RESEARCH ARTICLE

Synchronising Off-Site Fabrication with On-Site Production in Construction

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Abstract

The aim of this study is to explore how offsite fabrication (OSF) can be tightly coupled with production and assembly on-site. Prefabrication is a production method that has potential to yield significant productivity and sustainability improvements in the construction industry. Failure to synchronize production in the factory with on-site production can lead to financial losses for the client/owner, main contractor and subcontractors as well as to delays in the construction schedule. The study draws on two case-studies and the authors' experiences in the context of a critical review of literature on the concepts of flow and Just-in-time (JIT) construction delivery. The findings show the value of a buffer between suppliers, fabricators and the site as a way to help the whole supply team create production flow and more environmentally friendly results. A buffer can help while the team is learning to use collaborative short-term planning to create predictable production. The paper recommends ways to synchronise OSF with on-site production. The paper provides practitioners with ideas to reduce both work waiting for workers (or robots) and workers (or robots) waiting for work – and it contributes to theory by raising more questions for further research.

Keywords:

Lean construction; Sustainability; Production; Just-in-Time; Pre-fabrication.

Introduction

This paper is about improving the collaboration between off-site fabricators and their customers on-site. Late delivery of prefabricated elements leaves people on-site waiting for work. Early deliveries get in the way and require multiple handling or add cost as the delivery vehicle waits to be unloaded. Although prefabrication has emerged as a potential remedy to low productivity issues in the construction industry, the effective management of prefabrication in construction projects is yet to be explored and developed further (Jang, et al., 2021).

Prefabrication is not new. William of Normandy arrived in England in 1066 with a prefabricated wooden castle. Gibb (1999) describes several prefabricated hospitals built over the last two millennia! In each case, the focus is on construction. The focus of this paper is on logistics – the sequence and timing of the arrival of complex, multi-trade assemblies at site and what that means for the sequence and time of the fabrication of those assemblies.

In the last three decades there has been a determined attempt to move as much construction work as possible into factories that are geared up to produce major multi-trade sub-assemblies that can be simply and quickly installed and connected on-site. Growing labour shortages (Gibb, 1999), demand for greater safety, quality, rapid completion and cost reduction have all contributed to this. In the UK, government has pushed for the adoption of "*Modern Methods of Construction*" (a euphemism for off-site fabrication (OSF) and prefabrication) to help solve the housing shortage (Jang, et al., 2021). In the US, companies like Katerra (while it was still trading), Project Frog, RAD Urban, Digital Building Components (Hall, Whyte and Lessing, 2020) and Brydon Wood in the UK (Peltokorpi, et al., 2021) all use prefabrication. Their apparent success puts pressure on the sector. A 2017 McKinsey Global Institute Report added to the pressure.

The benefits of OSF to the construction industry have been widely reported in the literature (See Table 1).

Table 1: A rapid review of the benefits of prefabrication in construction (Authors)

	Benefits	Sources of information
Safer	• Work done in relative safety of factory reduces jobsite congestion. • Less work done at height • Sites are generally quieter and better for neighbours • More standardised procedures → facilitates quality control and site logistics→ less rework and re-handling of materials → reduced fatigue and injuries • Cleaner and tidier worksites → reduced tripping hazards • On-site construction dust reduction	McKay, et al. (2005) Tam, Tam and Zeng (2007) Lu and Liska (2008) Soto, Hubbard and Hubbard (2014) Jaillon and Poon (2014) Killingsworth, Mehany and Ladhari (2021) Jang, et al. (2021)
Faster	• Weather creates fewer delays • Parallel working off-site and on-site. → Significantly faster • Work better planned → better safety → less accident time • Less rework • Less scaffolding and shuttering • Easier to plan assembly work and logistics • Reduced use of wet trades	Gibb and Isack (2003) Goodier and Gibb (2007) Lu and Liska (2008) Ballard (2017) Love, Matthews and Fang (2020) Building and Construction Authority (2020) Killingsworth, Mehany and Ladhari (2021)
Greener	• Decarbonise projects during design, assembly and in use • fewer greenhouse gas (GHG) emissions • Reduced total life-cycle energy consumption • Reduction in dust and noise • Improved opportunities to seal the building • Less physical waste • Can be used for retrofitting • Wet trades use reduced → less operational water use	Gibb (1999) Gibb and Isack (2003) Lu and Liska (2008) Tam and Hao (2014) Hong, et al. (2016) Sandanayakea, Luob and Zhangc (2019) Building and Construction Authority (2020) Hao, et al. (2020) Jang, et al. (2021)
Better Quality	• Quality consistently better; easier to create quality in factory • Higher reliability product → easier to maintain → reduced maintenance cost • Maintenance and assembly process considered from start of design • Reduced snagging and defects	Gibb and Isack (2003) Goodier and Gibb (2007) Miles and Whitehouse (2013) Killingsworth, Mehany and Ladhari (2021)
Lower cost	• Higher reliability product → reduced maintenance cost • Reduced manpower and material usage • Less rework → lower cost • Fewer accidents → lower cost • Lower whole Life-cycle costs • Lower insurance costs • Reduced schedule → reduced indirect costs	Gibb and Isack (2003) Goodier and Gibb (2007) Pan and Sidwell (2011) Tam, et al. (2015) Killingsworth, Mehany and Ladhari (2021)

There are two major types of prefabrication, panelised and volumetric. With the former, a structure is created using combinations of flat panels and, with the latter, the build is assembled from units that enclose usable space generally of room size or part room size as well as volumetric elements such as plant rooms and highly serviced pods that are inserted into a structure. OSF makes economic sense when production/assembly on-site is predictable and flowing (Kalsaas and Bolviken, 2010). When either production on-site or deliveries of OSF sub-assemblies are unpredictable, workers at site are kept waiting and flow is impeded. Traditional project management assumes that variability in workflow is outside management control (Ballard and Howell, 2003a) yet delays and waiting create no value for the client and no-one wants to see workers standing idle. The temptation is to either put them to work doing something out of sequence or to assign them to a different project. Work done out of sequence can make subsequent tasks more difficult and it is often difficult to get workers back to site once they have been reassigned. In those circumstances traditional hand building is a better strategy for keeping trade crews busy.

In 2005 Ballard and Matthews described the lean ideal as "*to "simplify site installation to final assembly and commissioning". Pursuit of this ideal* [they continued] *involves every phase in project delivery and in the life of the products that are components of the facility being constructed*". In 2017 Ballard noted that prefabrication allows greater concurrency, thus reducing project durations. Working in a factory with increased mechanisation, repetition and lean manufacturing principles and methods improves productivity. He went on to say that the timely delivery of unique, *Engineered-to-Order* (ETO) and made-to-order products often *make* or *break* construction projects. As pressure grows to fabricate ever more significant elements of buildings, fabricators will adopt more and more traditional lean manufacturing methods. Realisation of this lean ideal will bring construction closer to series production (i.e., manufacturing).

As use of OSF continues to grow, it becomes increasingly important to create a smooth flow from raw materials arriving in the factory to the installation of the resulting sub-assemblies on-site. Predictable, Just-in-time (JIT) production in a factory is possibly easier than it is on-site, yet it is far from simple. Most factories serve a number of sites; some ETO sub-assemblies will be for a particular project and others, common to a range of projects and/or to a range of settings within a project, will be *Made to Stock* (MTS) (see e.g., Court, 2009). Coordinating and synchronising flow in this environment requires meticulous real-time production planning. It is this aspect that leads to the primary research question (RQ):

> ***RQ.*** **'How can OSF be synchronised with predictable production and assembly on-site, so that the site is more likely to be ready to receive each sub-assembly when it arrives and that site operations are not delayed waiting for delivery of sub-assemblies?'**

To begin to answer this question, the authors critically review the concepts of flow, production planning and control, and JIT delivery in construction through the lens of the Transformation-Flow-Value generation (TFV) theory of production. The authors then draw on lessons learned from two case studies to propose a sustainable-lean approach for prefabrication in construction.

Prefabrication and Flow – A Review

As individuals, when we are '*in the flow'* things are going really well. It is the same on a construction project. On a project using the services of an off-site fabricator, flow happens when both the fabricator and site are in step with each other. If each is moving at its own pace independently of the other, it is highly likely that the site will either have workers waiting for work or that it will not be possible to install the fabrications as they arrive (i.e., work will be

waiting for workers to be ready to perform it). Both work *waiting for workers* and *workers waiting for work* are wasteful and the owner/client usually ends up paying for that wait.
In this section, an overview of TFV Theory, Flow, Buffers, Capacity Utilisation, Last Planner System and the limitations of the critical path method and Just-in-time are provided.

Transformation Flow Value (TFV) Theory

Within the dominant construction paradigm, the focus is on making *transformations* – transforming a pile of bricks and a bucket of muck into a wall for example. Once it is done it can be ticked off. In lean construction the focus is also on ensuring that the *transformation* creates what the customer(s) want to pay for (i.e., *value* (Womack and Jones, 2003)) and that the transformations *flow* smoothly without interruption. As Koskela (1992 and 2000) made clear, if the flow of directives, resources and prior work (shown in Figure 1) to the workface is interrupted in some way, the *transformation* processes will not *flow* smoothly and the creation of *value* for the client will be interrupted or slowed. The interruption adds cost as well as delay to the assembly process. Flow is discussed next.

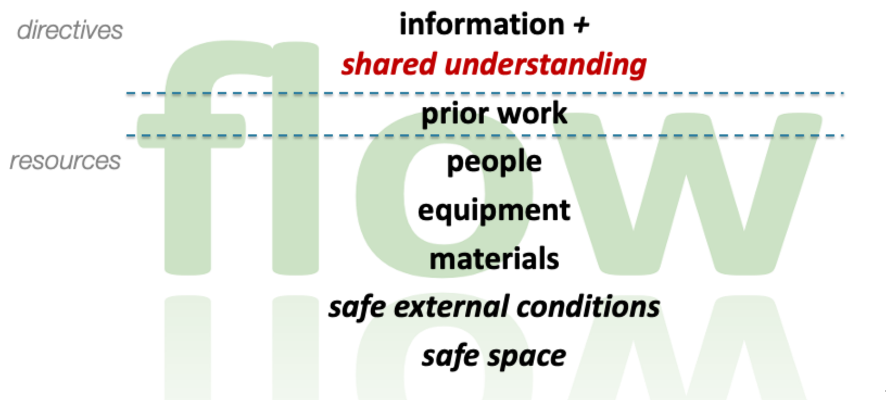

Figure 1: the eight flows required for work to be successfully done. Sources: Koskela, 2000; Pasquire, 2012; Pasquire and Court, 2013. (graphic after Mossman, 2020)

What is flow?

Flow comes with end-to-end coordination and synchronization of operations process (see e.g., Modig and Ahlstrom, 2015). There are two principal kinds of physical flow – laminar (or smooth) and turbulent. Turbulence in fluids is created by obstacles and obstructions. In construction, these ideas from fluid mechanics are used as a metaphor (Kalsaas and Bolviken, 2010). Liker (2021, p.131-2) cautions against confusing "fake flow" with the real thing.
On a highway, when one vehicle unexpectedly brakes even a little more than expected, a "ripple" speeds back down the highway as each following driver brakes just a little more to maintain an appropriate distance from the vehicle in front (Orosz, et al., 2009). Sometimes this small perturbation can bring the highway to a complete halt, kilometres down the road even though there has been no accident.
In a construction environment, when performers don't provide what their customers want and there is consequential rework and/or delay, flow in the production process is perturbed. If this happens too often, subsequent crews add a little extra time between the previous crew's declared finishing time and the time when they plan to start and/or they allow themselves more time to complete (a phenomenon frequently reported by practitioners). In this way, as on the highway, one small delay is magnified. On the road, the journey takes more time. On-site, the project is delayed.

In construction variation creates turbulence. Variation in dimensions, in delivery, in time, and in quality. While it is generally recognised that, as Shewhart said, "there is variation in everything" and that the performance of a production system degrades as variation increases (Hopp and Spearman, 2000, p.295), much of the focus of *lean* constructors is taken up with minimising variation and increasing predictability. Construction companies are using a number of ways to understand and minimise variation so that construction production becomes more predictable. These generally include a mixture of managing the use of buffers, managing capacity utilization and using the Last Planner® System to improve workflow.

Buffers

"Variation in a production system will be buffered by some combination of inventory, capacity and time" (Hopp and Spearman, 2000, p. 295). A '*buffer'* is an extra volume of some resource (e.g., material, time) designed to enable a system to meet expected fluctuations in demand or supply. Strategically placed buffers help to ensure smooth workflow. Each buffer has a cost and overly large buffers, especially on-site, interrupt flow. For example, materials on-site *just-in-case* can be in the way of work that needs to be done and lead to program delay and/or damage to those materials. So, it is important to design buffers carefully and to minimise them.

Using buffers to create a looser linkage between parts of a production system adds to the cost of the production system. These 'loose linkages' are useful as they mean that a temporary problem in one part of the production process doesn't stop the whole production process. Costs include the value of labour and materials in the buffer, the space occupied by each physical buffer, the cost of multiple handling of materials in a buffer – and rework and/or quality control costs if mistakes in preceding steps are not immediately identified as the work waits in a buffer (and further defects are produced until the mistake is identified) as well as the cost of delays incurred by using time buffers (Howell, Laufer and Ballard, 1993). What these costs mean is that buffers should only be used when absolutely necessary.

Capacity Utilisation

When traffic starts to build up on highways, it starts to slow down! In so called "rush hours" traffic crawls and can stop! Late at night, with few vehicles around, it flows fast and smooth. Roads have a finite capacity. At slow speeds drivers are willing to drive nose to tail; as speed increases, drivers, for self-protection, want more space between their vehicle and the one in front. This means that the capacity of the highway is higher at slower speeds, but it takes longer to get from A to B. Getting things done in construction is no different. Overloading subcontractor or fabricator crews through *acceleration, crashing* (Winch, 2010, p.291) or other interventions and putting too many workers in a single space on-site is likely to slow or delay production. To prevent this, it is good to ensure that spaces are not allowed to become overcrowded and that the work that trade crews commit to do will not overload the crew (Court, 2009).

In construction particularly, the capacity utilisation curve (Figure 2) can operate in a number of dimensions. A crew of two electricians working in a particular space can do the work that needs to be done in 3 days. If that is not fast enough, the electrical contractor can add an additional person to reduce the delivery time to 2 days. But adding the additional person in the space where the work is to be done may mean that the 3 operatives will get in each-others way and the actual time to complete the work will be >2 days.

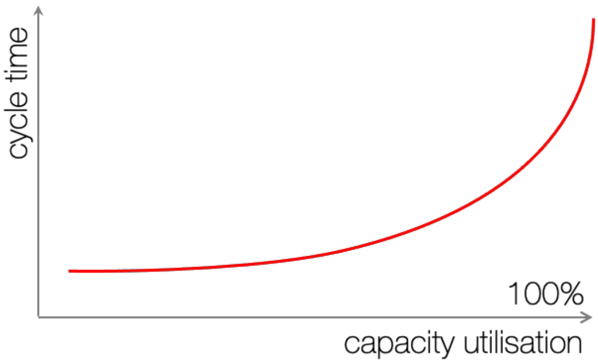

Figure 2: capacity utilisation curve – this graph illustrates the way that, as the use of productive capacity increases the time to complete production of each unit (cycle time) increases exponentially (after Hopp and Spearman, 2000).

Time and/or capacity (people, space and equipment) buffers can contribute to the smooth flow of production provided that the directives (information) and sufficient materials (inventory) are on hand to complete the work 'right first time'. The Last Planner® System can help the production team align their aspirations and minimise buffers while agreeing how they will work together to create flow in the production process.

The Last Planner® System - LPS[1]

Developed by Ballard and Howell from 1980 (see e.g., Ballard, 1994; 1995), LPS is a short-term planning system that aims to create more *predictable* production in construction and other project-based production environments. LPS has improved significantly since its public launch in the mid-1990s (Ballard, 2000; Ballard and Howell, 2003b; Mossman, 2020; Ballard, et al., 2020; Ballard and Tommelein, 2021). It has proved itself on projects large and small over the last 25 years.
In LPS there are at least seven key structured conversations that together make for more predictable production in a project-based delivery setting:

1. **Milestone planning** — planning the key milestones that the project will need to meet and specifying the Conditions of Satisfaction for each one; says what ***should*** happen
2. **Phase Planning**[2] —collaboratively creating and agreeing the production sequence and handovers (and compressing it if required in a phase of the project. Each phase (usually 2-3 months long during construction; shorter periods during design) leads to the delivery of a fully specified milestone; says what ***should*** happen.
3. **Look Ahead Planning** — Making tasks in the *Look Ahead* period ready (i.e., constraint free) so that they can be done when the crew want to do them; prepares what should happen so that it ***can*** happen
4. **Commitment Planning**— collaboratively agreeing *and promising* production tasks for the next period (shift, day or week); *promises* what performers believe ***will*** happen
5. **Operational designs, Method studies, First Run Studies (FRS)** — this conversation can be done at any time for any activity, particularly those that are repeated, complex, critical or potentially dangerous. It is an opportunity to find the safest, most advantageous method to do any part of the assembly process; it can be seen as a *kaizen* event.

[1] Last Planner, Last Planner System and LPS are all registered trademarks of the Lean Construction Institute.
[2] sometimes called collaborative programming, pull scheduling, pull planning, reverse phase scheduling, collaborative mapping, sticky-note planning

6. **Production Management** — collaboratively monitoring and adjusting production on a daily basis to keep activities on track; looks at and begins to learn from the work that is being ***done***
7. **Measurement, learning and continual improvement** — learning together from what ***did*** happen and improving project, planning and production processes every day, every week.

Three principles are important in thinking about LPS: (a) *"All plans are forecasts; all forecasts are wrong"*; (b) *"The longer the forecast, the more wrong it becomes"*; and (c) *"The more detailed the forecast, the* wronger *(sic) it is."* With these principles in mind, each of the first four planning conversations chunks activities to a smaller, more manageable level (Figure 3) — it is as if you were descending from cruising altitude at 10km where you can only see large objects until, when you have touched down, you can see fine detail. This happens as the date when the work is due to be done gets closer. Principle (a) entails acceptance that all plans have the potential to be wrong. This makes it much easier to maintain focus on reality, on what *is* happening and to adjust the plans to the way things are. Notice too, on the left, the planning conversations that precede any promise and how the conversations take what should be done and break it down into smaller chunks, to make the work ready to be done. Task-by-task, conversations 3 are about systematically removing constraints associated with any of the flows presented in Figure 1 above. Once a task is ready (constraint free), crew leaders are able to promise that it will be done in the next period and then do it. Conversation 5 is not shown here – like conversations 1 and 2, conversations 5 happen when needed.

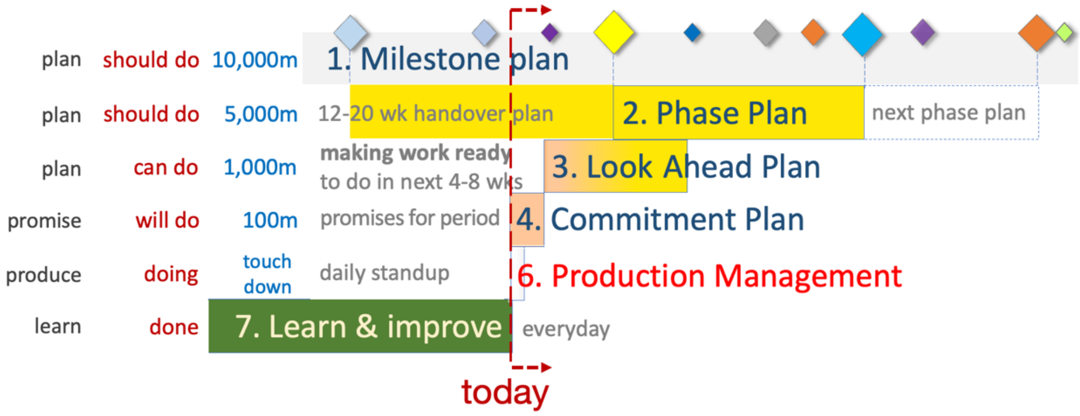

Figure 3: Level of detail in planning increases as the time for production approaches (graphic: Mossman)

LPS creates the conditions for JIT delivery to site and it has successfully helped many projects using OSF elements. For example, Skanska in Scandinavia chose to adopt LPS to help make their projects a reliable customer for JIT deliveries so that they could use more OSF (Reported by Dr Glenn Ballard on IGLC Industry Day 2011, Lima, Peru; Hämäläinen, Ballard and Elfving, 2014). When LPS is coupled with Building Information Modelling, the construction process can be simulated to check the feasibility of installing large components and to manage the flow of work.

Increasingly *Conversation 2: Phase Planning* is being supported by location-based planning systems and particularly by Takt Planning.

As activities move through the conversations, they move from what ***should*** be done, to ensuring they ***can*** be done, promising what ***will*** be done, to what crews are ***doing*** and finally to learning from what the project team ***did***. This is very different from CPM where the focus is on what ***should*** be done.

Critical Path Method (CPM) vs. LPS

CPM and LPS are very different ways of thinking about scheduling work in projects. CPM focuses on *transformations* happening in the right sequence (Dave, et al., 2015), yet it is blind to what is happening on-site. A CPM schedule is a great way to test the *feasibility* of completing project delivery by a particular date and identifying probable critical paths. That is its real value. LPS does not do that.

Based on what *is* happening in the present and on an informed view of what will happen in the immediate future, *LPS* is used for short-term planning. Work is *pulled* into production when the next-trade-in-line believes it will have everything it needs to work on the preceding trades' completed work. As Figure 1 shows, there are eight flows that need to come together at the workface for successful construction assembly work. CPM ignores most of those flows (Winch, 2010, p.291).

CPM has been widely criticized as inadequate to the task of *controlling* work in projects (Koskela, et al., 2014; Dave, et al., 2015). It is neither a *production* management nor a production control system. Even though many in the industry now recognise that (a) *"all plans are forecasts; all forecasts are wrong"* and (b) *"the longer the forecast, the more wrong it becomes"*, CPM is used to manage work in projects by *pushing* trade crews to deliver work based on a schedule prepared months, or even years, earlier by 'professional planners' using assumptions about weather, worker productivity, worker and material availability, among others. If one has not been developed during the design phase, *professional planners* will often prepare a CPM schedule during the tender or preconstruction period. That schedule becomes enshrined within the contract program and constrains later programmes (Winch, 2010, p.292). It is impossible to maintain a complete, up-to-date, plan in the way envisaged by the proponents of CPM-based project management (Koskela and Howell 2002).

There is nothing in the CPM schedule that links decisions to the current reality of the project — no information about whether planned work ***can*** be done (Ballard and Howell, 1995; 2003), nothing to ensure that producers and customers have a ***shared understanding*** of the Conditions of Satisfaction for each activity (Mossman and Ramalingam, 2021), nothing to guarantee that the necessary people, materials and tools, plant and/or equipment are available, let alone whether it is safe to do that work at that time at that workface, and no way to ensure a realistic estimation of crew productivity or time buffers between dissimilar trades (Jaafari, 1984). In CPM, buffers are often implicitly managed in task durations ("just-in-case" approach), thereby inflating the total duration and cost (Winch 2010). The main aim of LPS is to reduce the need for buffers – both flow and process-time variability of tasks (Koskela, Stratton and Koskenvesa, 2010). These are all reasons why CPM isn't appropriate for managing production.

In the early days of CPM, Kelly and Walker noted (1959, p.171) that "*the basic assumption that underlies* [CPM] *… is that* ***adequate resources are available*** *to implement any computed schedule"*. CPM is blind to what *can* be done, particularly when *available resources are shared by many projects*. CPM leads to unpredictable workflow and as Ballard and Howell (1998, p.5) stated "*when it is impossible to determine what and how much work will be available at a future time, it is impossible to arrange for the specific resources needed, and it is impractical to develop detailed methods and to make detailed preparations for doing what could be widely different types of work. Thus, the certainty of workflow from one production unit to the next is a key to productivity*."

In design and construction, work is able to flow when everything comes together smoothly at the workface time after time, after time. Conversation 3, making tasks ready (i.e., constraint free) so that they can be done when the project team wants to do them is key to making this happen – it moves tasks from what ***should*** happen to a state where they ***can*** happen. In this way LPS creates more predictable workflows than CPM.

Just-in-time (JIT)

Kiichiro Toyoda is credited with pioneering JIT at Toyota in the 1930s (Fujimoto, 1999, p.58). Hopp and Spearman (2000) describe how, by the 1970s and 1980s, the Japanese had developed a new style of manufacturing and associated techniques that became collectively known as *Just-in-time*. The way Taiichi Ohno made this work effectively in the 1950s was by using a simple signalling system (*Kanban*) (Fujimoto, 1999, p.59). This connected each step in the JIT process and synchronised them. Simultaneously it reduces both the volume of inventory in the system and the demand for management work (workers "pull" the materials and sub-assemblies they need from co-workers earlier in the process without the need for managers to intervene). JIT reduces waste by supplying parts only when the assembly process requests them.

Ohno was working in a manufacturing environment (Toyota). As Vriehoef and Koskela (2005) among others make clear, construction is generally different from manufacturing. Ballard and Howell (1995) conducted one of the earliest studies of the relevance of JIT to construction. LPS-managed *production* helps create predictability and flow that supports JIT. In construction, *kanban* requests can go from anyone on-site to whomever is supplying what is required. The aim, in a construction workflow, is for the right parts (ETO and MTS) to reach the assembly point with all the other 'flows' (as in Figure 1) at the time, and in the quantity, they are needed. For this flow process to work, it needs to extend back to the supplier of raw materials.

How green is JIT in OSF?

The findings of a systematic review of 25 Years of IGLC published research on lean and sustainable construction by Sarhan, et al. (2019) indicated a trade-off between production and environmental performance in construction. Their study also suggested that lean construction theories and strategies need to take a whole project-life cycle perspective.

There is a lack of consensus amongst scholars in literature on whether JIT and other lean practices are environmentally friendly or not (for e.g., see Sartal, Martinez-Senra and Cruz-Machado, 2018; Green, et al., 2019; Dieste, Panizzolo and Garza-Reyes, 2020). A study by Bae and Kim (2008) was conducted to assess the environmental impacts of a lean supply system through a case study of high-rise condominium construction in Seoul, Korea. Bae and Kim compared the amounts of CO2 emission, energy consumption and material loss for two different rebar supply systems — JIT and Batch. They found that the environmental impact depends on delivery distance and reported: "*JIT increases energy and CO2 emission per rebar consumption during rebar fabrication and transportation, especially when delivery distances are increased. If JIT is used in a case where delivery distance is short, it can be an environmentally-friendly option with decreased inventory loss rate*" (p.741). Their study took no account, however, of the costs and hassle associated with moving batch delivered rebar stored on-site – examples of what Koskela and Tommelein (2009) referred to as the 'means and management of production delivery' that is often overlooked when comparisons between alternative sustainability options are conducted.

Gibb (1999) listed potential benefits associated with OSF in addition to those mentioned in Table 1 above. These include better controls on atmospheric pollution, easier recycling of materials, if a building needs to be demolished or significantly altered it is easier to do with prefabricated elements and it may be possible to re-use them. Gibb also suggests less energy is used in transportation – though some would challenge that. As with Bae and Kim's study (2008) and particularly with volumetric, it depends on how far the fabrication shop is from the site.

Wan Amstel and Postulart (2017) reported that more than 15% of construction costs are transport related and "*30% of the commercial traffic in Dutch cities is for construction sites - more than 200,000 delivery vans and 20,000 trucks on a daily basis*". Building on the experience of the Hammerby Sjostad Logistics Centre, Stockholm, Sweden and Transport for London in the UK, Dutch construction companies and a transport company participated in pilot projects in Amsterdam and Utrecht. The projects were studied by the Netherlands Organisation for Applied Scientific Research (TNO) and Dutch universities. As in the London research a decade earlier (e.g., Department for Trade and Industry, 2004; Peter Brett Associates, 2007), the results are significant:

- nearly 70% fewer transport movements to construction sites (reducing vehicle movements improves road safety as well as reducing pollution (Davies and White 2015),
- nearly 70% fewer CO_2, NO_X and particulate emissions, and
- up to 40% higher productivity at the site
- fewer complaints from people in the surrounding area (van Amstel and Postulart, 2017)
- at least 7% less material losses and damage (Transport for London 2016, p.12)
- *3-5% lower construction costs.*

The cost reduction is equivalent to *doubling the profits* of some constructors. That alone may be a reason for using a local *consolidation centre* (CC) even if JIT is fully operational on a project. As project supply and delivery teams become more proficient at JIT and their trust in each other grows, they will need ever smaller buffers at a CC so the space required will fall. This allows CCs to be smaller or to serve more projects in their locality. This research studied CCs serving projects with very little OSF. It does show how JIT can help to improve the environmental sustainability of the construction sector.

The Heathrow Terminal 5 (T5) project used a CC about 2km from site as a *buffer* to ensure *JIT* delivery to site. In the earlier stages of the T5 project, part of the CC was used for producing rebar cages in the warm and dry. This reduced the time taken to create rebar cages, saved materials, was safer and helped speed up the foundation works programme. A CC is a form of *buffer*. It has both costs and benefits. In order to reduce the costs, it is important to minimise the time that materials and sub-assemblies spend in the CC. Ideally all bulk materials, large items and prefabricated elements will go directly to the site for just-in-time installation.

Research Design and Methods

This is a conceptual paper that takes a problem-focused approach. The paper is conceptual because it focusses on developing logical arguments and providing novel insights that can be used to inform further research, rather than testing existing concepts or theories empirically (Gilson and Goldberg, 2015). Such papers should be grounded in a clear research design that explicates and explains the theories and key concepts used to generate novel insights (Jaakkola, 2020).

This paper considers two case studies and the authors' experience in the context of a critical review of the literature on Flow, Capacity, Buffers, Critical Path Method, the Last Planner® System and Just-in-Time. The literature review is used to define and explain the conceptual ingredients of the empirical phenomenon in question – how OSF can be synchronised with onsite production and assembly. The case studies are used to illustrate specific real-life problems with JIT delivery in prefabricated construction, as experienced in two different

projects and counties (i.e., The United Kingdom and Canada). The first author of this study was involved in these projects through observation and/or interaction with the project teams. The two illustrative case studies are analysed using the TFV theory of production as an analytical lens. The lessons from the cases are then used to answer the research question, in the form of proposing a sustainable-lean approach for synchronising OSF with on-site production in construction and highlighting directions for further inquiry.
The researchers' personal experiences and insights are an important part of the inquiry and critical to understanding the phenomenon (Sutton and Staw, 1995). This is supported by Maslow (1966, p.45) who asserted that "*there is no substitute for experience, none at all',* to point researchers towards the value of using discovery, intuition and thinking as a primary evidence (Finlay, 2002). Thus, this process influenced this study in three main ways: (1) forming the research question; and (2) identifying and reflecting on lessons from the case studies – this required an understanding of the complex interdependencies and system dynamics; (3) framing the conclusions and developing the propositions. Being immersed in one's own emotions and experiences, though, may lead to bias and skewedness in a research. Yet, it is important to stress that "*preconceptions are not the same as bias, unless the researcher fails to mention them"* (Malterud, 2001, p.484). To overcome these challenges, 'reflexivity' was employed throughout this study in various ways:

- Conducting a multi-authored research study – this has helped in fostering reflexive dialogues, peer reviews and critiques, and reliability.
- Grounding this study on fundamental theories and concepts– this has helped to position the study and inform decision making
- Explicitly acknowledging the assumptions and preconceptions that the authors brought into the research – this can be useful in terms of establishing trustworthiness in the study.

Case Studies

Here are two short case studies. In the first, the off-site fabricator set itself up so that the site installation team is the client for the rest of the organisation. This means that the head office and the fabrication shop provide service and support to enable the installation to proceed as planned. In the second, the installation team were using LPS, and the factory claimed they were using lean methods and principles. Yet the factory did not think of the site installation team as the customer. Their focus was on optimising factory throughput. In the process they ignored value to the customer, a key lean principle.

Case Study 1: Hathaway Roofing

This first case illustrates the importance of understanding the different capabilities of each supplier and of trust in the supply chain.
Hathaway Roofing switched to JIT lean production (Figure 4) in the late 1990s so that it could better serve sites. The redesigned factory simplified the production paths for each of their main product types. In the redesigned factory, products flow. Most materials are delivered to the start of the production process on a JIT basis and never go into stores. At the end of the production process items are shipped to site.

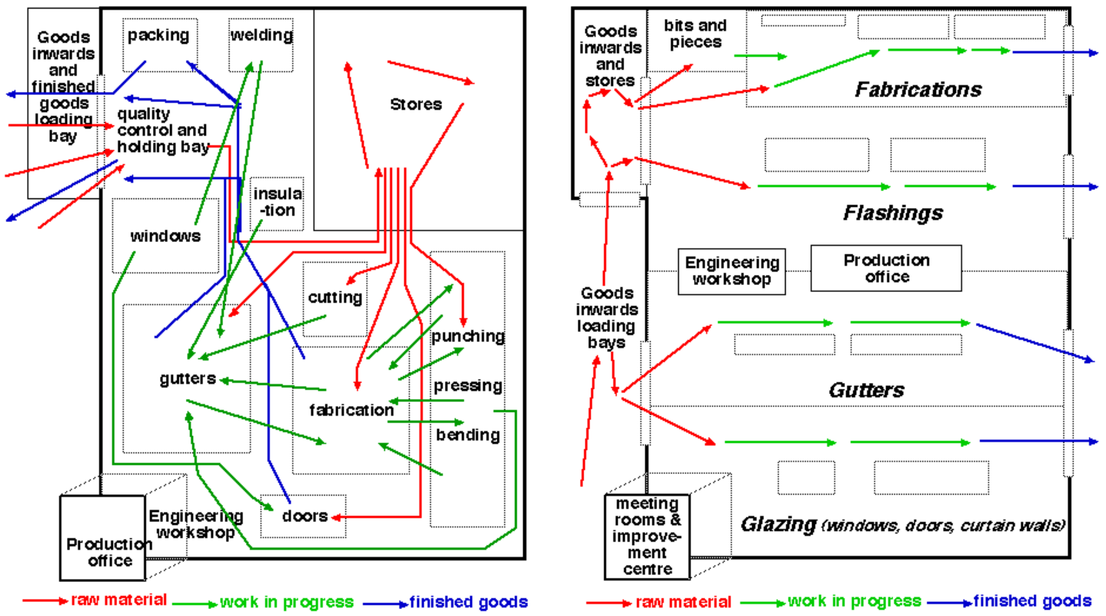

Figure 4: the Hathaway Roofing factory before switching to JIT production (left) and after (right). Source: Swain and Mossman (2003)

London Heathrow Terminal 5 (T5) client and main contractor, BAA plc, the then operator of seven airports in the UK, sought to minimize the risk of delays at site. They chose Hathaway Roofing to fabricate the 1500 roof panels in the north of England, about 6 hours by truck from the site. The transformed Hathaway factory was able to produce in one workday the panels that would be installed during the next workday and ship them to site overnight. They could produce them in the right order for installation. In this case, so that they could have security of supply, BAA decided that it wanted all 1500 panels in a warehouse close to site before any work started on the roof. Why did they choose to secure their supply in this way? What did they pay for that security of supply? … for that huge buffer? Whatever the reason, Hathaway management felt that BAA did not trust them sufficiently to permit JIT delivery.

Case Study 2: hydro-electric project: end-to-end coordination and synchronization are critical

The second case illustrates why it is important to consider the site as the *customer* for both JIT fabrication and JIT delivery of the right components in the right sequence at the right time – the whole system needs to be joined-up.
On a remote **hydro-electric project** in Northern Ontario the subcontractor responsible for supplying and installing the turbine and the generator used LPS at site and (supposedly) lean manufacturing at its production facility, yet it appeared that there was nothing lean about the way the equipment to be installed was shipped to site. The lean team in the European factory produced what was needed at site in a way that optimized their *local* production system – they saw no reason to consider the needs of their colleagues at site. Materials were shipped in production order – not in installation order. The major items, the ETO parts, were checked prior to shipping but it appears that no-one thought to check the MTS items such as critical ultra-high-strength bolts of specific lengths. The lack of sufficient bolts to complete the installation added cost and considerable delays as the missing parts made their way from Europe along the ice-bound St Lawrence Seaway, through customs and along ice bound roads.

Analysis and Discussion: Just-in-time

Synchronising production on-site and in factories and fabrication shops that supply the site is critical as we saw with the hydro-electric project. Both the site and the fabrication shops rely on just-in-time (JIT) deliveries. Together, these help on-time (or better) delivery of the project. In Figure 5, a simplified example, the site is supplied directly by some suppliers and by two different fabricators producing ETO and MTS items. For work at site to flow smoothly and without interruption, the site needs just-in-time delivery from each of the fabricators and the other suppliers. Late delivery to site is clearly a problem – workers must wait for work.

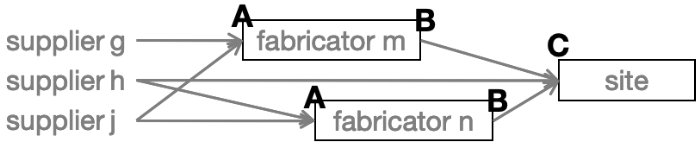

Figure 5. A simplified construction-process. Time runs along the horizontal axis.

It is not just the site that needs JIT delivery. Each of the fabricators needs JIT delivery too. So, in this simple system, signals (*kanban*) from site could start a production process at each of the fabricators who in turn send signals to each of their suppliers including the haulage company (or internal transport department) that will deliver their fabrications to site. This process will only flow if JIT thinking is embedded in the *end-to-end process*. As shown in Table 2, There are at least two potential interruptions to flow at each of the lettered locations shown in Figure 5.

Table 2: potential interruptions to flow at each of the lettered locations shown in Fig. 5.

A: fabricator good inwards:	B: fabricator shipping:	C: at site:
• waiting for raw materials and supplies from suppliers • raw materials and supplies waiting to be used	• sub-assemblies waiting to be delivered • delivery trucks waiting to take sub-assemblies to site	• sub-assemblies and supplies waiting to be installed • workers waiting for supplies and sub-assemblies to arrive

Each of these waits adds to the time it takes to complete the project and, generally, adds to the price paid by the client. Clients and main/general contractors (CM/GCs) want the benefits of prefabrication and associated JIT supply, yet, because of traditional procurement strategies, are generally unwilling (or unable) to *demand* JIT supply from their supply chain – they tend to ignore, or be blind to, the effects of the methods used on the outputs delivered as pointed out by Koskela and Tommelein (2009). This approach to sustainable construction assumes 'fixed input-output relations' and overlooks the means and management of production delivery (Koskela and Tommelein, 2009; Sarhan, et al., 2019).

Heathrow T5 was a highly collaborative project with its own bespoke contract. Hathaway was not one of the companies "in" the collaborative contract – they had a sub-contract. The T5 team did not trust them – or acted as if they did not. This underscores the idea that construction is a social process.

When a site is kept waiting for ETO sub-assemblies or critical MTS items that is a loss for the those waiting to install the sub-assembly on-site, as well as a delay for the client and CM/GC. If the site is not ready to install a sub-assembly when it arrives there may be an additional cost (e.g., demurrage) to the haulier, the fabricator and/or the sub-contractor (often passed on to the client as was the case with the Hathaway Roofing elements). If there is laydown space on-site, the sub-assemblies may be stored where they may:

- impede other activities and require moving one or more times

- be damaged by weather, site conditions, machines or equipment – or by pilfering.

In each instance it is generally the client that pays, even though little or no value has been created. Avoiding or reducing all these additional costs requires:

- *Predictable* production at site
- *Predictable* production of sub-assemblies by multiple independent off-site fabricators serving a range of unique sites.
- *Predictable* logistics connecting the site and the fabrication shops.

There are many uncertainties associated with each of these and LPS and JIT can help to reduce them. LPS was developed in the context of Design-Bid-Build (DBB) contracting and CM/GCs do not need client approval to adopt LPS. They *will* need a collaborative culture within their supply team.

Where JIT is not yet working

While waiting for supply chain partners to adopt JIT principles it is possible for clients and constructors to foster JIT production on-site by creating a *buffer* between the suppliers, fabricators and the site. A *consolidation centre* at a short distance from the site is one way to do this. This was done for T5 (Department of Trade and Industry, 2004) and for projects in the centre of London (Transport for London, 2007; 2016) for example. Ideally materials are delivered to a CC no more than 7 days prior to their being required on-site (and preferably less). The CC checks the materials delivered and returns any that are defective. Unnecessary packing can be removed before materials are delivered to site (reducing reverse logistics) and sometimes it is possible to minimise packaging at the fabrication shop as the sub-assembly will be weather protected from factory to site. Kanban signals from site trigger the delivery of materials and sub-assemblies JIT so that they can be moved directly to the part of the structure where they will be installed. A CC can provide a kitting service – separate but related items, say for a single space or zone, grouped and delivered together.

Suggestions for improving production effectiveness in prefabricated construction projects

Based on the analysis of the two case-studies and reflections on the lessons learned, using TFV-theory as an analytical lens, the answer to the study's research question (RQ) can be summarised in the form of three propositions presented in Table 3.

Table 3: Propositions for improving production predictability and coordination in prefabricated construction projects

	Current problem	*Proposed alternative*	*Why?*
P1	Using CPM planning and scheduling software (e.g., MS Project, Primavera)	Create steady predictable flow on-site using the LPS and other lean systems	The construction sector has been using CPM planning/scheduling for many decades. McKinsey Global Institute (2017) shows it has not made production more reliable or helped it to flow. LPS is already doing that.
P2	Materials delivered according to suppliers' schedule, *pushing* the product to the site-team	Allow site-teams to pull product from fabricators and from suppliers JIT or, if that is not possible, use a consolidation	Materials, sub-assemblies and fabrications moved to site when they are ready → potential costs for the client. Site teams using LPS can give fabricators and suppliers clear signals about when they will be ready to receive the

		centre as a buffer so that materials do arrive JIT.	materials. If that is not possible, a local CC can enable JIT delivery.
P3	Focussing on optimising individual production systems, each separately – optimising local production systems	Paying attention to the end-to-end process so the whole process flows, then begin to increase the flow rate.	In traditional construction, each trade or crew tries to optimise its own bit of the construction process and hardly anyone is looking at the effect on whole-system flow. Coupled with Takt Planning, the structured conversations in LPS, can help a whole-team focus on whole-system flow.

Conclusion

Creating a smooth, predictable flow in construction production with OSF requires just-in-time delivery throughout the end-to-end construction supply chain. In practice this level of coordination and synchronisation of operations is not possible with the traditional Critical Path Method. Over the last 25 years, the Last Planner System has shown itself capable of improving the predictability of site operations to a level where mixing on-site and off-site production is a realistic and cost-effective option.

In the context of OSF, this paper has shown that failing to fully implement JIT across an entire production system can reduce both productivity and profitability. This has the potential to disappoint clients and slow the uptake by creating poor experiences of using OSF, reducing or eliminating expected cost savings and extending anticipated construction times. Creating a buffer, such as a consolidation centre, between suppliers, fabricators and the site is one way to help the whole supply-team learn to create predictable flow. There may even be arguments for doing this anyway as it reduces some of the undesirable externalities associated with construction. As JIT proficiency improves consolidation centres can serve more sites.

The aim of this study was to generate ideas for empirical examination in future studies. It is suggested that the three propositions offered in this study (in table 2 above) can help clients and the whole supply team improve: production flow, production predictability, trust and collaboration in prefabricated construction projects. In addition, the study provides the following questions and ideas for further research.

- Designers tend to design for what they think any constructor can build. Not all constructors can or want to use OSF options, so in DBB procurement, use of OSF often requires significant design rework. Other than *Integrated Project Delivery* or *Alliancing*, are there ways to reduce that design rework?
- What are the advantages of managing logistics at the level of the organisation and at the level of the project?
- What are the typical costs of failing to synchronise production on- and off-site in terms of e.g.: time lost, financial loss, damage to sub-assemblies that arrive before the site is ready to install them, sub-contractor losses resulting from workers waiting for work, etc.
- Does JIT and OSF increase the sustainability of a construction project?
- What is the best way to introduce LPS to a project?
- What is the best way to embed JIT thinking and processes in the end-to-end supply team?
- Can LPS help to reduce accidents and safety concerns related to OSF construction?

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