

The development of a lean six sigma and BIM framework for enhancing off-site manufacturing

Lean six sigma
and BIM
framework

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Abstract

Purpose – This study aims to improve a construction company's overall project delivery by utilising lean six sigma (LSS) methods combined with building information modelling (BIM) to design, modularise and manufacture various building elements in a controlled factory environment off-site.

Design/methodology/approach – A case study in a construction company utilised lean six sigma (LSS) methodology and BIM to identify non-value add waste in the construction process and improve sustainability.

Findings – An Irish-based construction company manufacturing modular pipe racks for the pharmaceutical industry utilised LSS to optimise and standardise their off-site manufacturing (OSM) partners process and leverage BIM to design skids which could be manufactured offsite and transported easily with minimal on-site installation and rework required. Productivity was improved, waste was reduced, less energy was consumed, defects were reduced and the project schedule for completion was reduced.

Research limitations/implications – The case study was carried out on one construction company and one construction product type. Further case studies would ensure more generalisability. However, the implementation was tested on a modular construction company, and the methods used indicate that the generic framework could be applied and customized to any offsite company.

Originality/value – This is one of the few studies on implementing offsite manufacturing (OSM) utilising LSS and BIM in an Irish construction company. The detailed quantitative benefits and cost savings calculations presented as well as the use of the LSM methods and BIM in designing an OSM process can be



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leveraged by other construction organisations to understand the benefits of OSM. This study can help demonstrate how LSS and BIM can aid the construction industry to be more environmentally friendly.

Keywords BIM, OSM, Lean, Skids

Paper type Research paper

1. Introduction

The construction industry is well known for being fundamentally labour oriented, having poor labour productivity, delayed project completion, not adhering to regulatory requirements, low sustainability, inefficient processes and exceeding planned budgeted costs (Bertram *et al.*, 2019). In terms of productivity, it has lagged behind other industries, such as manufacturing, for years. The on-site construction method is costly, not environmentally friendly, highly inefficient and extremely risky, particularly in confined areas where several accidents, near-misses and disasters are common (Ginigaddara *et al.*, 2022). The Global Status Report for Buildings and Construction confirmed that in 2020 alone, the construction industry was responsible for 28% of global energy-related carbon dioxide (CO₂) emissions (United Nations Environment Programme, 2021). The risks with on-site construction can be higher because of the unpredictable working conditions, leading to many unwanted consequences.

Additionally, there is the risk of materials and equipment getting damaged on-site due to inadequate storage space (Spillane *et al.*, 2011). The high number of employees on-site can be highly unproductive, cause significant schedule delays, and lead to a high risk of accidents and injuries. In 2019 alone, 9,335 non-fatal injuries were reported to the Irish Health and Safety Authority, of which approximately 850 happened in the construction industry (Health and Safety Authority, 2020). Moreover, the construction industry was significantly impacted by the Covid-19 pandemic, challenging the construction industry to improve the safety and well-being of its workforce (Pamidimukkala and Kermanshachi, 2021). Production in the construction industry across Europe peaked sharply in June 2020, reaching 21.3% (Eurostat, 2021). Due to this sudden increase in productivity post-Covid-19, organisations have greater challenges and increased risks, with client demands to compensate for lost time on delayed projects.

Despite the construction industry's shortcomings, modern construction methods (MMC), such as off-site manufacturing (OSM), are significantly improving the efficiency of how projects are delivered. Research by Zhang *et al.* (2020) found that applying lean tools to the OSM process created great potential for design optimisation and a more efficient construction process. Lean has been increasingly utilised in the construction industry to improve the productivity and sustainability (Babalola *et al.*, 2019). Several studies have highlighted how construction industry stakeholders are exploring new processes, techniques and practices they see as having the potential to move the industry towards being environmentally friendly, less wasteful and leaner in terms of their project delivery (Dallasega *et al.*, 2018; Lu and Yuan, 2011; Stehn and Höök, 2008).

The case study construction organisation where this research occurred must enhance its construction capabilities to significantly improve its overall project efficiency and reduce the risk of negative impacts on the client or their business. Currently, the organisation has on-site construction and this process.

The main objective of this project was to improve the construction delivery process in OSM by deploying lean six sigma (LSS) and building information modelling (BIM) to reduce waste and improve green practices.

Following the introductory section, Section 2 provides a literature review, and Section 3 discusses the research design and methodology and provides the background of the study.

Section 4 presents analyses of findings. Finally, Section 5 discusses the results, while Section 6 concludes with the practical lessons learned and future research opportunities.

2. Literature review

2.1 Lean in construction

Mahmood *et al.* (2014) describe a construction project as a one-time activity completed within a defined scope, schedule and budget. Construction projects are very capital-intensive and characterised by lengthy, complicated and interconnected processes of planning, design and execution (Rosenfeld, 2009). Consequently, the construction industry has challenges with including non-value-adding activities and processes in its value stream, resulting in inefficiencies, low productivity and sometimes poor quality (Olanrewaju and Abdul-Aziz, 2015). In many ways, inefficiency in the construction industry is budget overruns resulting from delays in meeting project delivery timelines and material wastage (Hussin *et al.*, 2013). The construction industry has embraced Lean to be less wasteful and more sustainable in recent years (Hussin *et al.*, 2013; Lu and Yuan, 2011). While Lean has been extensively embraced in manufacturing (Antony *et al.*, 2018; Duggan *et al.*, 2022; McDermott *et al.*, 2022b; Nelson *et al.*, 2022; Snee, 2010), healthcare (McDermott *et al.*, 2022a) and higher education (Antony, 2014), it has started to emerge more in studies related to construction in the late to early 2000s (Babalola *et al.*, 2019; Feng and Ballard, 2008; Howell and Ballard, 1998).

The work on lean construction started in the early 1990s and focused on two major areas in understanding the application and implementation of production principles in construction. These principles were about understanding construction as a production process and planning and managing the workflow within the construction process (Bertelsen, 2002; Howell and Ballard, 1998; Koskela *et al.*, 2002). For example, “last planner” refers to the project team assigning work to specific performers and ensuring they have the materials, equipment and information to complete their assignments (Howell and Ballard, 1998).

Benefits of Lean in construction have been shown to achieve reduced construction times and costs, increased productivity, improved quality and increased customer value and satisfaction for customers; reduced consumption of resources, water and energy; reduction of emissions of particulates, noise and waste; improved health and safety at work and communication (Carvajal-Arango *et al.*, 2019).

Research by Zhang *et al.* (2016) also found positive results when lean tools were applied for optimising work schedules, managing the allocation of materials and equipment, production just-in-time (JIT) and planning congestion-free work environments. However, lean tools are typically only introduced into the construction industry to improve project management, specifically to reduce the schedule duration and costs.

The construction industry has recently embraced the lean and green agenda (Garza-Reyes, 2015). Green building, for example, is one of the measures put forward to mitigate the significant impacts of the building stock on the environment, society and economy (Zuo and Zhao, 2014). The construction industry has embraced lean principles and green initiatives, realising the interlinkages between the two agendas (Ahuja *et al.*, 2017). The industry recognises waste reduction as the common characteristic of both philosophies, with “waste” being defined differently (Carvajal-Arango *et al.*, 2019). In the case of lean construction, the seven types of lean waste are discussed (Howell and Ballard, 1998). In contrast, in the case of sustainable construction, waste refers to material and energy wastes resulting from inefficient use of resources and excessive consumption of materials and energy, emissions, pollution and bad working conditions (Verrier *et al.*, 2016). Carvajal-Arango *et al.* (2019), in a study on lean and sustainability in construction, found that of 56 lean practices, the majority led to positive effects on economic and environmental aspects.

2.2 Lean and sustainable construction

OSM and modularisation are MMC comprising designing, manufacturing and assembling various building elements off-site in a controlled factory environment before transporting them to the site (Goodier and Gibb, 2007). This OSM construction method enables a faster on-site build with a much higher finish grade than the stick build process. However, OSM has attracted limited attention from researchers and industry stakeholders, particularly in developing countries (Durdyev and Ismail, 2019; Sahin *et al.*, 2018). OSM and modularisation are similar techniques, equating to assemblies and subassemblies manufactured in a controlled off-site environment (da Rocha and Kemmer, 2018). Peltokorpi *et al.* (2018) describe OSM and modularisation as playing major roles in the standardisation and industrialisation of construction processes, resulting in increased client value and more effective processes when utilising the workforce and their time. Sawhney *et al.* (2020) state that the construction industry is on the cusp of a badly needed transformation with the pervasive use of lean tools, smart technology and OSM.

One way to encourage the adoption of prefabrication and OSM techniques and modular construction is to improve efficiency by utilising lean, which makes the technology more attractive to construction companies (Goh and Goh, 2019). Lean has been widely applied to improve the productivity and efficiency of construction projects, while modelling and simulation enhance Lean benefits by allowing the design and benefits to be analysed quantitatively before implementation (Goh and Goh, 2019; Matthew, 2017). However, the main challenge of lean OSM construction is related to the continuous production flow at the off-site factory. At the construction site, the flow is turbulent and unpredictable, with issues such as changes in customer demand or site conditions delaying customer orders (Mostafa *et al.*, 2014).

2.3 Lean and digital technologies in construction

Increasingly, studies demonstrate BIM as an enabler for Lean construction (Peiris *et al.*, 2022). Studies have demonstrated the application of lean construction and advanced digital technologies, particularly BIM, to improve project quality, productivity and performance (Aziz and Zainon, 2022). Technologies such as BIM as an innovative digital technology, point cloud scanning and virtual/augmented reality (VR/AR) installation equipment have a major impact on how construction projects are delivered (Enshassi *et al.*, 2018).

BIM enables the creation of information-rich and accurate simulation models. According to Eldeep *et al.* (2022), utilising BIM as a lean tool reduces owner-initiated changes and design errors/omissions by more than 80% due to BIM's ability to detect mistakes or omissions in the pre-construction stage. Utilising BIM helps create planning for Lean principles of pull, improving flow and adding value (Bhattacharya and Mathur, 2022).

Advanced technologies, particularly BIM, are also contributing to green building development (Zuo and Zhao, 2014). Many researchers have also asserted a strong synergy between BIM, lean and green by confirming the lean and green benefits achieved through BIM implementation on construction projects (Ahuja *et al.*, 2014, 2017). BIM enables lower additional building costs, adoption of passive design strategies and re-use of materials to reduce the environmental impacts of construction activities, perform energy analysis and design for optimal energy consumption (Rahman *et al.*, 2013).

2.4 Conclusion

Having reviewed the literature, it is evident that lean in construction has evolved in recent years and that the literature is related to the topic. Lean has been shown to have many benefits for construction, such as improving the quality of builds, reducing defects and rework, preventing material wastes, cost reduction and improving adherence to schedule.

However, there are fewer practical applications in the literature related to lean in construction than in manufacturing. Construction differs from most manufacturing functions as it is a mixture of providing a service and a product. Project management methodology, budgeting and scheduling are integral to managing construction projects, and lean must be merged with project management methodology to deliver successful projects.

3. Methodology

3.1 Background to the case study organisation

A case study approach is most suitable for a study where work is scarce on the subject (Yin, 2011), as there is literature on maximising benefits from Lean and sustainable construction case studies (Babalola *et al.*, 2019). Moreover, it further helps to better understand the context and setting to understand the phenomenon under study (Yin, 2016).

The chosen method for conducting this research was a case study utilising LSS within an Irish-based construction company. The company was manufacturing production equipment using “skids”. A skid is a common steel-framed platform-like structure over which heavy equipment is placed to facilitate easy movement and storage. It is constructed from I-beams, angles or channels and used as a shipping and support platform for various types of equipment. Typically, the company manufactures modular pipe racks for the pharmaceutical industry (Plate 1).

The off-site element of the construction was completing the welding on scaffolds. Skid systems are custom manufactured by fabricators as per the client’s requirements. Once assembled, the equipment can be permanently mounted on the skid with all process controls in one spot (Trenchless, 2022). Once installed, the skid can be easily transported to the final site location, where the process can be quickly started.

3.2 DMAIC methodology

The project was achieved by adopting a LSS methodology of define, measure, analyse, improve and control (DMAIC) and by researching, applying and analysing various lean tools.

The research question will be explored through the use of the DMAIC method to:

- Define the problem or research question via the use of supplier, inputs, processes, outputs, customer (SIPOC) and voice of the customer (VOC);
- Quantitative financial, productivity, timeliness, qualitative quality and safety data in relation to on-site manufacturing costs and schedules will be collected through



Source: Authors’ own

Plate 1.
Modular pipe racks in
skids

interaction with relevant stakeholders, creating a value stream map (VSM) and brainstorming with stakeholders;

- Problems will be analysed using analyse tools such as the cause and effect and five whys to aid in finding a root cause;
- Kaizen and a future VSM were utilised to identify and drive improvements to the root causes identified in the analysis phase; and
- Control – actions implemented were monitored, and “after” data was collected in relation to productivity, quality, safety, waste and timeliness and compared with the “before” project measures.

DMAIC was the chosen methodology because it aligned with the organisation’s existing strategy for problem-solving and continuous process improvement. Lean complements six sigma, as lean drives waste reduction and six sigma drives variation reduction (George, 2002). A DMAIC matrix was developed (Table 1), identifying the various tools and techniques utilised throughout the DMAIC project lifecycle.

An important element of research is benchmarking and observation. At this point in the research, OSM facilities were visited to observe the OSM process in operation.

4. Results

The study’s results are outlined below with examples of how the DMAIC process was followed, and the following tools, as referenced in Table 1, are demonstrated. In addition, the following are presented: 1. SIPOC, 2. VOC, 3. current VSM, 4. wastage analysis, 5. cause and effect and 6. future VSM, including examples of JIT and improvements from Kaizen.

4.1 DMAIC process results

4.1.1 *Defining the problem.* Firstly, a SIPOC diagram was drawn to understand the internal and external customer requirements (Figure 1).

A VOC analysis was subsequently utilised to capture the customer requirements as outlined in Table 2.

The construction company under study decided that based on the SIPOC and VOC analysis, there was an opportunity to utilise DMAIC to optimise the OSM process and eliminate on-site construction. The opportunity for OSM utilising skids was identified as having the potential for large savings but also for the benefits of deploying lean and green practices during the manufacturing process. As mentioned, a skid is a process scope within a frame that allows the processing unit to be easily transported (Lusardi, 2019). A skid is a system that comprises main equipment such as pumps, heat exchangers, filters and vessels. It is assembled with interconnecting pipework with inline items such as control valves, isolation valves and instruments to control and monitor the skid system. A production skid is a frame within which equipment is mounted and used for production purposes (Figure 2). Skid designs can vary, but the aim is to create a modular package easily slotted into an area. A process skid will incorporate components for production into the skid, such as a vessel, agitator, pumps and valves, heat exchangers and control panel for in situ adjustments (Flexachem, 2023).

After an extensive design process which involved the development of a BIM 3D model (Figure 3), piping and instrument drawings (P&IDs) and isometric drawings of the OSM design were issued to the client (a pharmaceutical organisation) by the construction organisation to approve the design for modular pipe racks. A piping and instrumentation diagram, or P&ID, shows a physical process flow’s piping and related components

DMAIC	Deliverables	Tools and techniques	Purpose
<u>D</u> efine	<p>Establish objectives Define the problem Formulate a plan Clarify the reasons Stakeholder approval Develop implementation and communication plan</p>	<p>Brainstorm</p> <p>Supplier, inputs, process, outputs, customer diagram (SIPOC) Voice of the customer (VOC) Current state value stream map (VSM)</p>	<p>Generate ideas Share knowledge Problem-solving Strategize Establish boundaries Identify inputs and outputs Develop an understanding of the process Identify key drivers of client satisfaction Establish the current state</p>
<u>M</u> easure	<p>Assess the current state of design, OSM and project delivery</p>	<p>Ishikawa/6M's</p>	<p>Focus on the team Investigate root causes Problem-solving Analyse cause and effects Determine the root cause of any problems. Find solutions, analyse and eliminate Work should be standardised before it can be improved Establish precise procedures Establish effective methods Prevent errors</p>
<u>A</u> nalyse	<p>Analyse the current state to identify improvement areas and areas for eliminating waste</p>	<p>5 Whys Standard work</p>	<p>Sort, set, shine, standardise and sustain Ensure that work areas are kept clean Ensuring employee safety Remove non-value add, eliminate waste, improve workflow and measure improvements</p>
<u>I</u> mprove	<p>Implement lean tools and techniques</p>	<p>Poka Yoke 5S Future state VSM Kaizen rapid improvement event (RIE) Just in time (JIT) Data analysis VSM future state map</p>	<p>Set aside other jobs to focus on working together to develop, test and implement the lean tools over 2 days Ensure the assembly is delivered only when required Check progress Verify improvements Re-measure future state until desired objectives are achieved</p>
<u>C</u> ontrol	<p>Verify improvements QC inspection/sign off. Monthly quality audits</p>		

Source: Authors' own

Table 1.
DMAIC project steps

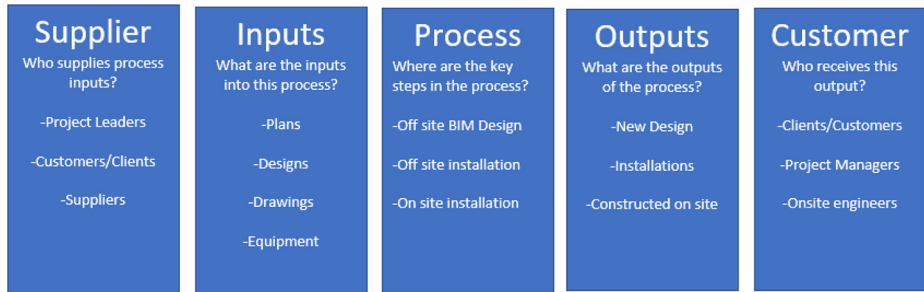


Figure 1.
SIPOC diagram

Source: Authors' own

Voice of the customer matrix		
Customer requirements (What are they saying?)	Priority (What is the priority?)	Customer requirement (What is the measurable target?)
Project delivered on time	Timeliness	On schedule
Project delivered correctly/right	Quality	Issue free installation
Project delivered on budget	Financial	Reduced cost
Project site installation (on schedule)	Productivity	No over runs on site
Project delivered with no safety issues	Safety	No safety incidents

Table 2.
VOC analysis

Source: Authors' own

(Lucidchart, 2022). These types of drawings are most commonly used in the engineering field. For example, BIM 3D and P&ID are used in conjunction with lean methodology in the construction industry to provide a visual of the process, aid sequencing and identify waste (Al-Saeed *et al.*, 2020; Tauriainen *et al.*, 2016; Tommelein, 1998).

4.1.2 Measure and analysis. The main objective of the measure phase was to establish the current state VSM of the OSM production process and identify areas for the removal of waste and for improving efficiency. To achieve this, several “go to the Gemba” steps and observations of the process in operation were held. The output of these workshops was the development of the current-state VSM (Figure 4), which included the full value stream from client order to final delivery to the site.

The analysis phase consisted of analysing and understanding the inefficiencies and the root causes of the inefficiencies in the OSM process. Using the cause and effect analysis and five whys enabled the stakeholders to solve the problem (Figure 5 and Table 3).

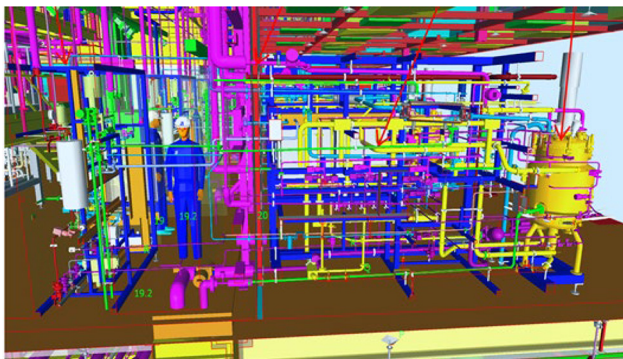
The aforementioned tools and analysis of the current state of the VSM helped identify several areas (Table 4) that would benefit from implementing lean tools and techniques throughout the various process steps. Wastage or non-value add waste analysis was utilised to identify various Muda, Mura and Muri types. The lean eight wastes acronym of TIM WOODS was used to classify the wastes into **T**ransport, **I**nventory, **M**otion, **W**aiting, **O**verprocessing, **O**verproduction, **D**efects or under-utilisation of employee **S**killsets as applicable.

After the analysis, the future state map was drawn up in Figure 6. Following the completion of the future state map, a milestone implementation plan was developed, capturing the major milestones and how and when the future state VSM would be



Source: Authors' own

Figure 2.
A production skid



Source: Authors' own

Figure 3.
BIM 3D skid model
shot

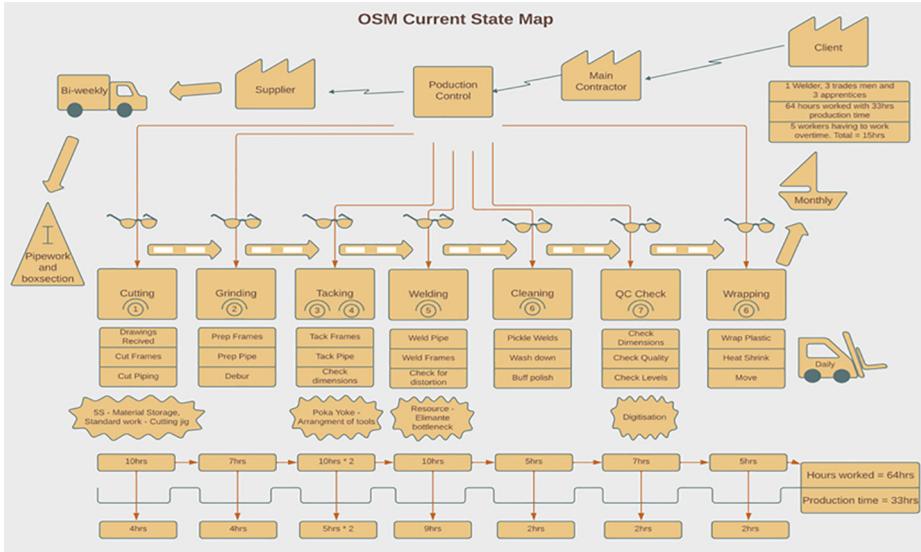


Figure 4.
Current state VSM

Source: Authors' own

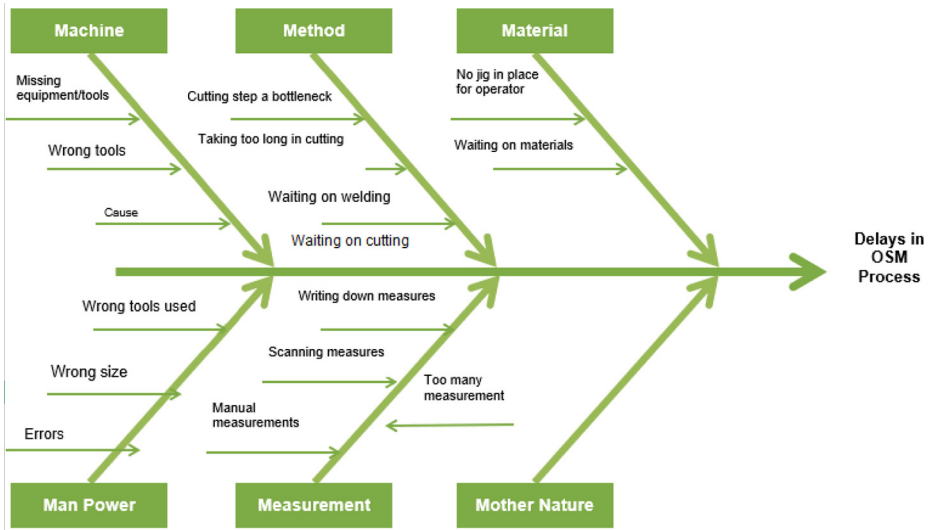


Figure 5.
Cause and effect diagram

Source: Authors' own

achieved. The future VSM was designed to reduce operator overtime (Muri), increase the production time and lower the hours worked at each step, create flow, eliminate Muda and make the process mistake-proof where possible. The improvements taken are highlighted in [Table 4](#).

<i>Fine whys</i>					
Why?	Why 1	Why 2	Why 3	Why 4	Why 5
	Because	Because	Because	Because	Because
Why is the cutting process taking so long?	Because there is missing equipment	Why is there missing equipment?	Because equipment is missing and cannot be found	Why is equipment missing and cannot be found?	Because there is no designated storage/organisation or 5S/housekeeping
		Why is there missing equipment?	Because there is no designated storage/organisation or 5S/housekeeping	Why is there no designated storage/equipment?	Because there are no designated areas or equipment for the area
		Why is there missing equipment?	Because there is no designated storage/organisation or 5S/housekeeping	Why is there no designated storage/equipment?	Because there is no designated storage/organisation or 5S/housekeeping

Source: Authors' own

Table 3.
Five whys example

Process steps	Examples of waste	Causes	Corrective actions Generated from the Kaizen
1. Cutting	<i>Muri</i> : The operator in the cutting step was working a 10-h shift to meet the demand of the other process steps while achieving just 4 h of production time <i>Overprocessing</i> : No jig in place operator measuring material for every cut	Lack of material organisation and storage Equipment not set up for standardised work	Standard work and an extra operator were introduced to improve the flow 5S system set up with equipment
2. Grinding	<i>Waiting</i> : Significant production time was lost due to waiting for material from the cutting step	A bottleneck in cutting step	Standard work was implemented, and an extra operator in cutting reduced the bottleneck
3. Tacking	<i>Waiting/motion/transport</i> : Lost production time due to lack of tools -missing jigs and clamps <i>Defects</i> : Wrong tools used	Lack of correct equipment Operator error	5S system set up with new equipment. Poke Yoke introduced
4. Welding	<i>Overburdened</i> : welder 10-h shifts High <i>defects</i> – scrap levels	Bottleneck More resources required	Standard work was implemented, and a new welder was added to improve the flow Poke Yoke introduced
5. Cleaning	<i>Waiting</i> : on welding	Bottleneck from the previous station	Eliminated with the new welder
6. QC check	<i>Overprocessing</i> – manual steps printing, writing, scanning	Not automated	A new process with standard work and an Automated scanner introduced
7. Wrapping	<i>Waiting</i> on welding	Bottleneck	Eliminated with a new welder. Merged with QC check
8. Shipping	<i>Transport/waiting/inventory</i> of skids	Outgoing inventory build-up/no space/delays in getting on site	A just in time (JIT) daily delivery of skids was implemented (just as required on site)

Table 4.
Wastage analysis
(analysis of process
waste from current
and future VSM)

Source: Authors' own

4.1.3 Improve. In tangent with the future VSM and brainstorming of solutions, a Kaizen rapid improvement event (RIE) was held. The actions generated from the Kaizen are outlined briefly in [Table 4](#) and expanded below.

The two-day Kaizen RIE commenced with a full 5S clean-up of the off-site facility. In addition, other potential improvements highlighted as part of the analyse phase and highlighted in the future VSM were implemented, such as 5S, Poke Yoke, Standard work and JIT. Furthermore, a just-in-time (JIT) delivery designed as part of the future VSM process aided the delivery of skids and super skids for final installation – delivered only as they were required on site. Thus, no delays were incurred, which are often caused when deliveries must be stored in a laydown or staging area before installation.

4.1.4 Control and savings. The project's initial objective was to reduce waste in the construction process and aim to meet the VOC requirements of improved productivity, quality, timeliness and financial and safety measures.

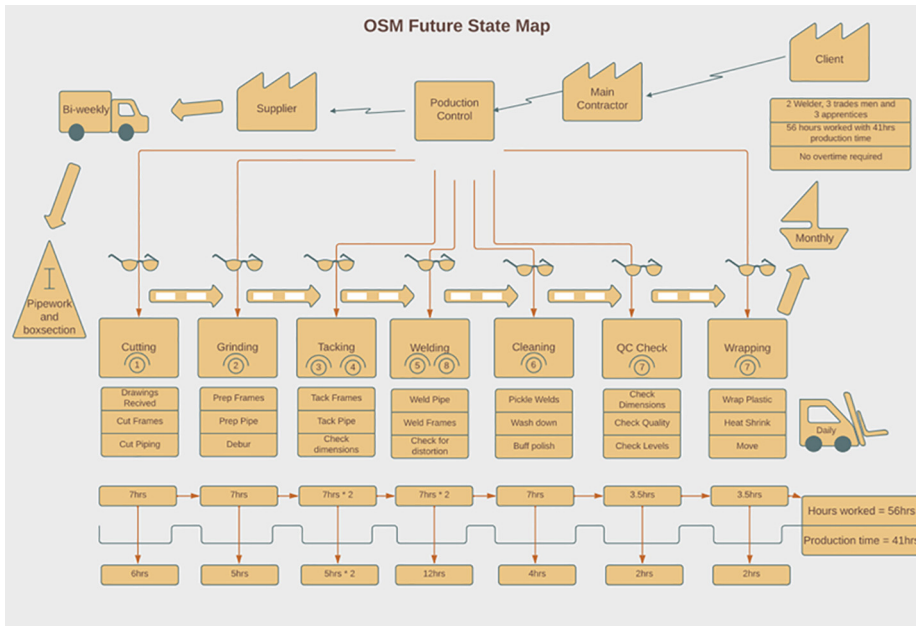


Figure 6.
Future state VSM

Source: Authors' own

The project met all of the aforementioned objectives, as outlined below.

Implementing the lean tools in the OSM process increased production time by 8 h whilst reducing the work hours required by 8 h, resulting in a 16-h per week production time-saving. The average employee cost calculated at €40ph over the 30 weeks meant a total saving of €19,220.00 was achieved (Table 5).

Thus, this enabled productivity, timeliness and financial benefits, providing benefits to the construction organisation and the client.

The contractor submitted progress reports weekly for review to ensure the targeted project milestones were achieved per the project schedule. This project also implemented a quality and lean reward scheme, whereby awards were presented regularly for process improvement suggestions, lean tools and excellent quality standard work. Recognition and reward are critical success factors for effective LSS implementation (McDermott *et al.*, 2022b).

VSM	Current state VSM vs future state VSM		Saving
	Hours worked	Production hours	
Current	64	33	
Future	56	41	
-8 h worked		+8 production time	16 h pw
@ €40ph = €320 saving		@ €40ph = €320 saving	€640pw
Project duration 30 weeks		@ €640pw saving	Total saved €19,220.00

Source: Authors' own

Table 5.
Savings

4.2 Comparison of off-site manufacturing savings with on-site construction

As is typical in the construction industry, this was a customised project. The significance of the project customisation is that it is impossible to compare the OSM process accurately with the traditional on-site stick build process (as no one project is ever the same).

To complete the analysis, the project costings were reviewed and compared with previously completed similar projects, and estimates were made of the cost savings. **Table 6** shows a high-level overall costing estimation for the project. To calculate the savings, the following costs were collected: 1. The design cost of the OSM versus the on-site construction; and 2. The building cost of the OSM versus the on-site construction.

While the design cost for OSM was an additional €30,000, a saving of €320,000 was achieved by completing the work off-site. This resulted in an estimated project cost savings of €179,220.00 (OSM + lean and BIM framework).

Financial benefits are often viewed as the most powerful influence on building methods. However, the motivation for this project was also the recognition of the link between OSM and the increase in employee health and well-being, along with the environmental and economic impact. In **Table 7**, the environmental, social and economic statistics show a high-level estimation of the overall improvements.

Eight different measures were calculated related to traffic, energy used in manufacturing and on-site installation, amount of waste material, energy used, schedule length, cash flow, rework hours and on-time schedule.

The project aimed to reduce process and environmental waste and deliver the project on schedule and within budget without any adverse quality or safety issues. All key performance metrics were met and exceeded. There were no unanticipated or adverse results of the project.

Table 6.
Savings from OSM
versus on-site project

Costs	OSM	On-site	% Savings (=/-)
Design cost	€90,000	€60,000	-50% (-30,000)
Build cost	€250,000	€440,000	+43% (+190,000)
Total	€340,000	€500,000	+40% (+160,000)
Total saving with OSM		€320,000	= 32% savings overall

Source: Authors' own

Table 7.
Environment, social
and economic
statistics

Category	OSM % improvement
Less traffic	≥50
Less energy-used-on-site	≥75
Less waste	≥60
Less energy-in-use	≥15
Health and safety	≥85
Shorter schedule	≥50
Increased cash flow	Substantial
Fewer punches/snags (less-re-work)	≥90

Source: Authors' own

4.3 Delivery of skids to on-site construction location

All elements within the skids were maximised to minimise follow-on work by on-site contractors, thus eliminating material wastage, non-value add work and rework time. OSM, utilising Lean and BIM, delivered a safe process and a completed project. All project specifications were met, and thus, there was a smooth transition through the commissioning and start-up of the new manufacturing plant. A working environment was created where integrated contractors could maximise productivity based on good safety practices, schedule compliance and quality management to meet mechanical completion. Ultimately, the project was also a financial success with the delivery of an affordable global solution for the construction process, and density challenges within the building were overcome by removing on-site work hours off-site, which saved high costs.

The main barriers or unanticipated problems encountered were the complexity of the design, the difficulties with transportation logistics and the required high level of engineering. The larger super skids and even some standard-sized skids required specific transportation considerations, which could have resulted in slight delivery delays and incurred additional costs, adding to the complexity. Detailed road surveys at the planning stage proved to be a key factor in ensuring effective project coordination and on-time delivery.

Even though the cost was considerably less for the OSM process, it required the onboarding of a company with an established manufacturing facility. The OSM process also required suppliers, contractors, designers and engineers who were experienced in and knowledgeable about the OSM process for construction. The lack of such experts in Ireland is a considerable constraint for implementing this process on a larger scale.

Both the research and the application of the research indicate that the sustainability of the construction industry is highly dependent on using the OSM process.

5. Discussion

The main research objective of this study was to improve the construction delivery process in OSM by deploying LSS and BIM methods to reduce waste and improve lean and green practices.

Firstly, the research demonstrates that for the construction industry to reach the productivity levels of other industries, they must consider the OSM process where possible during the building design process (Durdyev and Ismail, 2019). While there were increased design costs in developing the OSM project design for this project, the design efforts and plan delivered an end saving of 32% overall. Furthermore, the research also demonstrates that by utilising a lean framework with BIM for the OSM process in the design phase, the construction process can be significantly enhanced, wasteful activities can be removed and efficiency can be maximised. This finding is consistent with much of the literature on integrating lean, green and BIM in construction (Ahuja *et al.*, 2014; Tauriainen *et al.*, 2016). OSM reduced the personnel required for on-site construction and increased site productivity. BIM modelling aided skid and super skid module construction on the OSM site parallel to the on-site construction, reducing the overall project schedule duration. BIM also aided the designing and fabrication of key process elements to a consistent and repeatable level so that the skid modules could be delivered and assembled in the shortest time possible using a last planner system (Ahuja *et al.*, 2014; Al-Saeed *et al.*, 2020; Eldeep *et al.*, 2022; Tauriainen *et al.*, 2016).

All elements within the skids were maximised to minimise follow-on work by on-site contractors, thus eliminating material wastage, non-value add work and rework time. OSM, utilising lean and BIM, delivered a safe process and a project completed with zero safety incidents (Hu and Chong, 2021). All project specifications were met, and thus, there was a smooth transition through the commissioning and start-up of the new manufacturing plant. A working environment was created where integrated contractors could maximise

productivity based on good safety practices, schedule compliance and quality management to meet mechanical completion. Ultimately, the project was also a financial success with the delivery of an affordable global solution for the construction process, and density challenges within the building were overcome by removing on-site work hours off-site, which saved significant costs (Taurainen *et al.*, 2016).

Furthermore, a just-in-time (JIT) delivery designed as part of the future VSM process aided the delivery of skids and super skids for final installation – delivered only as they were required on site. Thus, no delays were incurred, which are often caused when deliveries must be stored in a laydown or staging area before installation. A well-designed JIT system with OSM is integral to the success of on-site construction and reducing environmental waste (Hu and Chong, 2021).

5.1 Challenges to the off-site manufacturing process

With the OSM and modularisation process, some challenges required considerable coordination, collaboration and planning. This was similar to findings described by O'Connor *et al.* (2016), which found that the project planning process for OSM and modular construction differed by approximately 37% from the project planning of traditional construction methods. Many sectors, including the construction sector, are still adopting digital technologies and their integration with lean. This study demonstrated that there is a synergistic relationship between lean and digital technologies and aligns with literature related to their combined use (Antony *et al.*, 2021, 2022; Tortorella and Fettermann, 2018).

6. Conclusion

This research demonstrates how OSM can be designed and improved by utilising LSS integrated with BIM modelling to design a project that increases productivity, quality and sustainability. The study met its objective to improve the construction delivery process in OSM by deploying LSS and BIM to reduce waste and improve green practices.

A limitation of this study is that it was only carried out on one organisation as a case study, but the results could be leveraged and generalised compared to on-site construction.

The implications of this study are both managerial and theoretical. The obtained results contribute to a body of knowledge on lean construction and provide practical knowledge for project professionals to adopt and implement lean construction.

From a managerial viewpoint, this study can be benchmarked by other construction organisations. The research introduces: 1. means for improving OSM processes specifically; and 2. measures for implementing digitalisation in off-site construction by positioning BIM as the key technology and lean principles to add value and reduce waste. Furthermore, industries can see evidence that the OSM process can be highly improved and yield significant gains by deploying a lean approach and implementing lean tools and techniques.

The theoretical implications of the study are that it serves as a case study for academics to demonstrate how LSS can be applied in a construction setting and thus demonstrates how LSS continues to have applicability across all sectors.

The main conclusions and recommendations are summarised as follows:

- The appraisal of the literature and the research indicates that, furthermore, in addition to the numerous benefits inherent in the OSM process, there are also challenges that require strategic planning during the project's design stage.
- OSM is a sustainable process for achieving social equality, economic prosperity and environmental quality.

- To deliver operational excellence throughout the project lifecycle, construction companies must consider developing a lean or LSS framework and integrating it with digital technologies to enhance their OSM capabilities.
- While traditional methods and approaches to construction will always be necessary, organisations must adopt new techniques to improve continuously. The implementation of lean methodologies in the OSM process has huge potential in relation to the reduction of waste, time and materials.

Future research opportunities exist to carry out more case studies in the organisation on how the LSS methods and BIM are deployed and developed for future projects, as there is much potential to maintain and enhance the benefits achieved. In addition, the researchers would also like to further research the deployment of the more developing digital technologies associated with LSS methods, such as BIM, 3D modelling, VR and AR, in the construction industry.

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