figures 5, 6 and 7, as shown in Table 2. In this comparison, Case 3 serves as the control case of an off-site digital fabrication case, where there is no con-

Figure 8. Case 2 - Arzo - site photo with the mobile factory at the marble quarry by dbt [29].

Figure 9. Case 3 - Tor Alva - off-site 3D Concrete Printing process by dbt [26].

Table 1. Background information of the three cases in this comparative case analysis.

	BUILDING SYSTEM	BUILDING TYPE	DIGITAL FABRICATION MATERIAL	METHOD	PROCESSES SOURCE	FABRICATION	ASSEMBLY
Case 1	Roof standing seam	Theatre Building	Aluminium	Robotic Bending	Off-site	On-site	On-site
Case 2	Floor Slab	Prototype	Marble	Binder Jet 3D printing	On-site	On-site	Off-site
Case 3a	Column	Theatre Building	Concrete	3D Concrete Printing	Off-site	Off-site	Off-site
Case 3b	Concrete Slab		Plastic	Formwork 3D Printing	Off-site	On-site	

Figure 10. Case 3 - Tor Alva - off-site pre-assembly of a module, which comprises the 3D-printed columns and the pre-cast concrete slab for one of the levels by dbt [26].

Table 2. Technical Parameters in regard to the mobile factories in Case 1, Case 2 and Case 3 respectively. For Case 1 and Case 2, a ✓ refers to relevant, a ✗ refers to not strongly relevant to that particular case

	CASE 1	CASE 2	CASE 3
TECHNICAL PARAMETERS OF THE MOBILE FACTORY CONTAINER			
Modularity of the container	✓	✓	N/A
Ability to operate energy independently	✗	✓	N/A
Adaptability to site conditions	✓	✓	N/A
Cost-efficiency	✓	✓	N/A
Virtual commissioning	✗	✓	N/A
TECHNICAL PARAMETERS OF THE MOBILE FACTORY'S ROBOT(S)			
Modularity of the robotic systems	✓	✓	✓
Ability to operate energy independently	✗	✓	✗
Adaptability to site conditions	✗	✗	✓
Cost-efficiency	✓	✓	✓
Virtual Commissioning	✓	✓	✓
Reliability & Safety	✓	✓	✓
OPERATIONS PARAMETERS OF THE MOBILE FACTORY			
Adequate inventory space	✗	✓	✓
24/7 operations with/without human	✓	✓	✓
Robot's mobility outside container	✗	✓	N/A
Climate-proof	✓	✓	✓
Make-to-order possible	✓	✓	✓
Remote control possible	✓	✗	✓

tainer or mobile setup; therefore, the container parameters are not applicable to Case 3.

Regarding the technical parameters of the mobile factory containers, the modularity and adaptability of the container to the site conditions are important to ensure that the container can operate on the site. For Case 1, the container could rely on the power supply at the site; therefore, the ability to operate energy independently is not relevant. Virtual commissioning of container movements for Case 1 is relatively less relevant, while for Case 2, it is more relevant due to the site condition of the raw material sources. For both cases, the cost efficiency for, for example, moving the container from one place to another is relevant to the cost plan of the adoption in the project.

Referring to the technical parameters of the mobile factory's robots, besides cost efficiency, the modularity of the robotic systems, virtual commissioning of the robotic movement or a similar concept to path-planning visualisation, reliability and safety are considered relevant in all three cases. The ability to operate with energy independence is not relevant to an off-site fabrication scenario because the power supply is provided by default. For Case 1 and Case 2, the adaptability to the site is less relevant because the robotic systems were installed inside the containers, respectively. For Case 3, the fabrication is relevant to the site condition refers to the logistic constraints, where the prefabricated and pre-assembled unit have to be fit to the regulatory requirements of the truck size and highway restriction of the country during the transportation.

Regarding the operation parameters of the mobile factory, all three cases demonstrate their make-to-order possibility. 24/7 operations and climate-proofing are relevant for on-site and off-site construction. Inventory space is relatively less demanding for Case 1 because each standing seam was fabricated only when the assembly process was ready; while for Case 2 and Case 3, an adequate inventory space for the prefabricated products is required before assembly processes, which took place elsewhere. For Case 1, the robotic system was fixed in the two-container set without being moved outside or around the containers' space; Case 3 does not have a container boundary but the lab space with the gantry system, where the robot arms are fixed. The robot's mobility within the lab space was essential. For Case 2, the remote control option is not relevant because the operations require a human worker to fill the stone materials into the robotic systems for the 3D printing process.

5 Discussion

5.1 KPIs for Mobile Factories

Three cases in this study did not explicitly adopt any lean-based project delivery model. Nevertheless, the processes show several lean concepts to different degrees. To elaborate on the potential Key Performance Indicators (KPIs) of lean implementation for mobile factories in current practice, in this section, the authors discuss the relevant lean concepts from the survey results as shown in Figure 4, based on the comparative case study. In this study, mainly those concepts rated above 50% are discussed, namely *just in time*, *just right in amount*, *5S*, *autonomation*, *pull planning*, *waste*, *andon* (*visual alert system*) and *takt time*. Candidate KPIs are organised into four dimensions: efficiency, standardization, synchronization & collaboration and waste reduction.

Efficiency: *Just in time*, *pull planning* and *just right in amount* could refer to, for example, in Case 1, the fabrication of a standing seam was conducted piece by piece only when they were ready to be assembled to avoid *overburden* with the demand of inventory space. In this regard, the KPIs could include lean mobile factory production lead time from machine setup to component completion, unit completed per shift/day, and materials used in defined *takt* window.

Standardisation: *5S* refers to *Sort, Set in order, Shine, Standardise and Sustain*. 5S and *takt time* was demonstrated in Case 3 during the process of robotically laying the horizontal rebar one by one while 3D printing the layers of concrete to fabricate the structure simultaneously with two robot arms, respectively. Simultaneous control and synchronisation were designated to avoid clashing of the two robot arms and ensure a smooth printing process, where each rebar was placed on the designated layer. The KPI could include *takt time* adherence (actual cycle time within the planned takt time), rework frequency, time required to switch between construction product variants and refers to the differentiation of workload and schedule of digital fabrication tasks during the fabrication and assembly processes.

Synchronisation & Collaboration: *Autonomation* and *andon* were not explicitly mentioned in the cases. It could happen in the case that, in the lab in Zurich, a robotic process would stop when the safety fence surrounding a robot arm detects anything unintentionally coming close by. *Kanban* was not adopted in any of the three cases. Nevertheless, it could be very relevant to, for example, human-robot collaboration in mobile factories. Furthermore, *Mistake-proof* usually refers to a design that avoids causing any mistake during the production or on the outputs. Although not explicitly mentioned in any of the cases, in Case 1, before robotic bending of the profiles, the roof systems, which comprise the roof tube-net structure and the build-up, were scanned for point cloud data, along with comparison of the BIM models built for construction, to ensure that each standing seam profile fit perfectly to the constructed roof systems. This precision is required because the standing seam serves as an important layer of protection against water leakage through rain. In this regard, the KPI could refer to mistake-proof indicator during digital fabrication processes through *kanban* and *andon* in visualisation. An example indicator is the detected clashes or sequencing issues per *takt time*.

Waste Reduction: All three cases demonstrate the importance of efficiency in the digital fabrication process to avoid *waste* of time and resources in production. In Case 2, the reuse of unwanted materials is the key objective of the research project. In addition, the funicular slab design reduces the use of material. The 3D printing of a hollow concrete structural column, as demonstrated in Case 3, significantly reduces the usage of concrete material compared to a traditional solid concrete column while maintaining comparable structural performance. The KPI could include the amount of waste in time, material consumption, inventory space, and reuse of materials when applicable.

5.2 Illustrative Examples

To illustrate how the proposed KPIs could be operationalised, the following retrospective estimates are provided as illustiative examples for Case 1 based on the first author's process study of the project. The production lead time per standing seam component, from machine setup to completion, was approximately 15-20 minutes. The mobile factory achieved roughly 20-25 completed units per shift (8 hours), including setup, fabrication and minor quality checks. Material waste was estimated at less than 5% of the aluminium input, as the robotic bending process is subtractive only in the trimming phase. These figures are retrospective approximations rather than systematically measured values; they are provided here to demonstrate the feasibility of the proposed KPI framework. Systematic measurement of these indicators across multiple projects is identified as a priority for future research.

6 Conclusions and future work

Emerging automation technologies require us to rethink how they interact with classical management models, such as lean principles, to improve productivity in construction production. This study examined how lean principles advance digital robotic fabrication through three mobile factory case studies and analysed both technical and operational parameters. The findings indicate that, beyond cost efficiency, modular robotic system design, virtual commissioning and path-planning visualisation, as well as reliability and safety, are consistently relevant across all cases of mobile factories. This aligns closely with the lean goals of waste reduction, process transparency and risk mitigation. Adaptability to site conditions showed context-dependent relevance. For example, it was less critical in Case 1 and Case 2 due to fixed robotic setups in a container, while in Case 3 it was primarily associated with logistical and regulatory constraints governing transportation rather than physical deployment. Operationally, all three cases demonstrated strong make-to-order capabilities to reflect lean pull-based production, while differences in inventory requirements highlighted varying degrees of coupling between fabrication and assembly processes. Human-robot interaction remained necessary in material-dependent processes, which could limit the possibility of full remote operation.

Future research should extend the empirical scope to a broader range of robotic fabrication typologies, materials, and deployment contexts, employing quantitative performance metrics, such as lead time, system utilisation, rework rates and operational reliability, for real-world data analysis. Regulatory and logistical constraints should also be integrated into mobile factory configuration to enhance feasibility and applicability.

Given the exploratory nature of this study and the limited sample size of the survey (N=16), the findings presented here should be regarded as preliminary hypotheses rather than definitive conclusions. Future research should employ larger sample sizes and established analytical methods, such as Exploratory Factor Analysis, to validate the identified parameters and their interrelationships. Furthermore, future investigations should more explicitly address the differentiated challenges of structural versus non-structural 3D-printed components in mobile factory applications, including the regulatory approval processes, structural testing requirements, and quality assurance workflows that are specific to load-bearing elements.

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