

1 **Process waste analysis for offsite production methods for house construction – A case study of**
2 **factory wall panel production**

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9 **Abstract**

10 There is a growing interest in the use of offsite manufacturing (OSM) in the construction industry
11 disregarding criticisms of lacking real improvement from some offsite approaches adopted by
12 housebuilders as compared to their onsite counterparts. Quantitative performance measures from
13 previous studies are based on conventional onsite methods, with little attention paid to the performance
14 and process improvements derived from various OSM methods.

15 In response, a case study was conducted based on two OSM methods using standardized and non-
16 standardized processes for the production stage of a factory-manufactured wall panel. Value system
17 analysis and root cause analysis using the 5Whys method was adopted to evaluate possible
18 improvements in terms of process waste. The study reveals that OSM production methods that replicate
19 site arrangements and activities involving significant manual tasks do not necessarily provide a marked
20 improvement from the conventional onsite method. Thus, there is a need to re-evaluate the processes
21 involved to eliminate such embedded process wastes as non-value-added time and cost and to consider
22 automating critical activities. The analysis adopted in the case study provides measurable evidence of

23 the performance gained from having a structured workflow over a non-structured workflow. It also
24 reveals how process wastes are generated in the production process of wall panels offsite.

25 **Keywords:** lean manufacturing; offsite manufacturing; process waste; process modeling; root cause
26 analysis, 5whys.

27 **Introduction**

28 Offsite manufacturing (OSM) methods are becoming increasingly popular in the housing and
29 construction sectors. OSM methods provide opportunities to exploit the lean production system in
30 manufacturing and achieve “lean construction” – a concept to reduce and eliminate wastes (including
31 both physical and process wastes) in the construction processes (Howell 1999, Dave *et al.* 2013). The
32 benefits of OSM have been widely studied, including reduced construction time, health and safety
33 risks, environmental impact and whole-life cost, increased quality, increased predictability,
34 productivity, whole-life performance, and profitability (Blismas *et al.* 2006, Pan *et al.* 2008, Pan and
35 Goodier 2012). According to Pasquire and Connolly (2002), these benefits are the outcome of process
36 improvements from implementing lean manufacturing in a factory environment. However, although
37 most of the benefits are linked to process improvements at the production phase, little attention has
38 been paid to how the choice production method may improve or reduce their acquisition.

39 It is reported that offsite manufacturing companies are inheriting lean manufacturing approaches in
40 their processes to minimize cost (Zhang *et al.* 2020) through optimization of the design and
41 construction processes by taking into account lean principles (Gbadamosi *et al.* 2019). This sometimes
42 necessitates various levels of automation to be implemented in OSM workflow to improve efficiency
43 and productivity (Zhang *et al.* 2016), including the introduction of robotic systems in production,
44 transportation, and assembly. While the offsite approach is continuously developing and advancing,
45 the process benefits from lean implementation may not be fully realized depending on the approaches
46 to production adopted due to practices in OSM processes being similar to conventional onsite methods

47 (Zhang *et al.* 2020). For instance, researchers (Pasquire and Connolly 2002, Zhang *et al.* 2020) have
48 reported non-standardized practices in OSM processes and emphasized the need to avoid repeating
49 ‘onsite practices under a roof’. This is because, compared to the traditional onsite method, OSM needs
50 to be taken as a process-oriented approach, where the benefits of standardization and repetitions can
51 be applied (Fernández-solís 2009). This implies the need for offsite manufacturers to take a process
52 view to establish and quantify improvements in their product development practices and to make
53 informed decisions on their choice of methods.

54 Several tools are available to support the analysis of processes. Of these, business process modeling
55 (BPM) is used in various industries, such as Engineering, IT, and software development and
56 Manufacturing (Nurcan *et al.* 2005, Doomun and Jungum 2008, Shi *et al.* 2008). This aims to eliminate
57 functional boundaries – focusing on how things are done (the process) rather than what is done (the
58 product) (Barber *et al.* 2003). BPM is well recognized for its ability to facilitate a shared understanding
59 of the process by enabling an understanding and analysis of the product/service development process
60 of an organization (Aguilar-Savén 2004, Akasah *et al.* 2010). It enables the modeling of actual (AS-
61 IS) and proposed (TO-BE) processes in order to identify gaps in current practices and ways to address
62 them (Doomun and Jungum 2008). The TO-BE model mainly involves a computer-simulated
63 workflow, which provides anticipated results prior to investment, which in turn reduces the scheduling
64 and financial risks of an organization (Nikakhtar *et al.* 2015).

65 This study evaluates the alternative production methods of OSM by quantifying and analyzing the
66 process wastes embedded in these methods in practice, based on the activities involved in a typical
67 factory housebuilding process. Applying a case study approach containing two units of analysis (i.e.,
68 two different OSM production methods representing the AS-IS and TO-BE processes), the root causes
69 of eight categories of the process waste from the two alternative production methods are analyzed
70 using business process modeling (BPM). The study contributes to presenting quantitative evidence of

71 the performance of structured and non-structured OSM methods in terms of process waste, to support
72 informed production workflow design decision making.

73 **Process benefit realization of OSM method of construction**

74 Traditional construction activities are labor-intensive by nature with mainly the performance of
75 workers as a critical factor affecting productivity. OSM attempts to streamline and automate
76 production in a controlled factory environment. It adopts a lean manufacturing approach to optimize
77 production performance and efficiency (Vernikos *et al.* 2013, Gbadamosi *et al.* 2019). The benefits of
78 OSM can be grouped into five types: process, product, organizational, marketing, and
79 social/environmental benefits. The key aspects and examples of benefits for each type as identified in
80 past literature are summarised in Table 1. These benefits may explain why the construction industries
81 in many countries are being encouraged to standardize and automate the production processes through
82 the application of OSM.

83 The OSM workflow involves a variety of concurrent and iterative activities, structured production
84 sequences, and various levels of automation. It is significantly different from the activities,
85 construction sequence, and use of plant and machinery for conventional linear onsite workflow (Zhang
86 *et al.* 2020). OSM has been classified with respect to the product, process, and people (Gibb 1999, Arif
87 and Egbu 2010, Quale *et al.* 2012, Ayinla *et al.* 2019), which provides the necessary elements for
88 understanding the different systems in OSM. Although the various benefits are well recognized, the
89 adoption of OSM in practice has been slow. The approaches for evaluating alternative production
90 methods are not well understood. Also, there has been no quantification of the benefits of different
91 types of OSM methods through systematic evaluation.

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95 **Table 1:** Categories of OSM benefits

Benefits	Key aspects	Example	Reference
Process benefits	Time	Improved delivery in terms of better logistics due to fewer trades on site. Delivery speed of up to 50-60% less than conventional methods.	(Miles and Whitehouse 2013).
	Productivity	Standardisation and economy of scale. Improved working environment and less distractions. Incorporation of some sort of automation.	(Pasquire and Connolly 2002, Gibb and Isack 2003, Eastman and Sacks 2008, Pan and Sidwell 2011, Quale <i>et al.</i> 2012)
	Safety	Increased occupational health and safety by improved working conditions. Dry construction process.	(Pasquire and Connolly 2002, Bertelsen 2005, Höök and Stehn 2008, Lawson <i>et al.</i> 2010, Kolo <i>et al.</i> 2014).
	Performance	Lean production approach: standardising processes that leads to formalised procedures, specialisation and a controlled production process.	(Pasquire and Connolly 2002).
Product benefits	Quality	Better quality products resulting from improved working conditions and quality management.	(Gorgolewski 2005, Larsson and Simonsson 2012).
	Cost	Lower unit cost of components as a result of savings from mass production and standardisation. Increased cost certainty.	(Ozaki 2003),
Organisational benefits	Management	Project management and programme improvements also termed “the structural factor”.	(Zakaria <i>et al.</i> 2018).
Marketing benefits	Client satisfaction	Client satisfaction as a result of mass customisation – that allows customers to interact with OSM suppliers and building relationships in the exchange.	(Cheung <i>et al.</i> 2016).
Social/environmental benefits	Waste	Waste reduction as OSM presents the advantage of executing projects with minimal amount of waste generation.	(Höök and Stehn 2008, Arif and Egbu 2010, Quale <i>et al.</i> 2012, Mao <i>et al.</i> 2013, Shamsuddin <i>et al.</i> 2013).
	Impact	Environmental impact reduction.	(Gorgolewski 2005, Nahmens and Ikuma 2012).
	Health	Improved health and safety practices.	(Pan and Sidwell 2011).

96 According to Lawson *et al.* (2010), OSM can take the form of simply replicating the onsite method,
 97 or automating activities using line manufacturing similar to automotive production. Automation is one
 98 core aspect for productivity gain, and OSM methods can be classified into four categories according
 99 to the level of automation involved:

- 100 • *Static* method – where prefabricated elements are manufactured in one position, and materials,
 101 services and personnel are brought to the fabrication point. This mostly replicates the onsite
 102 construction method in a factory environment.

- 103 • *Linear* method – where the process is sequential and carried out in a discrete number of
104 individual stages. Most activities are carried out manually by factory operatives.
- 105 • *Semi-automated linear* method – which shares the same principles as the linear method but
106 tends to have more dedicated stages and individual tasks may be automated.
- 107 • *Automated linear* method – which comprises linear production with fully automated sequential
108 stages.

109 Although the four categories may be very similar, or identical, major tasks and products as a result,
110 their activities and production and assembly specifications (such as resource requirement, information
111 flow, and sequences of activities) can vary significantly. Previous studies (e.g., Pasquire and Connolly
112 2002, Zhang *et al.* 2020) criticized the approach by housebuilders using the static method as not
113 realizing the full benefit of offsite production, and simply carrying out the manufacturing process as a
114 ‘mini construction project’ in an enclosed space, thus replicating onsite construction inefficiencies. On
115 the other hand, largely automating activities may not be always beneficial. This is due to the general
116 trade-off between the level of automation in design and the amount of investment required to facilitate
117 automation. Yet, while the static method may result in low productivity, it is flexible and arguably can
118 be used to produce products with a wider range of designs. This poses the question of which benefits
119 from Table 1 are obtained from which OSM methods, especially in the process category.

120 Previous research related to the evaluation of OSM methods in construction work includes studies of
121 their approach to applying lean and the critical success factors involved (Meiling *et al.* 2012, Pearce
122 *et al.* 2018), strategies for integrating offsite production technologies (Pan *et al.* 2012), barriers to lean
123 implementation (Shang and Sui Pheng 2014), company’s lean thinking implantation (Zhang *et al.*
124 2016) and design processes with reference to lean principles (Gbadamosi *et al.* 2019). These studies
125 have typically evaluated the OSM approach at a high level. One aspect that has not been well
126 researched is the process benefits acquired in terms of waste embedded in the competing OSM
127 production methods.

128 **Process waste in lean manufacturing**

129 The traditional mass production line, known as the ‘push system’, contains standardized parts that are
130 processed following a station-by-station plan. This can lead to an unsynchronised flow of processes,
131 and often overproduction as a result (Wilson 2010). In contrast, the lean manufacturing method
132 implements a ‘pull system’, involving such concepts as pulling products forward and a single unit flow
133 (Howell and Ballard 1998). Implementing a balanced and synchronized operation helps reduce waste
134 in the process and prevents inventory build-up as the process flows smoothly. The term ‘lean’ is used
135 to denote ‘less’ resources (Koskela 1992). Lean manufacturing aims to minimize process waste and
136 maximize value by meeting service demands with minimal inventory. In practice, it relies on the use
137 of a set of tools that assist in the identification and steady elimination of process waste (Howell and
138 Ballard 1998), which arises from activity-centered thinking (Howell 1999).

139 Process waste in this regard is anything in addition to the minimum requirement for a business
140 operation to function, i.e., the minimum amount of equipment, materials, and manpower vital to
141 production. Previous studies suggest that there are five major aspects of minimization: material,
142 investment, inventory, space, and people (Wilson 2010). Process waste can be classified into seven
143 categories as summarised in Table 2 (Melton 2005, Wahab *et al.* 2013, Nikakhtar *et al.* 2015).
144 However, some researchers (e.g. Wahab *et al.* 2013) have argued that there should be additional waste
145 relating to people’s ability not being fully utilized: thus, leading to an additional category of “unused
146 or underused talent” as explained in Table 2. Process waste can also be classified according to (i) waste
147 generated from non-value-adding activities (NVA), and (ii) unavoidable waste generated due to the
148 nature of the work, e.g., indirect work (Koskela 1992, Nikakhtar *et al.* 2015). The latter is unavoidable
149 due to product quality, health and safety, or specific customer requirements. Thus, they are necessary
150 non-value-adding activities (NNVA). For an activity carried out in a process to be considered value-
151 adding (VA), three criteria must be fulfilled: (i) it must physically transform the product a step further,

152 (ii) the customer must be willing to pay for the change, and (iii) it must be correctly carried out with
 153 no need for rework (Wilson 2010).

154 **Table 2:** Different types of process waste in manufacturing processes

Type	Description	Example of cause
Overproduction (OP)	Production of excess product thus leading to other types of waste such as the need to store, transport, inventory and rework on the waste.	<ul style="list-style-type: none"> • Result of making products too early. • Products that cannot be sold due to defects. • Imbalanced production process
Waiting (W)	Workers being idle for whatever reasons either in the short or long term not adding value to the customer.	<ul style="list-style-type: none"> • Short-term waiting as a result of an unbalanced line • Long-term waiting for results from this, such as waiting due to machine failure. • Intermediate product waiting for processing. • Large amount of work in progress (WIP) inventory
Transportation (T)	Moving parts around between processing steps, production lines and shipping products to the end consumers.	<ul style="list-style-type: none"> • Moving pallets of intermediate products within the factory or between/to site • Movement of materials continuously before final destination
Over-processing (P)	Processes/steps in product development beyond the needs of customers.	<ul style="list-style-type: none"> • Over specification • Overdesign • Iterative design • Poor and inefficient processing equipment
Movement (M)	Unnecessary and non-value-adding movement of people. Active workers looking busy does not equate to adding value to a product or process.	<ul style="list-style-type: none"> • Looking for tools or materials • Inefficient workstation design
Inventory (I)	Intermediate storage of products, raw materials, equipment, tools, etc.	<ul style="list-style-type: none"> • Queued batches of materials waiting to be used. • Warehouse/site inventory not translating to sales
Defect (D)	Producing defective work requiring additional work or generating scrap leading to a waste of material, manpower and machine processing time and overall a loss of production unit.	<ul style="list-style-type: none"> • Error in design • Error in processing • Miscommunication • Omission
Un/Under used Talent (UT)	More people involved in the job than necessary and not leveraging the potential of workers to the optimum.	<ul style="list-style-type: none"> • Uneven work distribution • Unchallenged employees • Wrong staff to task • Wasteful admin task

155 There is considerable research pertaining to quantifying the process waste involved in various
 156 traditional onsite construction activities. For instance, Lee *et al.* (2012) analyzed the waste involved in
 157 an onsite steel erection process for a university building, recording 56.93% NVA activities. Mossman
 158 (2009) also reported 56-65% NVA, 30-35% NNVA and only 5-10% value-adding (VA) activities in
 159 the traditional construction process. Similarly, Forsberg and Saukkoriipi (2007) found the average time
 160 spent by workers on productive activities in the traditional construction method to be only 30% of the
 161 overall construction time. This form of quantification has not been well addressed for the various OSM

162 methods. A recent study by Zhang *et al.* (2020) concluded that the lead time is reduced by 20% from
163 the factory ‘stick-built’ method of OSM with the introduction of semi-automation in the production
164 line. However, few published studies have analyzed process wastes in the OSM production workflow,
165 particularly between the various OSM methods.

166 **Evaluation tools for lean manufacturing and process modeling**

167 The need to analyze process waste necessitates an evaluation of the techniques available in practice.
168 There are various tools and techniques used in supporting lean manufacturing. Lean tools can be
169 focused on various aspects, such as waste, inventory, quantity, quality, people, and process controls.
170 However, techniques with objectives of identifying or eliminating process wastes or non-value-adding
171 activities – including value system analysis (VSA) and the *5whys* method (Murugaiah *et al.* 2010) –
172 are used for analyzing processes and identifying sources of waste located throughout the process and
173 are the focus in this study. In order to visualize a process, business process modeling (BPM) tools are
174 used as a means of systematically describing the activities in a process, such as their relationships and
175 information flow: it helps to understand the best way to perform a task by describing its operational
176 performance that produces an output (Nurcan *et al.* 2005).

177 There are various tools developed for modeling business processes that focus on one or a combination
178 of aspects, such as functional, information, organization, or behavioral aspects in a process. Business
179 Process Mapping Notation (BPMN) is an advanced language due to its more advanced explanatory
180 power. BPMN is clearer and is easier to understand by non-experts since it is similar to a flow chart.
181 There are also industry-specific tools used in manufacturing, e.g., Value Stream Mapping (VSM) as
182 an approach to modeling materials and information flow in a production process as the product makes
183 its way through the value stream (Sundar *et al.* 2014). BPMN is used in this study and some concepts
184 from VSM, such as waste and cycle time, are included in the process model for analysis.

185 **Research method**

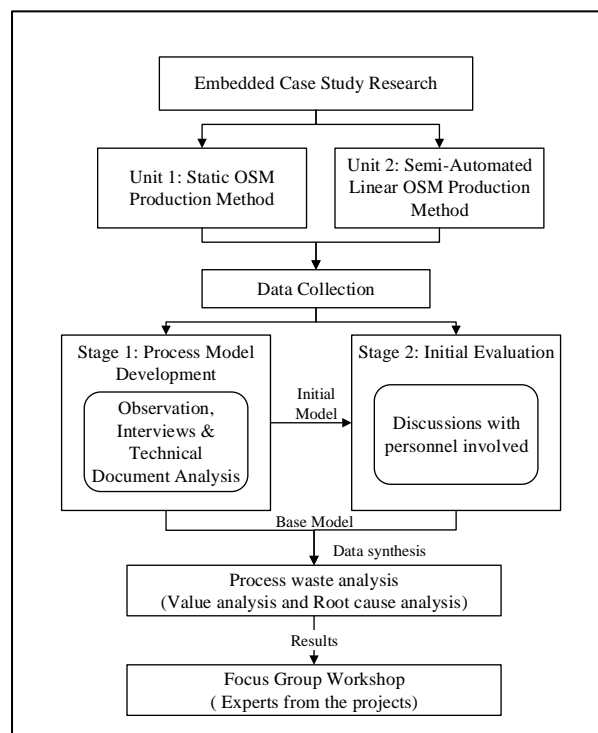
186 The study requires an in-depth analysis of processes, which is heavily data reliant. The presence of
187 data silos, typically existing in the context of construction businesses, creates complexity in the
188 modeling processes. Hence, a case study research method is chosen as it is known for its strength in
189 allowing for a holistic in-depth exploration of a subject in its real-life context (Yin 2009). There are
190 two types of case study design: multiple and single case study designs. A single case study involves
191 the use of only one case, while a multiple case study involves a combination of two or more cases that
192 are used to build a theory about a phenomenon (Yin 2016). For this study, a single case study design
193 has been selected to conduct the exploratory research required – the standpoint being that the single
194 case study approach is better for creating high-quality theory, and better when the aim is to shed light
195 on a single setting (Yin 2009).

196 **Data collection and strategy**

197 Understanding a business organization and its operation is challenging as the researchers are detached
198 from the business operation. This is overcome through an exploratory study investigating the
199 production processes closely over a period by first observing the AS-IS process and then with the
200 design and implementation of the TO-BE process. An iterative data collection process is followed,
201 with the use of a wide range of data including observations, information from internal and published
202 documents, interviews with key OSM experts within the case company, and consolidated opinions
203 from focus groups. The purpose of the case is revelatory (Schell 1992), with an embedded single-case
204 research design containing two units of analysis – the production processes of static and semi-
205 automated linear OSM production methods – in order to obtain rich content in place of the breath that
206 can be obtained in multiple case design (Sarvimaki 2017). The static method workflow is the AS-IS
207 model (i.e., actual production workflow), while the semi-automated linear method is the TO-BE model

208 (i.e., optimized production model). Figure 1 shows the combination of methods used for data collection
209 and synthesis at different stages of the study.

210 The initial data collection process featured different approaches, starting from a review of technical
211 documents that include the production flow diagram, station design, building design, and organization
212 structure. Also identified is the key information required for analyzing process wastes on the activities
213 performed including their sequences, together with data that could not be collected from documents,
214 i.e., the primary data required for the analysis. For instance, questions were set to identify the
215 quantifiable aspects of each activity, such as delays and waiting, as they cannot be captured directly in
216 the documents. The primary data were then collected through interviews with key experts and
217 observation of production in the factory. The output from this stage is used to develop an initial process
218 model based on the activities performed on the shop floor, and to sketch the shop floor arrangement
219 of production space. BPMN notations and protocols are used to represent the processes.



220
221 **Fig. 1. Research Design**

222 An evaluation of the initial process map was then organized with the parties involved to enable
223 assessment of the model and ensure accurate representation of the activities, sequences, and resource

224 requirements involved. The output from this stage (Stage 1 in Figure 1) provides a base model for
225 analyzing the process waste. The identified lean tools from the review are used for value analysis and
226 waste identification in the process according to the eight categories of process waste: this was used to
227 categorize the activities into VA, NVA, and NNVA, respectively. Finally, a focus group comprising
228 key experts of the existing production (such as the production manager, director for the project, and
229 the commercial manager) was formed to identify the root causes of the waste using the *5Whys* lean
230 tool for root cause (RC) analysis – a questioning method that identifies the root cause through asking
231 the question, ‘Why does the issue exist?’.

232 **Case study – Panelised system OSM of light steel frame buildings**

233 The case study is based on one of the largest housing associations located in the UK’s West Midlands
234 region (hereafter named HAX). HAX procures social housing using the traditional method through
235 contracting. It has recently recognized the potential for integrating house delivery within the business
236 after internal market research. The business decided to consider OSM as a major delivery approach to
237 align with the new funding body’s requirements and the national strategy to adopt Modern Methods
238 of Construction (MMC) as well as to help meet the increased housing delivery target, i.e., 60% increase
239 of the number of houses delivered per annum. A consortium was formed with a steel manufacturer, an
240 architect production engineer, and a university to develop OSM house products.

241 While there is a need to determine a suitable OSM method to achieve the set objectives, this data is
242 not readily available. During the 2-year study period, HAX used the static method of production for a
243 house prototype to analyze the suitability of the method and the cost involved. Concurrently, an OSM
244 scheme was developed for the production of panels forming the building frame and envelop of the
245 houses using a semi-automated linear method. The semi-automated linear method in the case study is
246 based on a scheme developed by the production engineer. The scheme incorporates the simulations
247 based on actual production information and detailed workflow incorporating automated stages of sub-

248 assemblies. For instance, the data for the time cycle study is derived from industry-known values for
249 discrete activities. Operator times are based around MTM (Methods-time Measurement) standards
250 while the transfer times are based upon conveyor speeds of 10 meters per min and screw insertion
251 times are based upon trials carried out in previous applications for similar product production. The
252 time cycle study was run with a full sized layout as per the proposed placement of the loading bay and
253 the guarding, buffer station and pallet positions. The cycle time simulation was carried out using the
254 engineer's company template that aggregates the cycle time taking into account the overlapped
255 activities in the production process.

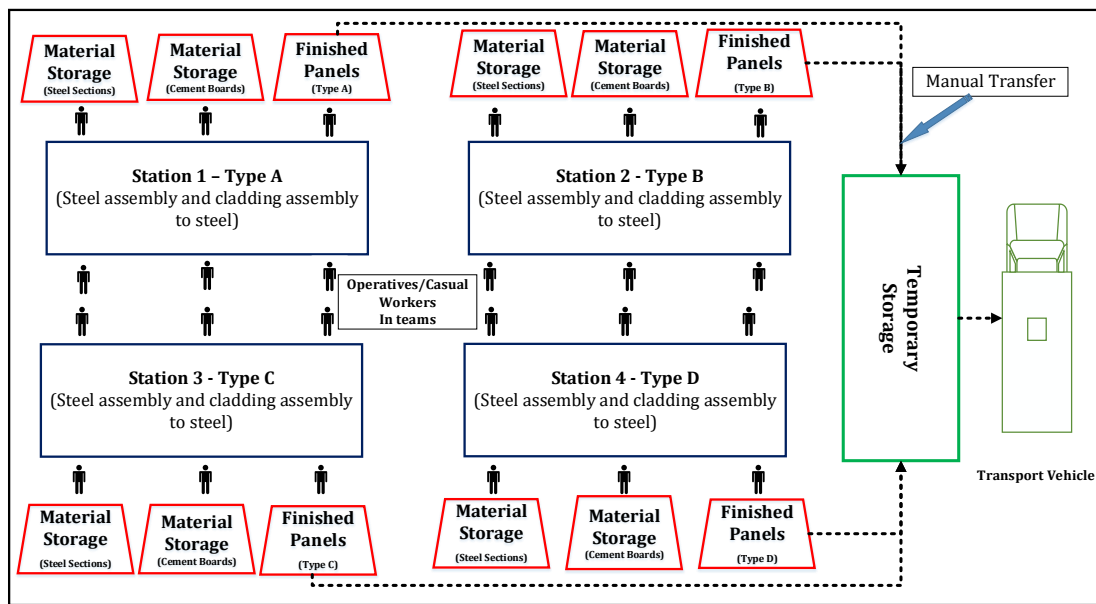
256 The workflows for wall panel production were chosen for a like-to-like comparison between the two
257 methods. Lean manufacturing theory relating to the eight categories of process wastes is applied to
258 analyze the constraints of the two methods and the waste involved to quantify the improvement in the
259 TO-BE method and provide recommendations for CI.

260 **Modeling and implementation**

261 **Static method OSM production process activities**

262 The static production process of wall panel production as done in a HAX factory is used as a reference
263 for the process modeling: this is an actual (AS-IS) workflow intended to be compared with the
264 simulated workflow. For wall panel production, the key stages are to: 1) assemble the steel frame for
265 wall panels, 2) install the cladding on steel frames, and 3) apply finishes on the cladded steel frames.
266 In the static system, the production is done in silos. Various team members and trade specialists where
267 needed are required to move from one station to another to render services on the panels. The station
268 is arranged such that a team is working on a one-panel type/design while the processes within these
269 stations follow no particular sequence. Also, there is no defined flow of materials or unfinished
270 products between the various stations (see Figure 2) and stations sometimes have an individual
271 production plan. Figure 3 illustrates the BPMN process map representing the activities in the static

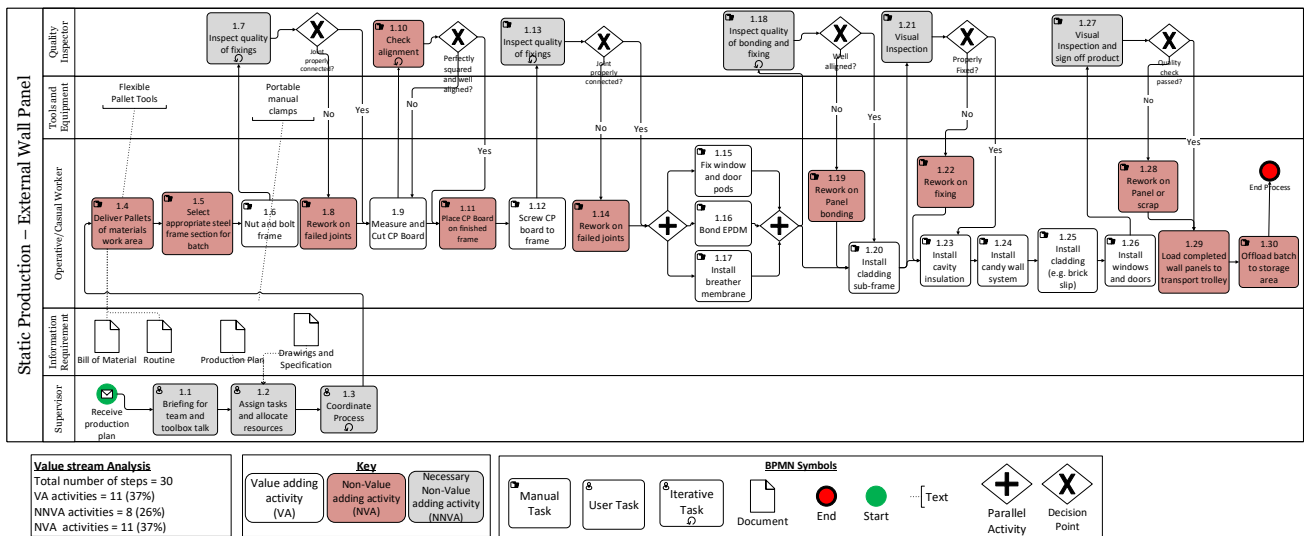
272 process (one of the stations, as the activities are the same and are repeated for each station), which is
 273 a typical push system of manufacturing.



274
 275 **Fig. 2. Static Production Arrangement**

276 The overall cycle time involved in a manufacturing process consists of (i) process time (relating to
 277 working directly on a product), (ii) waiting time (activities that involve waiting), (iii) loading time
 278 (relating to moving materials, partially completed products or completed products) and (iv) inspection
 279 time (relating to quality or health and safety). The activities as identified in the process map are
 280 classified into three types: value-adding (VA), non-value-adding (NVA), and necessary non-value-
 281 adding (NNVA). For the analysis, the VA activities are activities with a process time, NVA activities
 282 involve a waiting and loading time, while NNVAs are activities involving an inspection time.

283 However, the challenge with manual production is that the identified VA activities carried out by
 284 operatives may also include some idle time and it is difficult to identify or quantify the embedded
 285 waste involved. Hence, some of these may have been missed in the evaluation, which is a limitation.
 286 The eight process waste categories are used to identify the NVA and NNVA activities in the process
 287 and are denoted in Table 3.



288

289

Fig. 3. Production process model for wall panel construction using static method.

290

The cycle time for each activity is modeled using the average time it takes to complete a unit of an offsite product of cladded wall panel for house construction. For each station, the work for a batch is completed by a team of 5 workers: 3 fixers (one is a senior fixer also acting as a supervisor), 1 casual worker, and 1 quality inspector. The activities performed can be categorized into different levels for the purpose of the cycle time estimation, unit or batch level activities. A unit-level activity is required to be carried out on each product while a batch-level activity is performed on a batch of products and the time taken to complete the activity is distributed equally to each unit. Activities 1.1 to 1.5, 1.29, and 1.30 are batch-level activities and the cycle time will be shared by all products from the batch. Other activities are to be performed on every unit of the product; hence, the cycle time recorded in Table 4 is the time taken to complete the activity for each wall panel. Based on observations of the process, the static method has a 15-20% chance of rework due to minor errors or deviations in the drawings and specifications requirements. That is, for every 10 panels built, there is a chance of additional rectification work being needed on at least 2 panels. Therefore, this assumption is considered when recording the cycle time for rework activities.

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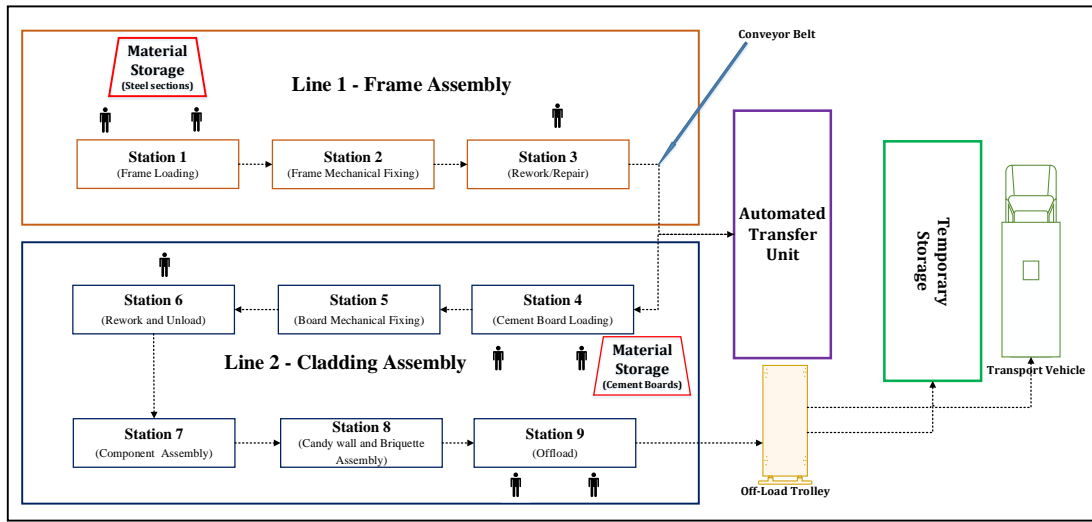
306 **Table 3:** Process waste analysis in static production method

Production Station			Lean Waste Aspects								Time (min)			
Activity Code	Activity	Type	OP	W	T	P	M	I	D	UT	Cycle time (CT)	VA Time	NVA Time	NNVA
1.1	Team briefing	NNVA									1	-	-	1
1.2	Resource allocation	NNVA									1	-	-	1
1.3	Process coordination	NNVA									-	-	-	-
1.4	Material delivery	NVA		x	x		x				5	-	5	-
1.5	Choosing suitable steel profile sections	NVA		x				x			5	-	5	-
1.6	Nut and bolt frame	VA									60	45	15	-
1.7	Quality inspection	NNVA									10	-	5	5
1.8	Rework on frames	NVA		x					x		15	-	15	-
1.9	Measuring and cutting cement plasterboard	NVA	x								45	-	45	-
1.10	Check alignment	NVA	x								2	-	2	-
1.11	Load CP board on frame	NVA					x				10	-	10	-
1.12	Screw board to frame	VA									40	20	20	-
1.13	Quality inspection on fixings	NNVA		x		x					10	-	5	5
1.14	Rework on failed joints	NVA							x		15	-	15	-
1.15	Fix window and door pods	VA									40	20	20	-
1.16	Bond EPDM	VA									40	20	20	-
1.17	Install breather membrane	VA									20	15	5	-
1.18	Visual inspection on bonding	NNVA									5	-	-	5
1.19	Rework on bonding	NVA							x		5	-	5	-
1.20	Install cladding sub-frame	VA									120	60	60	-
1.21	Visual inspection on sub-frame fixing	NNVA									5	-	-	5
1.22	Rework	NVA							x		5	-	5	-
1.23	Install cavity insulation	VA									30	20	10	-
1.24	Install candy wall system (backing board)	VA									60	45	15	-
1.25	Install cladding-brick-slip system	VA									60	45	15	-
1.26	Install window and door	VA									80	60	20	-
1.27	Quality inspection and sign off	NNVA		x							5	-	-	5
1.28	Rework on defect or scrap	NVA							x		5	-	5	-
1.29	Load finished panels to transport trolley	NVA					x				5	-	5	-
1.30	Load to storage area	NVA	x					x			5	-	5	-
Total Time (Min)											709	350	332	27
Total Time (%)											100	49	47	4

307 **Semi-automated linear method OSM production process activities**

308 In the semi-automated linear method of wall panel production which is based on simulated results as
 309 an alternative to the static method, some of the root causes of constraints in the static method are
 310 addressed. This method comprises two automated lines for frame and cladding assembly with the use
 311 of automated machines and various robotic arms (see Figure 4). Compared to the static method,
 312 production is in an assembly line with dedicated stations that allow synchronous flow. Each station
 313 has dedicated production team members. Partially completed units are moved in various dedicated
 314 interconnected stages. The units are moved on a conveyor belt and the completed units are picked up
 315 by fork-lift trucks to be stored or loaded on transport vehicles. The batch manufacturing method is

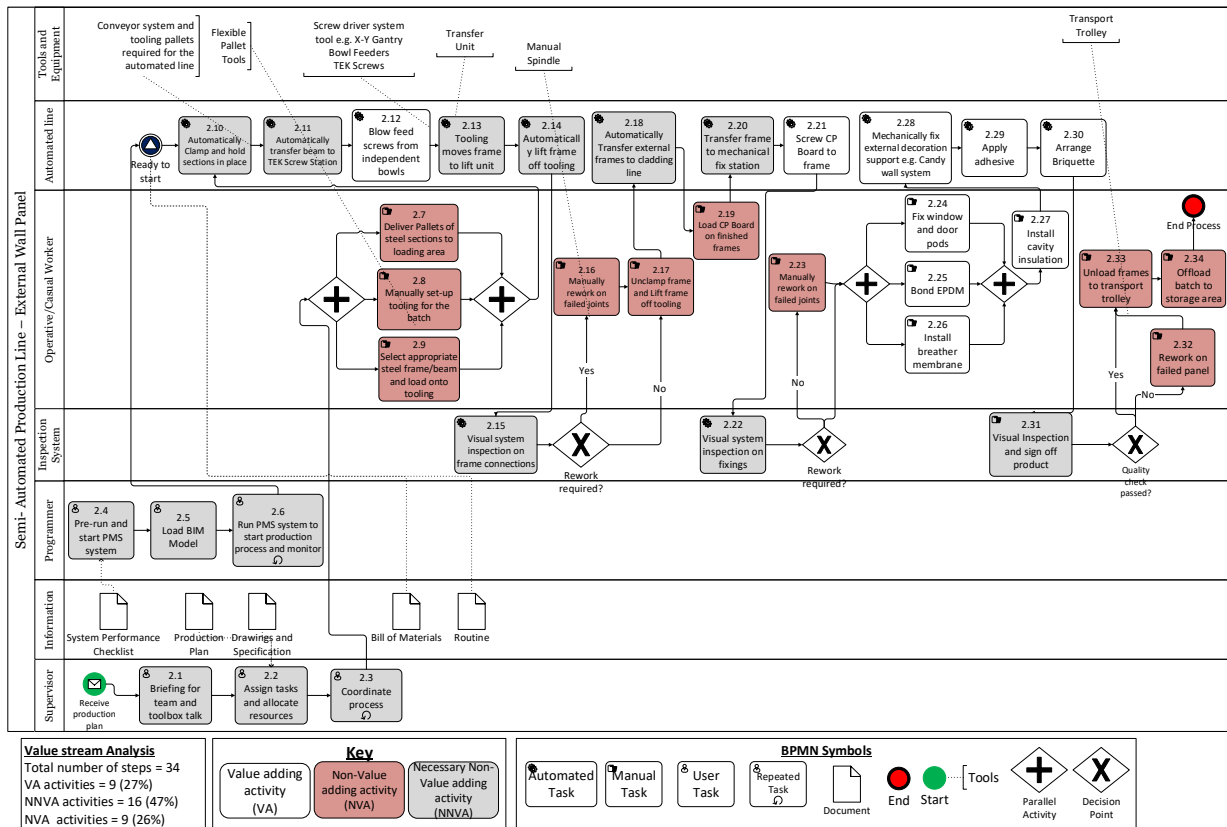
316 used, which is a push system. Figure 5 illustrates the BPMN process map representing the activities in
 317 the semi-automated linear process of wall panel production.



318

319

Fig. 4. Semi-automated linear production arrangement



320

Fig. 5. Production process model for wall panel construction using semi-automated method.

322 Similar to the method used in analyzing the static process, the cycle time for each activity in the batch
 323 manufacturing line is modeled for the new production line using the estimated maximum process time

324 for each activity in every station (Table 4). With this method, the time and waste predictions are based
 325 on the production engineers' estimates using the simulated production model according to the
 326 workflow arrangement and estimated time of product movement through different stages. The
 327 activities contained in the process are also categorized as either unit or batch level activities similar to
 328 the static method. In this case, activities 2.1 to 2.9, then 2.33 and 2.34 are batch-level activities, while
 329 others are unit-level activities: hence, the cycle time is shared by the number of units of wall panels
 330 produced for the batch.

331 **Table 4:** Waste analysis in semi-automated production method

Production Line			Waste Aspects									Time (min)			
Activity Code	Activity	Type	OP	W	T	P	M	I	D	UT	Cycle time (CT)	VA Time	NVA Time	NNVA Time	
2.1	Team briefing	NNVA									1	-	-	1	
2.2	Resource allocation	NNVA									1	-	-	1	
2.3	Process coordination	NNVA									-	-	-	-	
2.4	Pre-run PMS system	NNVA									2	-	-	2	
2.5	Load BIM model	NNVA									2	-	-	2	
2.6	Monitor system	NNVA									5	-	-	5	
2.7	Material delivery	NVA		x	x		x				5	-	5	-	
2.8	Tool set-up for batch	NVA		x							2	-	2	-	
2.9	Choosing suitable steel profile sections	NVA		x							5	-	5	-	
2.10	Clamp section in place	NNVA									0.5	-	-	0.5	
2.11	Transfer to screw station	NNVA									0.5	-	-	0.5	
2.12	Screw frame on both side	VA									6.78	6.78	-	-	
2.13	Tooling return	NNVA									0.5	-	-	0.5	
2.14	Lift frame off tooling	NNVA									1	-	-	1	
2.15	Visual inspection by system	NNVA									1	-	-	1	
2.16	Rework on failed joints	NVA							x		5	-	5	-	
2.17	Unload frame from tooling	NNVA		x							2	-	2	-	
2.18	Transfer frame to cladding line	NNVA									0.5	-	-	0.5	
2.19	Load CP board	NVA		x							5	-	5	-	
2.20	Transfer frame for mechanical fixing	NNVA									0.5	-	0.5	-	
2.21	Screw CP board to frame	VA									6.78	6.78	-	-	
2.22	Visual inspection by system	NNVA									1	1	-	-	
2.23	Rework on failed joints	NVA								x	5	-	5	-	
2.24	Fix window and door pod	VA									40	35	5	-	
2.25	Bond EPDM	VA									20	20	-	-	
2.26	Install breather membrane	VA									20	15	5	-	
2.27	Install cavity insulation	VA									20	20	-	-	
2.28	Fix external decoration support	VA									6.78	6.78	-	-	
2.29	Apply adhesive	VA									5	5	-	-	
2.30	Arrange briquette	VA									10	10	-	-	
2.31	Visual inspection and sign off product	NNVA									5	-	-	5	
2.32	Rework on failed panel	NVA								x	5	-	5	-	
2.33	Unload frames to trolley	NVA				x	x				5	-	5	-	
2.34	Offload batch to storage area	NVA				x					5	-	5	-	
Total Time (Min)											201	126	54	21	
Total Time (%)											100	63	27	10	

332

333 Discussion

334 The process analysis of the two methods of OSM production revealed some data on the differences in
335 the units of analysis. A summary of the results of the comparison of both OSM methods is provided
336 in Figures 6 and 7. Based on Figure 3, for the static method, the total number of activities required to
337 produce a unit of wall panel is 30, with 37% of these activities being non-value-adding (NVA). In
338 contrast, the semi-automated method automates some of the key activities and introduces additional
339 steps to enable a structured workflow. This method contains 34 activities in total, of which 26% are
340 non-value-adding activities (NVA) since some human intervention is eliminated, which is an
341 approximately 30% decrease in NVA activities compared to the static method (Figure 6).

342 In terms of process time analysis, only 49% of the actual time spent in the production workflow is
343 value-adding time in the static method (Figure 7), which is at a similar rate to the onsite methods
344 reported in past literature, i.e., up to 50% non-value-added activities (Liu *et al.* 2011, Nikakhtar *et al.*
345 2015). This implies that there is little improvement to the static method of production in terms of
346 reduced process waste, which supports the criticism by Zhang *et al.* (2020) that some factory house
347 building methods simply replicate onsite construction inefficiencies. In contrast, in the semi-automated
348 method, the use of robotic arms for the fabrication of the steel frame for wall panels significantly
349 reduces the time required to manually assemble steel members. Therefore, the semi-automated method
350 reported improved productivity with the VA time of 63% compared to 49% in the static method, which
351 is an increase of approximately 29% in the VA time. Also, it takes 201 minutes of overall lead time
352 (total time required from the first to the last workstation) to produce a single unit wall panel in the
353 semi-automated method, with 126 minutes of value-added time (actual process time). In contrast, the
354 static method takes 709 minutes based on the workflow to complete the processing of a unit wall panel,
355 with only 350 minutes of value-added time. This implies that the semi-automated method provides a
356 70% reduction in the lead time from the static method, which is significantly greater than the 20%
357 reported by Zhang *et al.* (2020). The variance can be explained as a result of the production line design,

358 workflow arrangement and level of automation involved, as no two manufacturers incorporate the
359 exact same process since the manufacturing environment offers different options for producing the
360 same product.

361 Upon further analysis of the root cause (RC) of the waste generated with the static method, some
362 constraints in the processes are revealed as detailed in Table 5. In terms of process waste resulting
363 from waiting (W) and movement (M), factory/workstation arrangement and inefficient process flow
364 were reported as the RC of the issues in the static method of production. The *ad-hoc* nature of activities
365 led to a non-guaranteed cycle time for each activity, as no standardized sequence was adopted.
366 Although activities relating to Quality Inspection (QI) are classified as NNVA, QI is major source of
367 delay in the static method due to operatives waiting for inspections to be completed in order to move
368 to the next step. Although QI is highly important for avoiding scrapping finished panels due to defects,
369 it is observed that this causes over-processing waste (P) because of the excessive number of
370 intermediate inspections incorporated in the process which, as seen in the semi-automated method,
371 could be reduced with better efficiency enabled with the help of automation. For instance, the use of a
372 manufacturing line with dedicated stages improves the workstation arrangement and flow as a result.
373 A visual inspection system displaying the position of fault screws was included in the semi-automated
374 method manufacturing line, which enables the operators stationed in the rework station to quickly
375 rectify faults. This system was introduced after the analysis of the RC in the static method and results
376 in the elimination of some waste relating to waiting and movement in the static method.

377 Another major waste in the static method is due to the frequent rework required in the process, where
378 the chances of process waste due to defects, thus resulting in rework, is around 15-20%. In contrast,
379 the need for rework is projected to be below 5% with the semi-automated method due to the efficiency
380 of the robotic arm used for key activities (e.g., screwing and fixing) that are prone to error. The 5%
381 rework is mainly due to some value-adding manual activities e.g., bonding the breather membrane.

Table 5: Root cause (RC) analysis for static production method NVA activities

Production Line		Waste	Issue/ Symptom	5Whys of lean				
Activity Code	Activity			Why 1	Why 2	Why 3	Why 4	Why 5 (RC)
1.4	Material delivery	Waiting	Operatives waiting for stock on production line.	Needs to be moved from store to production area	Inventory checks need to be carried out	Process too slow, causing impact on production flow	Variable task duration	<i>Inefficient process flow design</i>
		Movement and transportation	Moving and transporting materials from store to production area	Moving materials from storage	Storage not close to production line	Space management	Factory arrangement	<i>Inefficient factory arrangement</i>
1.5	Choosing suitable steel profile sections	Waiting	Operatives sorting appropriate frames from material batch	Variable task duration	Non-balanced line	Non-balanced flow	Ill-designed space to pick and store frames	<i>Inefficient workstation</i>
		Inventory	Batches of materials waiting to be processed	Inventory needs to be completed	To ensure correct materials are being chosen	Ensure specifications are being followed	Correct drawings in place	<i>Problem from the push production method</i>
1.8	Rework on frames	Waiting	Waiting for quality inspection to be completed, which slows down following process	Not enough QI inspectors to meet production flow	Bottleneck in production flow	Bottleneck in production flow	Trades not being used to full capacity during shifts	<i>Lack of investment in automated inspection systems</i>
		Defect	Frame joints not properly connected	Human error from operatives such as omission	Delay in target which causes work to be rushed	Time constraints to meet customer demands	Delay and waiting in the process, such as stage sign off by Q1	<i>Inefficient flow of production with many delays</i>
1.9	Measuring and cutting CP Board	Over-processing	Extra processing on cement board before being used.	Cement board not pre-cut from supplier	Process is slow due to dust generation	Process not automated for machine cut	Process not automated for machine cut	<i>Process not automated for machine cut</i>
1.10	Check alignment	Over-processing	Too many quality checks that could be avoided	Human error from operatives	Inexperienced trades carrying out the works	Re-skilling of workforce not adequately invested in	Lack of investment in people and skills training	<i>Lack of investment in people and skills training</i>
		Waiting	Operatives having to wait for checks to be completed to execute next process	QI inspection process too slow	Quality inspector working on other jobs	Operatives not skilled to self-check	Lack of investment in automated inspection systems	<i>Lack of investment in automated inspection systems</i>
1.11	Load cement board on frame	Movement	Operatives moving from material storage to line.	Fork-lift truck not available	Not enough CAPEX invested for more than one fork-lift truck	Not forecasted correctly with new orders	Lack of understanding of supply & demand	<i>Lack of understanding of supply & demand</i>
1.14	Rework on joints	Defect	Wall joints not properly connected	Rushed work and quality of installation inadequate	Too much of a backlog	Work shifts not planned correctly	Work not planned correctly	<i>Inefficient process flow design</i>
1.19	Rework on joints	Defect	EPDM and window joints not properly fixed	Rushed and quality of installation inadequate	Too much of a backlog with too many defects	Not enough skilled workforce	Lack of investment in people and skills training	<i>Lack of investment in people and skills training</i>
1.22	Rework on sub frame	Defect	Sub-frame not properly fixed	Too many mistakes in joint fixings	Rushed work and quality of installation inadequate	Too much of a backlog	Work shifts not planned correctly	<i>Inefficient process flow design</i>
1.28	Final rework on defect wall	Defect	Panel did not pass quality checklist	Rushed work and quality of installation inadequate	Sequencing broken down due to too many defects in previous panels	Too much of a backlog with too many defects	Not enough skilled workforce	<i>Lack of investment in people and skills training</i>
1.29	Load finished panels to transport trolley	Movement	The need to move completed batch from work area	Movement of workers in the factory	Large amount of work in progress (WIP)	Overproduction	Overproduction	<i>Overproduction</i>
1.30	Transport and load finished panels to storage	Transportation	Movement of finished panels to storage area because not ready to deliver to site	Not due to arrive onsite	Overproduction	Push manufacturing system	Push manufacturing system	<i>Push manufacturing system</i>

383 Nonetheless, although the semi-automated method helped eliminate some of the process waste in the
384 static method, some process waste relating to inventory (I) is similar in both methods due to the batch
385 production system adopted. This method of production causes inventory to build up: thus a storage
386 area is needed in the factory to stack the work-in-progress (WIP) panels until they are ready to be
387 moved to the site – resulting in an additional estimated waiting time of between 4-5 days in the static
388 method. This would consequently result in an added cost for a single unit of the product and perhaps
389 increase the cost of offsite production. There is a need to consider and implement other lean practices
390 targeted at preventing waste due to inventory in the manufacturing process to increase the
391 competitiveness of OSM houses as compared to houses built onsite.

392 **Conclusion**

393 The case study presents a systematic analysis of two offsite house building methods using two lean
394 tools of value system analysis and RC analysis. The efficiency of the production process of a wall
395 panel in terms of the eight process waste types is analyzed. The result from the study reveals that up
396 to 47% NVA time is spent in the production process in the static method involving non-structured
397 workflow, and a potential to reduce this to 27% with the semi-automated method of production. From
398 the case analyzed, it is revealed that the overall lead time taken to produce a unit wall panel (in the
399 static method) can be reduced to up to 70% with a more structured workflow and the automation of
400 critical activities in the process (using the semi-automated method). It is concluded, therefore, that the
401 static method may not provide significant improvement in process waste when compared to the onsite
402 production method based on the quantification results from previous studies. Similar unstructured
403 processes are used in both methods, leading to the repetition of such constraints with the onsite method
404 in factory production as wastes relating to waiting, movements, and defects. Thus, moving construction
405 to a factory environment does not necessarily provide the leanness desired, unless approaches to lean
406 manufacturing are incorporated (such as a structured workflow flow, repetition, and automation).

407 This study is based on a case study of a specific production line design and workflow, only an
408 analytical generalization (Hyde 2000) can be achieved, e.g. based on the degree of similarity between
409 the two similar contexts, such as offsite manufactured products with similar production to the steel
410 framed panel in this case. In addition, while the study is based on only one OSM system, i.e., a
411 panelized system, similar processes and constraints are likely to be present in other OSM systems such
412 as volumetric or hybrid methods.

413 The study presents quantitative evidence of the performance of structured and non-structured OSM
414 methods in terms of eliminating process waste. The implication of the result is the need for offsite
415 manufacturers to take a process view of their production approach, recognizing the impact of
416 automating critical activities and the importance of incorporating structured workflow and repetition
417 to support mass customization. This paper also documents a simple approach that can be adapted to
418 analyze other production methods and OSM processes to support decision-making relating to the
419 choice of OSM methods.

420 **Data Availability Statement**

421 The data used in this study to support the findings such as the production line design, simulated
422 production line process data and the wall panel design were provided by third parties and the industry
423 partners working on innovate UK funded project No. 104798 and are confidential in nature. The data
424 may only be provided with restrictions.

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