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On-site factories to support lean principles and industrialized construction

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Abstract:
Purpose: The purpose of this study is to investigate the use of on-site factories that combine the strengths of both prefabrication techniques and a traditional work environment to support lean principles and promote industrialized construction for on-site operations.
Design/methodology/approach: Based on the principles of lean construction and design for manufacturing and assembly (DfMA), discrete-event simulation is used to evaluate different arrangements and configurations of an on-site factory for the prefabrication of structural insulated panels (SIPs).
Findings: The proposed on-site factory provided a feasible way to promote lean and industrialized construction principles. Also, these types of factories are particularly relevant for projects in remote areas that do not have sufficient infrastructure. Further, it is also a good solution for strengthening the local economy by using local labor and suppliers, hence assisting in the creation of a socially responsible framework.
Originality/value: This study presents the design of an on-site factory for the prefabrication of SIPs. This type of on-site assembly supports not only lean principles but also promotes social responsibility by capitalizing on local labor. This approach could be particularly interesting for construction companies in developing countries or working in a project with limited infrastructure.

Keywords: design for manufacture and assembly, flexible factory, flying factory, lean construction, lean manufacturing, industrialized construction

1 Introduction

The use of off-site production plants for the prefabrication of building elements has added significant value to productivity and sustainability in the construction industry. In most cases, shifting assembly processes from regular on-site construction work to implementation of prefabrication increases quality, safety, and the overall return on investment in construction projects. This is mainly due to the development and utilization of a working environment that is no longer constrained by on-site conditions and where principles of mass production and mass customization apply. This brings new opportunities for further integration, optimization, and automation (Popovic and Winroth 2016; Garcia de Soto and Skibniewski 2020).

However, in general, the long distances between prefabrication factories and construction sites are a clear disadvantage when compared to traditional assembly techniques (Staib et al. 2008). This trade-off may result in a low flexible supply chain in the case of changed orders, loss of potential local labor, or increased impact on the environment. Additionally, it may also significantly affect the feasibility of prefabrication on smaller projects because the costs of the prefabricated systems would be proportionately very high (Tam et al. 2007; Panjehpour et al. 2013). The purpose of this work is to investigate the potential of a hybrid approach, that is, an on-site factory that combines the strengths of both prefabrication techniques, and a traditional work environment.

The concept of on-site factories is not new and has been used in different forms for a long time. Recent examples can be found in applications of construction automation in Japan where they used "sky factories" for the construction of high-rise buildings in the 1990s (Cousineau and Miura 1998; Bock and Linner 2016). Some underlying principles of on-site factories benefit from the design for manufacture and assembly (DfMA) approach. DfMA can be defined as the process of designing products to rationalize cost, improve quality to ensure customer satisfaction

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(Belay 2009), and arguably, they share many common goals with lean construction.

More recent derivations of this approach are known as “flexible” or “flying” factories. According to Designing Buildings Wiki, *Flying factories (sometimes referred to as field factories) are temporary facilities used to manufacture prefabricated components. They are different from conventional off-site factories in that they only operate for the duration of a project and are then closed. Operations may then “fly” to a new location to service another project.*[1] Martínez et al. (2013) proposed a concept for a robotized field factory designed for on-site prefabrication as part of the EU 6FP ManuBuild Project. They based their design on manufacture and assembly principles and lean manufacturing. When comparing the total cost of the proposed flexible field factory with those of a fix factory and traditional (in-situ) assembly, they found that the flexible field factory provided savings of 37% and 23% with respect to the traditional assembly and the fixed factory, respectively. Young et al. (2015) did a case study of a flying factory that was set up to produce pre-assembled utility cupboards for a residential development in London. In total, 855 utility cupboards were required (535 built in a traditional factory and 320 in-situ). The in-situ ones were assembled using the flying factory concept. The goal was to reach a full production capacity of 20 units per week. Although they reported benefits about cost, efficiency, and safety, there were also challenges during the implementation, particularly related to the setting time and adjustments in the supply chain to ensure smooth operations. In line with these concepts, this study investigates the idea of the on-site factory for the prefabrication of structural insulated panels (SIPs). SIPs are high-performance building panels primarily used in the residential and light commercial construction sector for interior and exterior walls, doors, and roof assemblies. They are increasingly being used as an alternative to conventional framed building systems. Even though their production cost is higher than conventional panels, SIPs have a wide range of advantages that improve overall productivity, efficiency, and feasibility. Better grouting, improved insulation properties, and standardized assembly procedures reduce the occurrence of droughts, lower operational costs, decrease overall construction time, and improve the utilization of human labor. Besides, the high similarity in the production procedure for different element types leads to excellent opportunities for standardization, which is one of the prerequisites for prefabrication.

The rest of this paper is structured as follows. Section 2 gives an overview of the main principles behind the motivation of on-site factories, primarily lean and sustainable construction and prefabrication. Section 3 presents a proof of concept for the design of an on-site factory for the assembly of SIPs. Section 4 provided a discussion about the proposed design and the expected benefits and challenges. Finally, Section 5 summarizes the findings and identifies elements for future research.

2 Literature review

Productivity of the construction sector has mainly been affected by a wide range of factors, such as imposed regulatory controls (e.g., environmental and structural regulations), climate factors, shifts in energy prices, and ineffective and inefficient management practices, resulting in a significant part of resources being wasted. Between 25% and 50% of the construction costs are due to different kinds of waste generated during construction (Forbes and Ahmed 2011). These include over-allocation of unnecessary equipment, workers or materials on-site; material loss or deterioration; and wasting time and money by waiting for others, equipment, or more skilled workers (Patil et al. 2013). Some of these issues can be addressed using lean principles. Lean addresses competitiveness while managing the limited resources by reducing waste, and giving value to the customer by working on integrated and collaborative teams (Sanchez and Nagi 2010; Iqbal 2015, Poudel et al. 2020). The application of lean thinking in construction aims to improve work throughput in the construction process. Lean operating principles have their origin in the manufacturing industry. This concept emerged after WWII when Taiichi Ohno led Toyota to build a greater quantity and a greater variety of cars with less labor, less capital, and less inventory (Krafcik 1988). This principle is called by a wide range of synonyms, such as lean manufacturing, lean production, and the Toyota production system (TPS) (Kilpatrick 2003). In general, lean refers to a theory that aims to increase the value for the customer while at the same time, conserving resources and minimizing waste. Although it initially focused on the automobile manufacturing industry, Lean theory later made its way into other industries. In the early 1990s, Koskela (1992, 2000) argued that several lean production principles and methods could be adopted in the construction industry.

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[1] https://www.designingbuildings.co.uk/wiki/Flying_factory_for_construction_works

2.1 Lean construction and sustainability

Lean principles, as described above, are interlinked with financial key performance indicators (KPIs) and are not necessarily based on non-financial KPIs such as the impact on environmental measures, i.e., sustainability. In recent years, both financial and non-financial indicators have leveled in their importance within the construction industry. This is also partly due to their interdependence as well as the acknowledgment that non-financial performance indicators are equally important to improving the bottom line of a project or company. Both focus on eliminating waste, and the elimination affects both financial and environmental goals (Nahmens and Ikuma 2011). The social dimension includes the consideration of work safety and well-suited working conditions, which may include the sourcing of local labor or providing the right environment and equipment for production.

The environmental dimension is related to the practice of creating sustainable and resource-efficient processes that reduce the impact on the environment. Sustainability may be improved by sourcing materials locally, which reduces transport distances, and, in turn results in minimizing carbon emission from vehicles. In addition, this has the potential to empower the local economy and a reduction in the dependence on external sources. Resource-efficient processes can also be established by optimizing geometry, processing procedures, etc.

2.2 Prefabrication

Prefabrication is the practice of assembling components at a location other than the location of a product's intended use or its final destination (Gibb 1999). Prefabrication can be seen as a lean method as it reduces waste produced during more precise factory production or squeezes waste from the process, eliminating rework (Fewings 2013). In the construction sector, there are two main types of prefabrication, namely, modular and panelized. As indicated, the study presented in this paper focuses on SIPs.

Generally, prefabrication is categorized into off-site and on-site prefabrication based on the location of the assembly of the different components. Off-site prefabrication is very common. In these cases, a factory is built at a fixed location and materials are supplied by a fixed group of companies.

2.2.1 Advantages and disadvantages of (off-site) prefabrication

The main advantage of prefabrication is that it allows production and assembly of materials to take place in an environment that is usually not influenced by any external factors that generally prevail on construction sites, such as weather or dirt. Further, machinery used in prefabrication are highly specialized, and its specifications are tailored to the production requirements for producing output with specific characteristics and features. The condition of stationary, temporary, unique fabrication, as construction is generally defined, is no longer valid. Instead, prefabrication allows for leveraging economies of scale, reducing material and production costs by scaling and increasing production output while reducing construction time (Neelamkavil 2009).

Construction site management becomes less stressful and more efficient when some of the tasks are performed in the prefabrication phase, and fewer activities have to be done on the construction site itself (Väha et al. 2013; Rauch et al. 2015). One of the benefits is that common climate factors, which can have a detrimental impact on the quality of non-weather resistant materials such as timber, do not influence production schedule and quality (Tam et al. 2007; Richard 2005).

Improved environmental performance can be achieved by reducing construction waste caused due to poor site management practices (e.g., poor handling of materials or inadequate protection of finished work), lack of environmental awareness (e.g., less-standardized designs), damage during the delivery of products (e.g., method of transport), or rework due to poor quality (Tam et al. 2005). One example of the improved performances is the effective increase in material consumption from spontaneous solutions regarding design adaptation on structural panels. The cut off material ends up as waste that cannot be recycled for other production tasks and is therefore just thrown away. It is produced, transported, and stored and ends up being burned.

Statistically, the construction industry is one of the most hazardous industries in many countries (Wang et al. 2006; Forbes 2013). But, through prefabrication, many activities that are typically carried out on-site are undertaken in a safer and more stable working environment (e.g., on even, solidified or sealed factory grounds). This significantly reduces the likelihood of accidents and waste that occur due to external factors or adverse working conditions (N.P.C.A.A. 2017).

Even though prefabrication techniques have great potential to improve the sustainability of construction projects, they also have some disadvantages (Mokthar and Mahmood 2008). One of the main disadvantages is the inflexibility to amend orders due to the nature of the pre-fabrication concept and the fact that production plants are only seldom located near construction sites (Staib et al. 2008). Generally, the long distances between a factory and the construction site result in high order lead times since the ordered product has to be manufactured and transported to the construction site. The logistics of transporting prefabricated materials can be challenging because an efficient route to the construction site must be determined. Order modifications that arise in the short term lead to even more extensive time delays and increase costs for both supplier and client (Popovic and Winroth 2016; Tam et al. 2007; Panjehpour et al. 2013; Rauch et al. 2015). In addition, local jurisdiction can limit allowable routes for the transportation of oversized and often hazardous loads.

The costs induced by long transportation times between prefabrication plants and construction sites often have a tremendous economic impact on the overall product cost and result in higher risk related to damages. Furthermore, some remote areas may not even have reliable infrastructure and transport capacities, which may make it more difficult and costly to transport materials to their designated destinations (Weckenmann, n.d.).

The higher the costs for operators involved, the greater the needs for the production volume to maintain the same level of feasibility. This means that, due to the geographical separation of a specific construction process, such as the assembly of wall panels, additional operators are required to execute the same process. In addition to these disadvantages, off-site fabrication will have a great toll on local labor.

2.3 On-site prefabrication

On-site prefabrication refers to the implementation of prefabrication techniques on or near an actual construction site. This can be conducted using either temporary or mobile and fully functional on-site factories (Staib et al. 2008; Rauch et al. 2015). Due to their temporary and mobile character, adjustments have to be made to the occupied space regarding the fabrication environment itself, as well as consideration for the storage of raw materials and products required. Also, the internal working area required for machines attached to the assembly line has to be considered. Resource planning also has to be taken into account, which includes shared labor, shared equipment (e.g., a crane), and electricity and water supply. Terms regarding mobility have to be considered, such as weight and claimed volume in the transport state and how a mobile factory (or its components) is to be transported (e.g., truck, train). Constraints originating from these points lead to design challenges in the possible product range that is going to be produced, the production rate, and the production system in general, and the flexibility to changing customer demand rates and changing orders.

One mobile on-site factory fitting the definition above is the “Mobile Battery Mold” by the German concrete company Weckenmann Anlagentechnik GmbH & Co (Weckenmann, n.d.). The on-site factory enables the production of precast concrete slabs on or close to the construction site. It consists of mobile casting beds or tilting tables as well as molds for structural precast concrete parts (columns, joist girders, or stairs). They are organized or assembled in a way so that the parts can be mounted and dismounted inexpensively and moved between several construction sites. The shell resembles an accordion and is transported on a truck trailer in its closed state and is ready to produce in its open state (Figure 1).

2.3.1 Opportunities for on-site prefabrication

The advantages and disadvantages for off-site prefabrication stated in sub-section 2.2.1 show that it has already led to leaner construction. The disadvantages can be considered as possible opportunities for potential improvements. The following list introduces these opportunities and explains why they can be faced easily when establishing on-site prefabrication.

- ***Flexibility to order changes and reduction of lead time***—In traditional prefabrication, configuration and assembly take place at a location other than that of the final installation. As a result, lead time penalties may occur. Lean producers strive towards shorter lead times to reduce waste by reducing installation time, increasing safety, and handling efficiency or quality (O’Brien et al. 2008). Shifting the prefabrication from off-site to on-site affects the lead time significantly by reducing both conveyance and processing waste and leads towards more flexible and scalable manufacturing (Rauch et al. 2015)
- ***Incorporation of local labor***—The use of local labor is of social and ethical importance and is part of the corporate social responsibility framework.

Fig. 1: Mobile Battery Mold in its closed (left) and open state (right) (Weckenmann, n.d.).

However, the decision to utilize or not to utilize also affects the construction process in the long term. When operation is off-site prefabrication, a certain amount of work is shifted from the actual construction site and, therefore, it is no longer available for local tender. In the case of SIPs, primarily carpenters are affected since parts of their work are outsourced. Reducing the variety of work also reduces workers' opportunities to earn money and can make them desist from placing an offer. Furthermore, local hiring reduces the environmental impact of commuting and fosters community involvement. In some places, hiring is governed by local hiring policies, which can be an additional motivation to use local labor.

- ***Better communication***—Traditional off-site prefabrication demands communication between off-site prefabrication worker, and conventional on-site workers. Know-how on the same type of product is shared between the operators of the off-site prefabrication factory and the labor assembling it later. In the long term, this can cause an additional source of flaws and inefficiencies, since the off-site prefabrication operators do not know about any requirements or improvements regarding the installation of their product, and workers on-site do not have an in-depth knowledge of panel construction and may not be qualified enough to take measures other than installing them. Using local labor vitalizes not only local economies but also follow lean principles by bundling know-how on-site.
- ***Reduction of sunk cost***—When selecting a location for a factory building, availability of workforce, expandability of the land area, the purchase price per area, infrastructural connection for transports, time duration for clarification, purchase and building law, contamination, quality of the location and the attractiveness of the site regarding environmental measures have to be taken into account (Wiendahl et al. 2014). On the contrary, a mobile on-site solution eliminates many of these factors since they are decided upon in the choice of the construction project. Therefore, the mobile solution should be as flexible as possible regarding these criteria in order to be fully functional in various setups.
- ***Independence on local infrastructure and weather conditions***—Traditional off-site prefabrication is located at a different place than the installation site. In order to reduce lead times and achieve a continuous production supply flow, multiple trips are necessary during the entire construction phase, from the factory to the construction site. This requires the infrastructure to provide a sufficient level of service (LOS) for this entire period. The LOS, however, can be limited, especially in rural regions, by climatic impacts. For example, snow and ice may lead to an insufficient LOS where infrastructure accessibility is limited or temporarily closed. This may result in considerable delays in construction projects. A mobile on-site factory solution can be provided with fewer, larger deliveries of raw materials, depending on the possibility of storage on the construction site. In addition, these raw materials have to be transported with less risk of damage since they are in a "raw state."
- ***Reduce cost and emission from transportation***—The use of local material suppliers will provide the economic advantage which means that transport routes from suppliers to the construction site remain within an economic distance, just like it would be the case when planning a locally dependent factory solution. However, by placing the

mobile on-site factory near or on the site, transport distances between the factory and the construction site are significantly reduced, leading to fewer carbon emissions and transportation costs.

- ***Increased market reach***—In addition to the reduction of sunk cost, the site selection of a factory affects the market reach. The so-called market factors play a decisive role. Potential for sales, trade barriers, market activities, and the competition situation are determined to assess a potential location. Long-term changes must be taken into account in the assessment. They harbor high risk since they can negatively affect a selected factory's location in terms of economic efficiency (Erlach 2013). Also, choosing a fixed location means limiting the potential market reach to a certain radius. With the advent of a mobile on-site solution, this radius would be significantly larger because only the mechanical setup required for production needs to be transported and would be served by local labor and material suppliers. The broader market reach leads to a more substantial number of potential customers and construction sites.

3 Implementation

The conceptual design of the SIP on-site factory, as defined within the scope of this paper, is based on lean principles and uses a design for manufacture and assembly approach. The goal is to rationalize lead times and waste in the production processes while reducing resource usage in order to provide excellent mobility.

A Structural Insulated Panel (SIP) is a prefabricated engineered lightweight building component that consists of a rigid insulating polymer foam core sandwiched by two layers of facial skins. This work focuses on the production of magnesium oxide (MgO) SIPs, where the facial layers are made from MgO boards, and the polymer foam core consists of extruded polystyrene (XPS) foam. It may come with pre-cut electrical chase holes to simplify on-site wiring and piping (Chen et al. 2017), which is not taken into further investigation as this is not within the scope of this paper. MgO boards and insulation materials are compounded using hot melt or low-temperature glue, which is brushed using a glue spreading machine. Compression also needs to be done using an appropriate hydraulic press. For both brushing and compressing, automation is assumed to be mandatory to achieve a certain level of quality set by regulations for maintaining consistent glue spread and structural integrity. The panels are used in many different dimensions up to 12 × 10 feet (3.6 × 3 m).

3.1 Assembly line design

An assembly line is defined as a production environment in which parts are assembled to create a product sequentially (Hu et al. 2011). It is a flow-oriented production system in which all the tasks are balanced using simple industrial engineering techniques to get the highest benefit. That may consist of maximizing resource utilization or minimizing the cycle time, the number of workstations, or the number of operators. In general, production facilities are seen as business enterprises and strive to rationalize costs to increase their competitiveness level. Waste originates from various and different production levels, which are assumed to be the primary source of waste in assembly line design (ALD) (Erlach 2013). The most critical factors are line balancing, takt time, resource planning, logical layout, and outer shell design. Takt time provides a constraint on the assembly line's cycle time and has to be determined by implementing line balancing and resource planning based on a logical layout. Furthermore, constraints regarding the outer shell design have to be considered.

3.1.1 Logical layout

A work breakdown structure (WBS) of the SIP manufacturing process was defined through a video analysis showing a typical SIP manufacturing process.

Time studies, reference projects, and expert opinions are used to determine task times. These may vary as they depend on the level of automation at which they are executed, and other factors such as labor participation, motivation, and physical abilities (Erlach 2013). Therefore, each task was considered to have a range of possible durations, which was modeled using a beta-distribution with $\alpha = \beta = 4$. Manual tasks that could be recorded in the video analysis were considered with minimum and maximum durations within a range of 15% and the tasks that were at least partly automated were considered to have a constant duration. Tasks that were not undertaken in the process procedure in the video analysis and whose durations had to be assumed based on expert opinion were modeled with higher duration ranges of 25% in both directions, maximum and minimum (Table 1).

The next step entails defining the relationships between the tasks. These "logical relationships" can either be arranged in a parallel or sequenced manner

Tab. 1: Task times obtained from video analysis and corresponding range of possible values

Task ID	Task Name	t_e [s]	max–min [%]	t_e max [s]	t_e min [s]
1	Place first MgO board (1)	15	15	17.25	12.75
2	Place second MgO board (1)	30	15	34.5	25.5
3	Place first MgO board (2)	15	15	17.25	12.75
4	Place second MgO board (2)	30	15	34.5	25.5
5	Place insulation material (1)	20	15	23	17
6	Place insulation material (2)	20	15	23	17
7	Spray glue on MgO board (1)	20	0	20	20
8	Spray glue on MgO board (2)	20	0	20	20
9	Spray glue on insulation material (1)	20	0	20	20
10	Spray glue on insulation material (2)	20	0	20	20
11	Compress (1)	30	0	30	30
12	Compress (2)	30	0	30	30
13	Prepare timber frame	60	25	75	45
14	Add timber frame	30	25	37.5	22.5
	TOTAL	**360**		**402**	**318**

and are strongly dependent on the number and quality of resources used. The general logical layout for a MgO SIP standard panel consists of different tasks. There were 14 tasks in total for the process used in this study, and are summarized in Table 1.

3.1.2 Takt time

Takt time is defined as the ratio of total available production time to the time required to produce one unit (or customer demand). In other words, it is the rate at which a finished product needs to be completed in order to meet the customer demand. This element is of great importance because the assembly line needs to be adjusted to reach a given takt while maintaining line efficiency (Erlach 2013). Since the takt time depends not only on work efficiency but also on the number of resources used, a range of takt times is taken into account in order to determine a reasonable ALD.

The takt time and the demand rate are highly correlated. As customer demand changes, the takt time also changes, and it requires a rebalancing of the production line (Chang et al. 2013). It is used to ensure that all the work to be performed for a given product in a given station is completed in the specified time before proceeding to the next or subsequent station (Qattawi and Chalil Madathil 2019).

3.1.3 Resource planning

During the flow of material through the assembly line, the material is processed at workstations that may include resources as machines or operators. The number of workstations required to process a product strongly depends on the time it takes to manufacture one piece and the delivery time of the products as demanded by the customer, i.e., the takt time. The number of operators required at a specific workstation is dependent on the level of automation applied to the process. The choice of the number of workstations may affect both the cycle time and the line efficiency since the evenness of task distribution is limited most of the time by the number of workstations among which the tasks are distributed.

3.1.4 Line balancing

Line balancing affects how well material flows through a production line when aiming for uniform workstation cycle times that are close to customer takt time and minimizing the number of workstations and operators or, in sum, maximizing economic efficiency (Thomopoulos 2014; Erlach 2013). Two different measures can be used to adjust line balancing:

1. Shifting of work tasks from one workstation to another
2. Upgrading (or downgrading) the workstation's level of automation to increase (or reduce) the workstation operation time.

The shifting of work tasks from one workstation to another can also be viewed as assigning more than one working task to one workstation. This measure is quite simple and has a significant effect on balancing. Stacking together work tasks at different workstations may also lead to a reduction in the number of workstations, which reduces not only the cost but also the required area for the production line. The second measure can be achieved with a higher level of automation and, in some cases, an increasing number of operators. Higher levels of automation may lead to tasks being finished very quickly or becoming obsolete. In summary, the first one consists of shifting of work tasks from one workstation to another and the second one consists of upgrading/downgrading of workstation resources in terms of the level of automation to increase/reduce the workstation operation time.

3.1.5 Outer shell design

Generally, the on-site factory can be located temporarily in rented space near the construction site or at the construction site itself through mobile factory structures (e.g., shipping container) or on the growing building structure (e.g., climbing concrete factories) (Rauch et al. 2015). The shell has a significant effect in terms of its mobility, which is referred to as “outer mobility.” Outer mobility is, of course, strongly related to “inner mobility,” which refers to the mobility of workstations, machines, and general interior installations related to a factory. While providing a certain level of inner and outer mobility, a shell design has to meet requirements to ensure functional reliability and work safety (Erlach 2013). The shell structure has to satisfy static and climatic requirements. Depending on the shell structure system, the shell has to be transportable or easy to assemble. If it is transportable, it must follow road traffic laws and regulations. If the shell is a system that needs to be assembled, it has to be suitable for multiple assembly and disassembly without wear and tear, or otherwise would lead to a less reliable system. In addition, the shell structure has to be capable of withstanding stress from rain, snow, ice, and wind to be workable for the long term and to provide functionality regardless of climatic conditions. Moreover, the shell needs to be soundproof up to a certain point (Wiendahl et al. 2014).

3.2 Determination of the final design using CYCLONE simulation technique

The described method was applied in a case study on a North American company, whose mission is to provide affordable, durable, and culturally-appropriate housing to communities located in remote areas. The company’s interest to explore the use of on-site factories is not only for economic reasons (e.g., reduce overhead costs and improve profit) but also for social and environmental ones. Providing housing to remote areas requires the integration of local labor, and using local materials whenever possible, which strengthens the local economy, and, in this particular case, it is of social and environmental value. The selected tool for conducting the quantitative assessment and optimizing required for the design of the on-site factory assembly system is the CYCLONE (CYCLic Operations NEtwork) discrete event simulation system, which is considered as one of the most useful tools for modeling and analyzing construction operations (AbouRizk et al. 2016). The overall process is shown in Figure 2.

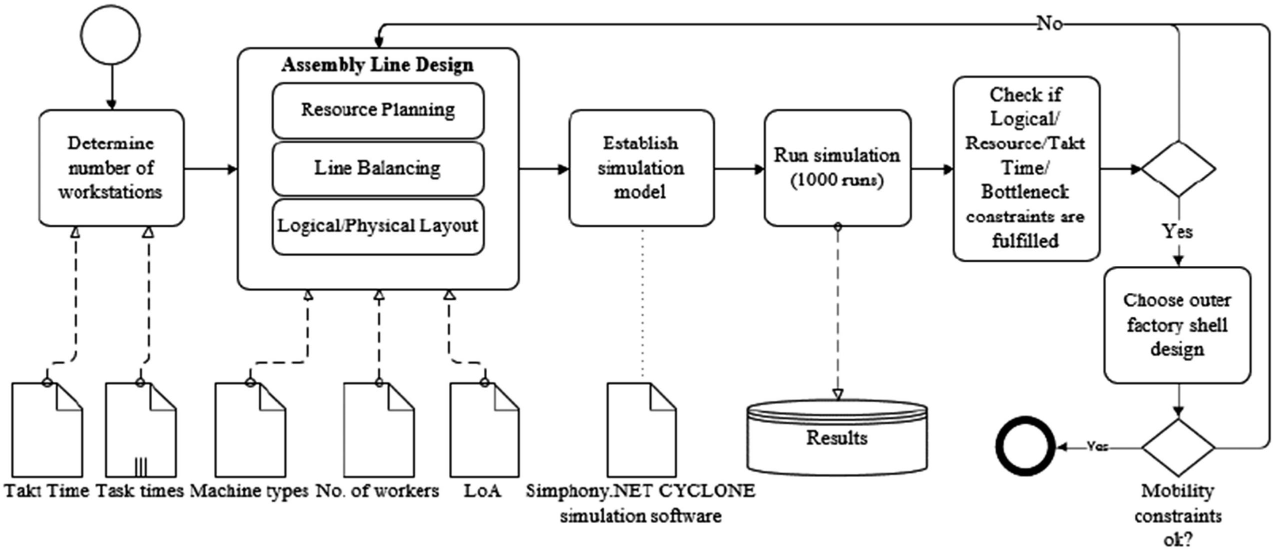

Fig. 2: Process map showing the implementation of CYCLONE into the ALD.

First, the number of workstations is derived from the considered task times and takt times. Second, assembly line design, as described in this section, is conducted, providing an "initial solution." The solution is then modeled in CYCLONE and tested for the fulfillment of the given constraints related to the physical and logical layout, takt time, and bottlenecks. If the chosen solution fulfills these requirements, the last step, which consists of the outer shell design, is executed. If the mobility constraint is fulfilled, the design process is completed. If not, the assembly line design has to be adapted to fulfill the prior failed constraints.

3.2.1 Determination of the process logic

The relationships between the tasks and their arrangement (e.g., in parallel or sequenced manner) were determined to define the process logic. Figure 3 shows the process logic containing the main tasks for the manufacturing of standard MgO SIPs.

It consists of 14 working tasks (Table 1). The "add timber frame" task (ID 14 in Table 1) can only start when the other three processes (i.e., prepare timber framing, produce MgO panel (1), and produce MgO panel (2)) are finished. The "produce MgO panel" process is executed twice in this layout and consists of the tasks shown in Figure 4.

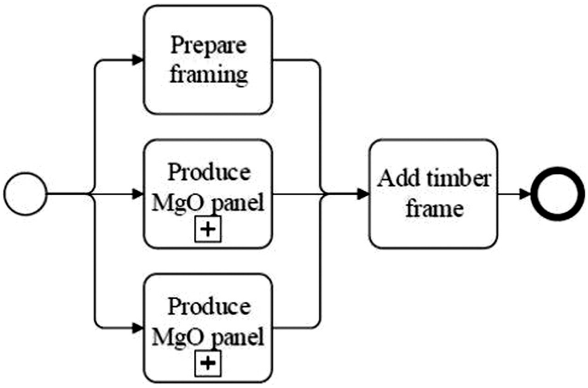

Fig. 3: General logical layout for a MgO SIP panel.

3.2.2 Determination of task times

Task times were determined from a video analysis showing a typical SIP manufacturing procedure and crosschecked with experts' opinions and previous studies. The task times vary depending on the level of automation. Other factors include labor participation, motivation, and physical abilities (Erlach 2013). Depending on the scope and the certainty with which task times can be stated, either stochastic or deterministic approaches were considered for approximation. However, for short discrete construction productions, the duration variances tend to be small, and there are not numerous varieties for their distributions. The tasks and their corresponding minimum and maximum durations for this study are shown in Table 1. Those durations were used in the modeling template of Simphony.NET (Simphony.NET 4.6, release Build 4.6.0.272 2017-08-11). Tasks that are considered to have a range of possible durations were modeled using a beta-distribution. A beta-distribution was used as it generally provides a better fit for activity durations (Shtub et al. 2004). For simplicity, α and β were set to 4 to get a symmetrical continuous distribution and facilitate the simulation. The lower and upper bounds of the frequency distribution for the different tasks were set to t_e*min* and t_e*max*, respectively. Manual tasks that were included in the video analysis (Task IDs 1 through 6 in Table 1) were considered with minimum and maximum durations within a range of ±15% in order to account for variations originating from the motivation and skill level of the workers. Tasks that were at least partly automated were considered constant in their duration (Task IDs 7 through 12 in Table 1). For the tasks that were not part of the video analysis (e.g., Task IDs 13 and 14 in Table 1), durations were estimated based on expert opinion and modeled with higher ranges (±25%) to account for extra uncertainty.

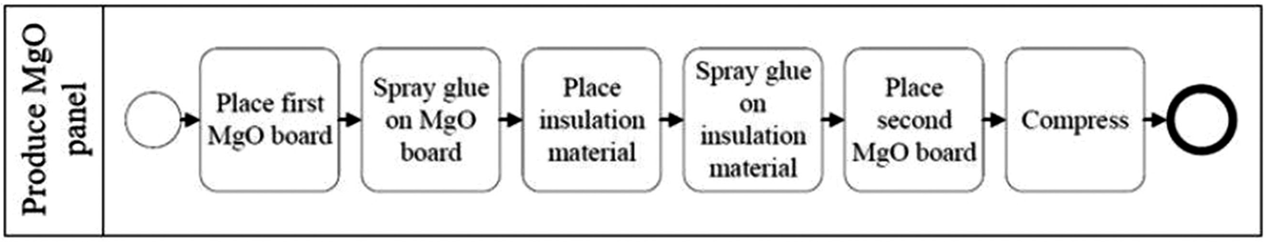

Fig. 4: Expanded "produce MgO panel" process.

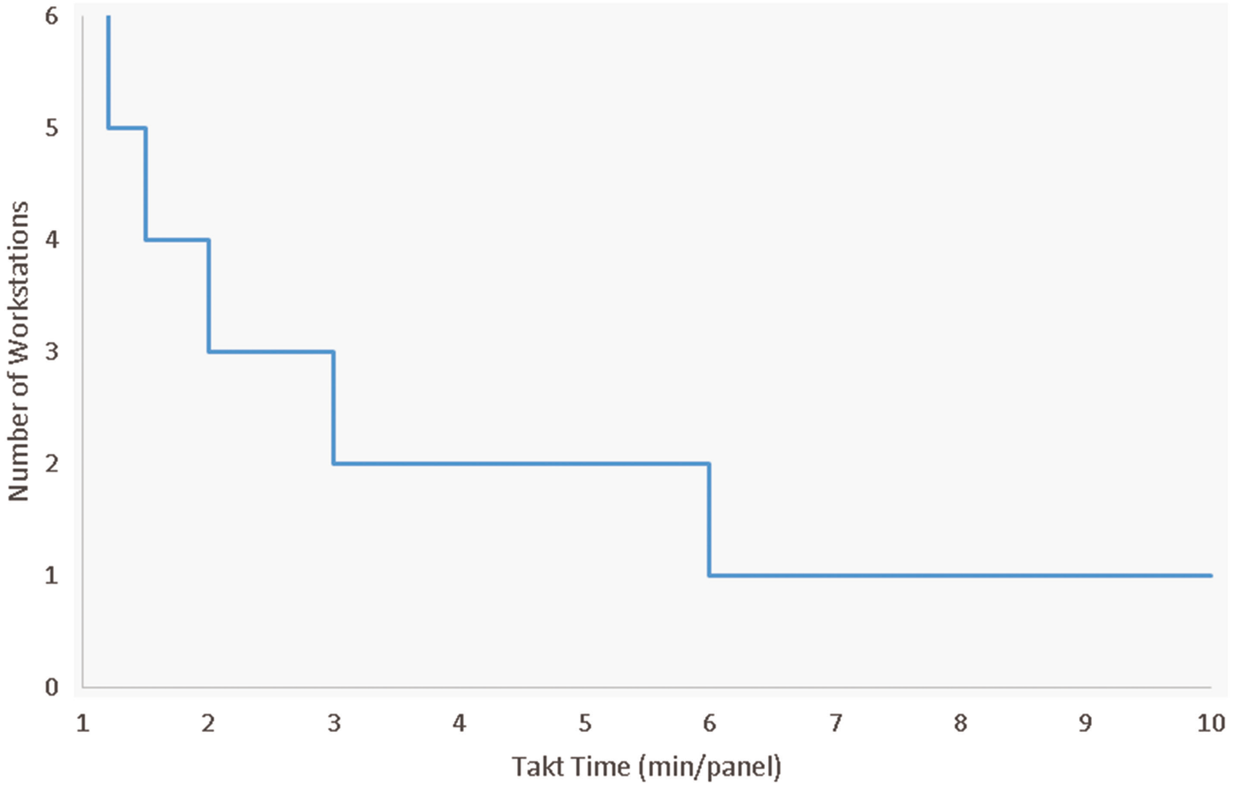

Fig. 5: Required number of workstations depending on customer takt time.

3.2.3 Determination of assembly line designs using the CYCLONE Simulation

Determining the assembly line design in terms of distributing working tasks to workstations depends on the sum of the working task times, which was found to be 360 s (6 min) on average (see Table 1). The takt time from a conventional operation is the summation of all the times for the necessary tasks. In this case, the time it takes to hook a finished panel to the crane, place it, install all required elements, unhook it from the crane, and bring the crane back into the starting position in order to hook the next panel was 11 minutes. Figure 5 shows the relationship between the number of required workstations and takt time. A maximum of 1 min and a minimum of 10 min were considered for the takt time, since the assembly line has to consist of at least one workstation, and takt times—with reference to the takt time for one customer at the time of being supplied—lower than 1 min are highly unlikely. Such takt times can only be achieved if more than ten customers are supplied with SIP panels at the same time. Here, customers are defined as separated working processes that run in parallel and require SIPs. Such situations can occur if a construction site uses more than one crane and labor group for SIP installation, which could be the case of bigger projects that typically consists of more than one building and/or construction cranes.

As shown in Figure 5, takt times greater than 6 min require an assembly line with only one workstation to process SIPs on time, referred as assembly line variant 1 (AL-1). In addition, takt times from 6 to 3 min from 3 to 2 min, and 2 to 1 min are considered for variants AL-2, AL-3, and AL-4, respectively (Table 2). Lower takt times may occur from higher productivities by the producer or by a higher number of customers demanding SIPs at the same time. Higher productivities mainly originate from above-average skilled labor or higher levels of automation (e.g., the use of nail guns, automatic screwdrivers, or jigsaws). The influence of the learning curve due to the frequent-changing of operators is a significant factor, but for purposes of this study, it was simplified by assuming that the learning curve effects were considered for the average values used.

Table 2 shows the different assembly line configurations and information related to the simulations done in order to determine the best fit regarding labor cost (i.e., number of workers), total weight and size (to ensure mobility of the assembly line), average cycle time, distribution of tasks to workstations (WS), required space for the setup, and total utilization.

Tab. 2: Information related to each assembly line (AL) used for simulation

	AL-1	AL-2.1	AL-2.2	AL-3.1	AL-3.2
Distribution of tasks for each workstation (WS) (see Table 1 for Task IDs)	**1** **WS 1: all**	**2** **WS 1: 1–12** **WS 2: 13,14**	**2** **WS 1: 1–10** **WS 2: 11–14**	**3** **WS 1: 1,3,5–10** **WS 2: 2,4,11–12** **WS 3: 13,14**	**3** **WS 1: 1,2,5,7,9,11** **WS 2: 3,4,6,8,10,12** **WS 3: 13,14**
Capital cost (USD)	10.700	10.700	10.700	11.500	19.400
Labor cost (USD/hr)	100	200	200	300	300
Workers	2	4	4	6	6
Avg. cycle time (s)	368	281	210	187	141
Space required (mounted state*) (m^2)	91.6	91.6	91.6	107.6	107.6
Space req. (unmounted state) (m^2)	27.1	27.1	27.1	32.0	43.7
Total weight (tons)	2.0	2.0	2.0	2,2	3.4
Total WS utilization	100%	66.6%	89.5%	80.7%	88.7%

*includes the area required for workers.

3.3 Selected assembly line

The determination of assembly line design was based on different ranges of takt times. Applying the framework as shown previously, and implementing a simulation model determined the possible assembly line layouts with a focus on minimizing the number of machines and the area used while continuously increasing the production rate. The indicators that were considered as most important can be divided into two groups. The first group includes indicators regarding the actual assembly line performance. This includes indicators such as the labor cost, number of workers, average cycle time, production rate as well as the total workstation utilization, and the balance delay. The second group includes indicators that are rather important for the assembly line performance but are decisive for the selection of an outer shell in which the assembly line is set up. This includes indicators such as weight and space both in the unmounted and mounted state. A 3D view of the selected assembly line (AL-1) is shown in Figure 6.

4 Discussion

The assembly line design showed that material costs are a large portion of the total costs of SIP production as soon as near-optimal production rates (maximum production rates) for each design are achieved. Using local material suppliers can be considered as a positive impact in socio-ecological terms, but it also has economic disadvantages resulting from unexploited economies of scale. Most of the time, off-site prefabrication uses one contractor for each material, demands high volumes, and, therefore, can use the economies of scale to significantly lower costs on the material. Capital costs that have to be spent on glue extruders, conveyors, hydraulic presses, etc. were found to be lower than expected. The costs were either taken from literature or based on the expert opinion.

Even for relatively high production rates compared to the customer demand rate, no cost increase was found. Additional machines used in the layout provided a low-medium level of automation since no higher levels were required; however, high levels of automation would probably result in increase of non-linear costs. In addition, capital costs per panel are, of course, very closely related to the number of panels produced in the lifetime of the factory. Labor costs were found to be very sensitive to the number of panels produced per hour. Their stake in the total panel costs is very low if production rates are near the highest possible value for each design but increase exponentially beyond that rate. This implies that production rates have to be kept relatively high in order to keep labor cost per panel down.

The ALD is based on lean ideas and principles and aims for continuous flow production. When looking at the construction process from a broader perspective, it is generally not very smooth and continuous, which leads to several problems. Optimal production rates are not achieved continuously. There might be considerable variations in demand due to other construction processes being done in parallel.

Another problem is the limitation on the number of panels that can be assembled per day due to the rationale of the construction process. Once all panels for one floor are installed, additional measures are required before starting the construction of the subsequent floor. Such measures may include wiring, flooring, or other interior assemblies. The production rate for the number of panels

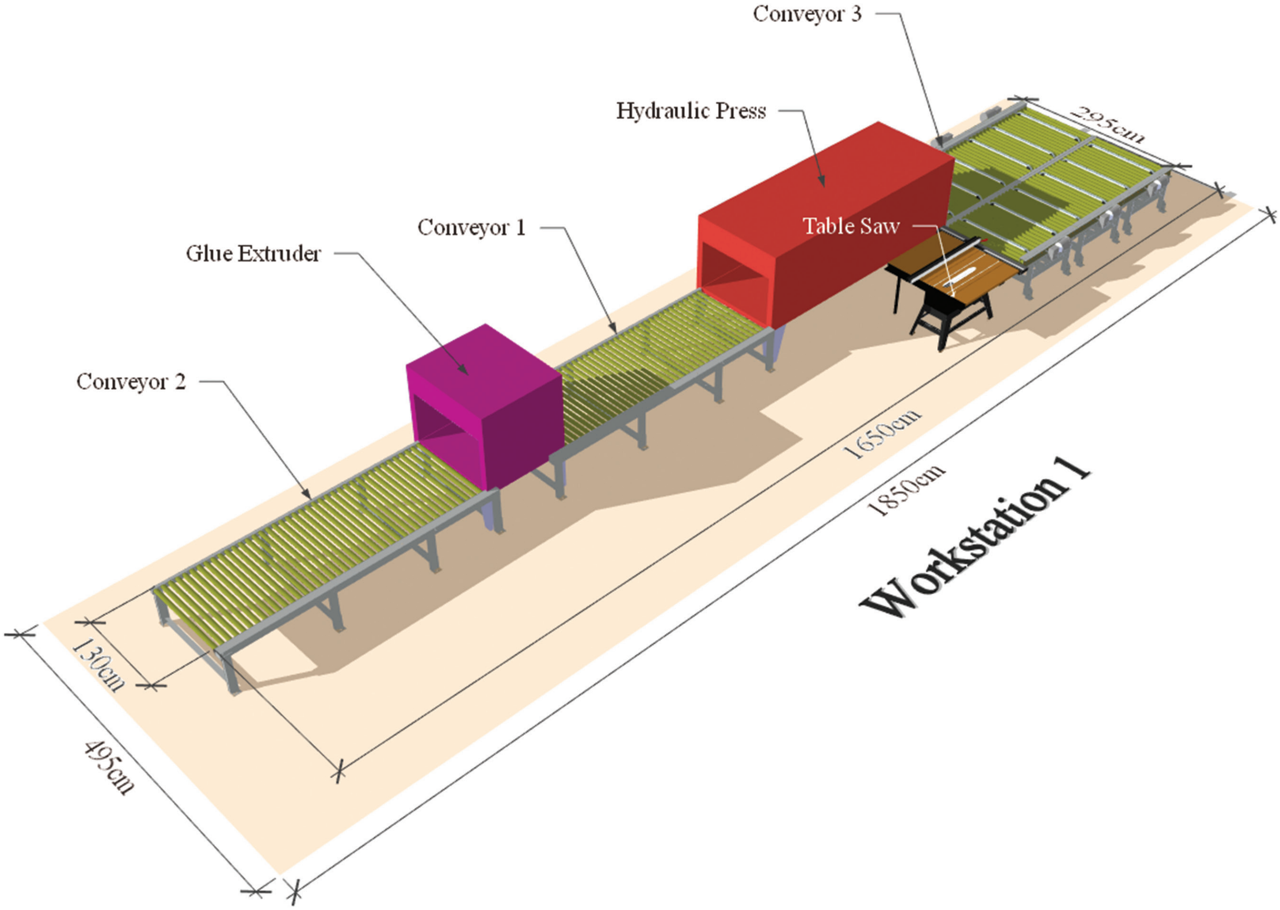

Fig. 6: 3D model of AL-1 consisting of a single assembly line with a low-mid level of automation.

is almost twice as high as the demand rate for a single house construction project, which is typical in most cases. This leads to a large amount of idle time for the workers in the factory. So, the same workers who work in the on-site factory should be utilized to do the SIP assembly to improve this scenario.

Furthermore, it was found that the layouts are created with reasonable production rates; however, the details on spatial requirements could be improved. A bi-directional setup for MgO panel production was used for all assembly lines and provided improved spatial alignment.

The factory shell should be designed as a mobile-container to support the idea that on-site factories could be used in different projects and be scalable depending on the project needs. Using the configuration shown in Figure 6 as a baseline, additional modifications could be made to facilitate the mobility of the assembly line. For example, some of the components from AL-1 could be rearranged so that it could fit into two standard containers. During traveling, one will contain the different assembly line elements while the other could have required materials and supplies. Once on-site, the two containers could be temporarily arranged together to house the assembly line.

5 Conclusion and outlook

This work has identified opportunities arising from the use of an on-site factory when compared to traditional off-site prefabrication, with a focus on using lean principles. The concept of an on-site factory aims to improve productivity, profitability, and sustainability with the intent of reducing waste mainly from transport, rework, and storage by obtaining better outputs from improved inputs. The goal is to design on-site factories that reduce lead times and waste in the production processes while minimizing resource usage in order to provide excellent mobility. This study investigated the on-site prefabrication of panelized wood components. In this study, the factory producing prefabricated elements is mobile and located near or directly on the construction site. Suppliers are not fixed but are chosen locally and vary from project to project.

In particular, the production of MgO SIPs for the construction of affordable houses in communities located in remote areas was used as an example. It is observed that a proper sequencing of work tasks and a comprehensive understanding of interdependencies between cycle time, resources, number of workstations, and spatial constraints are needed to successfully design a production unit such as the proposed MgO SIP on-site factory. Therefore, techniques such as line balancing and resource planning were used to meet the design requirements. By developing simulation models for different customer takt times using CYCLONE, an appropriate baseline for further investigations was created.

Although additional elements should be considered to determine the optimal configuration of on-site factories (e.g., productivity, profitability, influence on the supply chain and the production flow), it has been shown that the concept of an on-site factory is technically feasible. However, the developed conceptual design needs to be tested in a real project as the applied evaluation in this study is based on several assumptions that need to be verified in real conditions. Since the focus is on reducing the number of machines/workers and the area used while continuously improving production rate, our approach is very closely related to the parameters of task duration, the number of workers, machines/workstations, as well as the design of the outer shell. These factors directly influence the line design and, therefore, the production rate. Future work to optimize the proposed assembly line should include a sensitivity analysis to evaluate the impact of task durations, the number of workstations, and workers/machines. In addition, additional research should be done to evaluate the effects of on-site factories on the local economy (i.e., using local labor and materials) and the related social implications that they might have.

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