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EXPECTED LEAN EFFECTS OF ADVANCED HIGH-RISE FORMWORK SYSTEMS

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ABSTRACT

The selection of formwork systems in high-rise buildings is often governed by their competence in optimizing concrete activities in an isolated manner, without relating this choice to the entire construction workflow. Known research efforts do not address this important aspect in analyzing high-rise formwork technologies, and formwork selection is usually left to constructors' experience, and corresponding organizational knowledge. In this context, this paper studies the role of formwork systems in high-rise construction from a lean perspective and analyzes this role in shaping not only the progress of concrete activities, but the entire construction sequence. Employing lean concepts, the paper investigates advanced high-rise formwork systems versus traditional ones to better advise scholars and practitioners. Results highlight the importance of advanced high-rise formwork systems in streamlining the workflow of concrete and other downstream activities, allowing for more waste reduction, smaller work batches, less inventory, and safer working environment. This study is a conceptual framework for future related works involving case studies and field investigations, and may be further developed to target more aspects of high-rise construction.

KEYWORDS

Workflow, Logistics Planning, Inventory Control, Waste Reduction, Safety.

INTRODUCTION

High-rise construction witnessed a rapid growth in the past few decades. Several aspects of high-rise projects, from architectural and structural designs, environmental strategies, lifting techniques, firefighting systems, construction methods, and safety procedures have seen major developments. However, high-rise projects encounter several challenges throughout their construction stages. Beyond engineering and construction difficulties, planning of logistics appears to be a major concern on such projects. Most skyscrapers are built in tight land lots in city centers with serious limitations on available storage areas to the extent that sometimes there are none available. This fact imposes high pressures on the supply chain management where timely and proper material delivery is important. Other difficulties encountered on

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high-rise construction can be related to building design complexity, technologies used on site, labor availability and skills, adequacy of the methods followed, and capacity of planners to foresee the dynamics of their site and proactively shape its progress.

While technical constraints are resolved by advanced engineering solutions, construction constraints can be removed by better planning and scheduling, using advanced technologies on site, and by employing lean ideals. Several studies targeted the application of lean principles in various high-rise construction aspects (Sacks et al., 2005; Bae and Kim, 2008;Al Hattab, Zankoul and Hamzeh, 2014), whereas other efforts investigated the use of lean principles in enhancing construction workflow in general (Arbulu and Ballard, 2004; Hamzeh, Ballard and Tommelein, 2008; Yassine et al., 2014). However, none of the literature reviewed addresses the role of formwork systems in shaping the workflow of concrete and non-concrete activities in high-rise construction, and their impact on the application of lean concepts.

In this regard, addressing the role of formwork systems in directing construction workflows on high-rise projects is a novel approach that allows researchers and practitioners to link the choice of formwork systems to construction workflows on one hand, and to logistics planning, inventory dynamics, crane schedule, labor and material delivery, and safety procedures on the other. Accordingly, this paper aims to: (1) compare advanced and regular formwork systems, (2) track construction workflow changes, and (3) underline major lean principles enabled by the use of advanced formwork technologies.

RESEARCH BACKGROUND

The repetitive nature of high-rise construction helps planners maintain workflow continuity, decrease labor and equipment idle times, reduce hire and fire actions, and take advantage of the learning curve effects (Ranjbaran, 2007). However, these repetitive activities advance simultaneously in vertical and horizontal directions and may create spatial constraints that hinder the execution of work (Thabet and Beliveau, 1994). To account for these constraints, practitioners and researchers sought scheduling solutions to navigate the execution of tasks under these restrictions. Since the drawbacks of applying the Critical Path Method (CPM) to schedule repetitive tasks were investigated in many studies, (Hegazy and Wassef, 2001), alternative scheduling techniques using the Line of Balance (LOB) method were employed. LOB allows operations on site to continuously flow from one activity to another by balancing different tasks, resources, and space simultaneously (Hegazy, 2002). While some researchers worked on combining both the CPM and LOB methods to enhance work scheduling in repetitive construction (Suhail and Neale, 1994), other researchers used 4D modeling techniques provided by Building Information Modeling (BIM) technologies to simulate the construction sequence and to proactively account for possible on site clashes (Staub-French and Khanzode, 2007).

These scheduling solutions (LOB, LOB-CPM combined, and 4D scheduling) assume the availability of labor and material necessary to execute the work at the right time and location; however, this is not always the case. Delays and cost overruns are often attributed to the failure of delivering resources to work areas when needed, especially on high-rise projects. Hence, a clash free schedule is not necessarily translated into smooth workflow on site, thus highlighting the importance of day to day site dynamics including delivery procedures, hoisting capacity and speed, and crane availability. In this context, the choice of formwork system greatly influences the workflow of concrete and non-concrete activities. Core-wall and floor formwork systems directly affect concrete cycle times and indirectly influence the interlocking flows of walls, shafts, and slabs where different tasks from different trades are involved. For instance, formwork lifted by a crane would interrupt the crane schedule and may delay the delivery of materials to other work areas for several trades, resulting in significant delays and additional costs. Therefore, the selection of a convenient formwork system is a key decision on every high-rise construction.

Several parameters, presented in Table 1, affect the choice of formwork systems. While internal parameters fall under designer and contractors control, external ones are affected by owner requirements, project milestones, project location, and corresponding local rules and regulations (Gnida, 2010). Other studies linked the selection of the formwork system to building height and weather conditions (Ciribini and Tramajoni, 2010). Based on these parameters, many contributions were made to improve the efficiency of formwork systems resulting in wide variety of formwork types. In addition to the previous parameters, the selection of formwork is mainly governed by cost considerations where contractors try to minimize the total cost of the concrete package in isolation of the indirect costs of the resulting schedule.

In this context, the paper presents scholars and practitioners a comprehensive understanding of formwork role in high-rise projects, where advanced systems are expected to enable the realization of several lean principles such as waste reduction and workflow enhancement.

Table 1: Parameters governing the selection of formwork systems (Gnida, 2010)

Internal Parameters		External Parameters	
Geometry	• Repetitive • Simple/ Complex • Changing Geometry	Space	• Existing Road or Building • Storage Area • Assembly Area
Concrete	• Rate of Pour/ Concrete Pressure • Concrete Finish • Curing Time	Wind	• Wind Load
Sequence of Work	• Cycle Time	Crane	• Capacity/ Type • Availability • Boom Reach
Formwork Choice	• Existing Formwork Material to be Reused • Rental or Purchase • Best Value for Current Project Vs. Flexibility for Future Projects	Safety	• Special Requirements Needed
		Construction Planning	• Milestones • Working Schedule/ Shifts • Project Duration • Holidays
		Local Rules/ Regulations	• Permits • Restricted Noise • Safety Requirements

RESEARCH METHOD

This paper investigates the role of high-rise formwork systems in shaping the workflow of concrete and non-concrete activities. It also addresses the effects of formwork choice in governing site dynamics, labor and material delivery, inventory size, logistics planning, and cranes' schedule. Comparing advanced and regular formwork systems, the paper underlines major differences from a lean perspective, and employs a process model to describe the workflow alterations in both cases. The paper concludes by highlighting major lean principles enabled by the use of advanced systems. Figure 1 illustrates the roadmap followed to achieve paper objectives.

Figure 1: Research Roadmap

RESEARCH LIMITATIONS

The paper investigates the role of advanced high-rise formwork systems based solely on theoretical analysis. Field data collection and case studies can be addressed in future efforts to provide required quantitative analysis.

FRAMEWORK DEVELOPMENT

ADVANCED AND REGULAR FORMWORK COMPARISON

Advanced and common core-wall formwork technologies used on high-rise projects are self-climbing systems, lifted using hydraulic jacking mechanisms independent of any external crane or lifting equipment. However, advanced systems are available as single or double jump formwork assemblies that jump two floors at a time. Another important feature that distinguishes advanced core-wall formwork systems is the shaft trailing platform attached to it as shown in Figure 2. The trailing platform could drop up to six floors down the core-wall formwork allowing elevator specialists to start fixing elevator rails and accessories early on (Double-Jump System, n.d.).

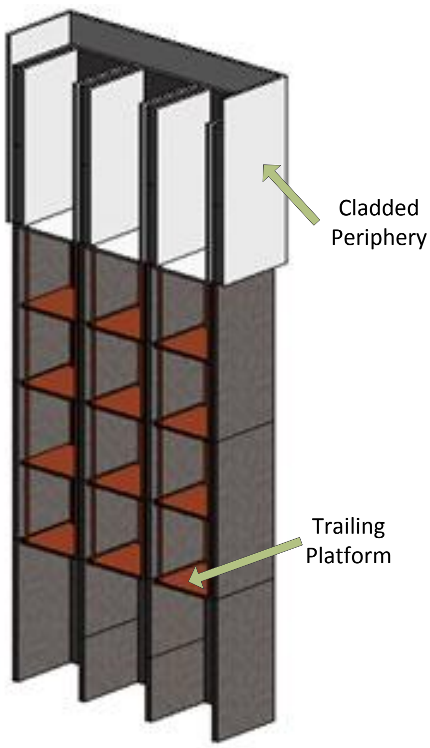

Figure 2: Schematic representation of advanced core-wall system

As for the floor's formwork, practitioners try to benefit from the repetitive nature of slab construction by standardizing formwork size and material, and by maximizing the number of formwork reuse. In this context, table forms are widely used to decrease formwork setup time and to decrease slabs' construction cycle time. But, regular table forms are crane dependent and congest the crane schedule every time they are moved from one floor to another. Regular vertical forms are also modularized and moved by cranes from a floor to another. On the other hand, advanced formwork technologies provide innovative perimeter system which combines construction and safety requirements. A self-climbing system is used to form vertical elements such as columns and walls independent of floor slab construction. The jacking points of the system are above floor slab giving clear access for slab formwork, reinforcement, and concrete pouring below the system, as shown in Figure 3. The key advantage of the perimeter system is the accelerated construction of columns and slabs that progress independent of each other. The system can also provide lifting services to move slab table forms internally without any use of the tower cranes (Double-Jump System, n.d.).

Figure 3: Advanced perimeter system (Double-Jump System, n.d.)

For the purpose of comparison, Table 2 serves as a reference for the major differences between regular and advanced formwork systems discussed in this study.

Table 2: Advanced and regular formwork comparison

Feature	Regular Formwork System	Advanced Formwork System
Self-Climbing Core-wall Formwork	✓	✓
Core wall Formwork Internal Lift	X	✓
Core wall Trailing Platform	X	✓
Perimeter System	X	✓
Internal Table Lifting Capacity	X	✓

CONSTRUCTION WORKFLOW DIFFERENCES

To examine the role of formwork in shaping construction workflows, two process maps, illustrated in Figures 4 and 5, were developed to trace the differences in the construction sequence resulting from the use of advanced and regular formwork systems. While the trailing platform allows internal lifts specialists to start fixing lift rails and necessary accessories early on, elevator related tasks would not start until finishing core-wall construction in the case of regular formwork. Accordingly, service elevators can be made functional before final core-wall erection and can be used to hoist labor and material. Another schedule difference between the two cases occurs at the columns (walls) - slabs construction interface. While advanced systems allow the progress of vertical and horizontal elements independently, regular formwork systems are bound to the column (walls) – slabs sequence in every floor.

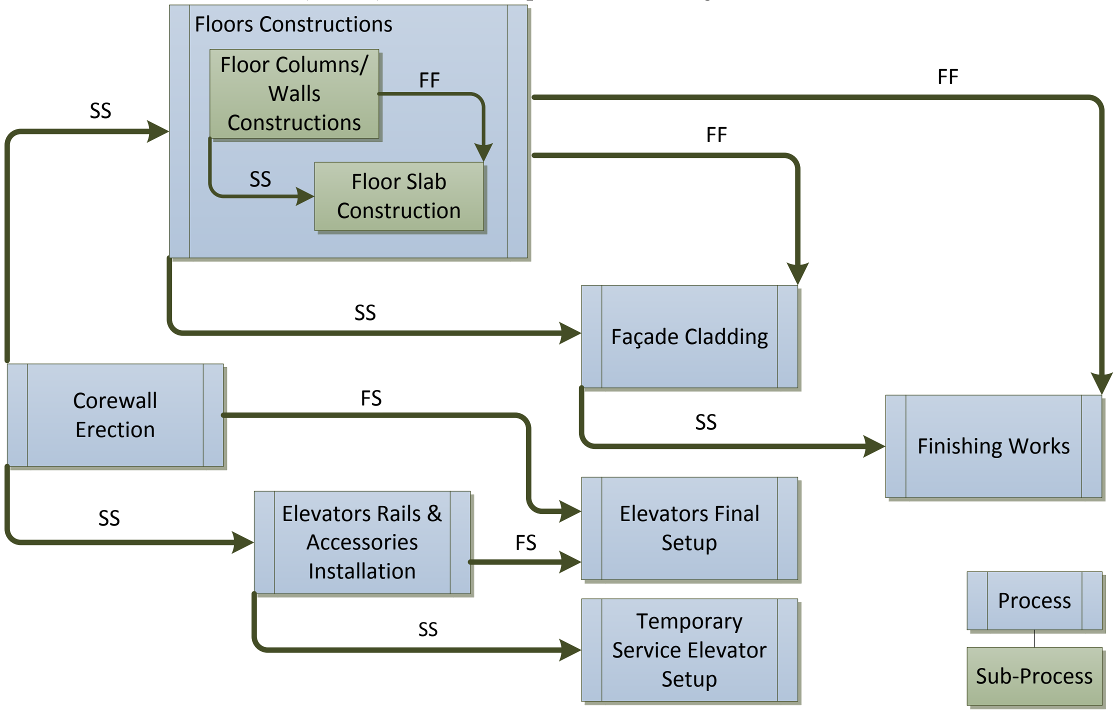

Figure 4: Construction process map using advanced formwork systems

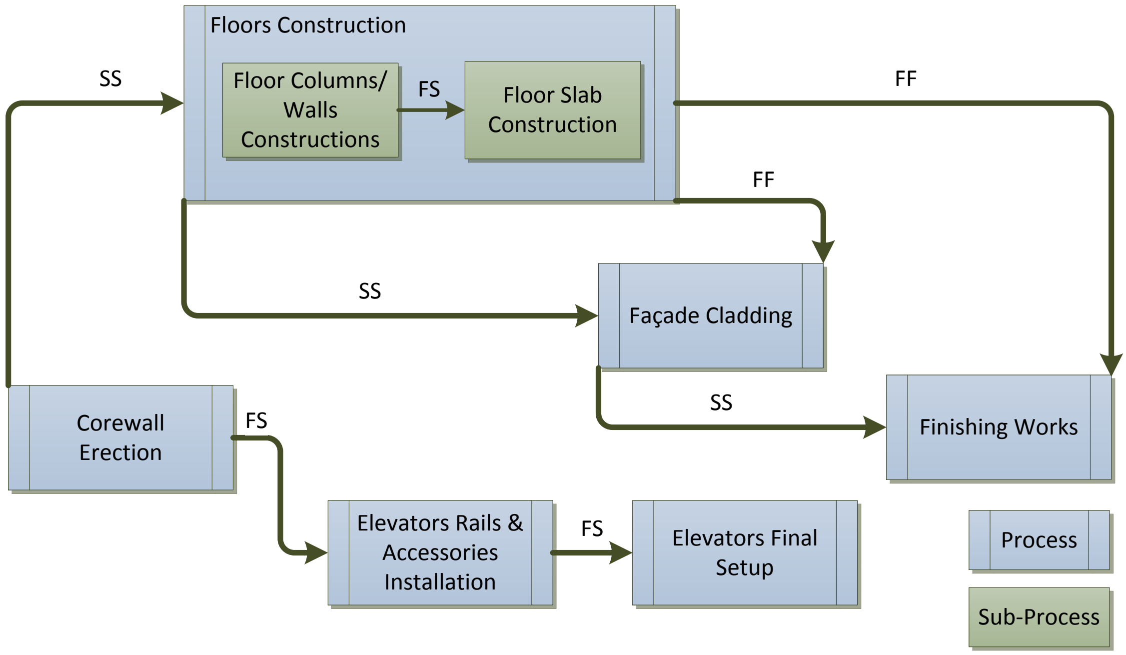

Figure 5: Construction process map using regular formwork systems

(SS: Start to Start, FF: Finish to Finish, FS: Finish to Start)

RESULTS AND DISCUSSION

WORKFLOW ENHANCEMENT AND CYCLE TIME REDUCTION

Advanced formwork systems enhance construction workflow on several fronts. The shuffling of construction sequence supported by the trailing platform allows the use of buildings service lifts early in the execution phase to transfer labor and material into the building, necessary to boost finishes and MEP activities. This fact decreases the demand on external hoists and tower cranes that are made available for other critical activities such as external cladding, and heavy material lifting. On one hand, the independent progress of columns and slabs, enabled by the self-climbing perimeter system, helps streamline both activities together and reduce the risk of one process delaying the other as in the case of regular formwork. It also boosts the production rates of both activities due to learning effects. On the other hand, advanced core-wall systems, like the case of double-jump system, can jump two floors at a time leading to significant reduction in cycle time; the work can be literally halved. For instance, steel fixing activities are done only once every two floors, and the same concept applies to concrete pouring as two consecutive floors are poured together. Other time consuming activities such as surveying operations, formwork alignment, and reinforcement inspections are also optimized to boost core wall construction speed. Therefore, as the number of cycles is largely decreased, the construction time undergoes substantial drops. Even with the single jump option, the system has been proven to reduce the cycle time to three to four days per floor (Naylor, 2006), especially that the formwork is totally isolated from external weather conditions by cladded screens and the top formwork deck is free from mass constraints providing workers a safe and adequate working environment.

Figures 6 and 7 schematically illustrate the expected differences between both schedules. First, production rates are expected to be higher in the case of advanced systems due to core-wall double-jump construction and the released cranes' and hoists' schedules. Second, elevators' installation starts and ends earlier, with the elevators temporarily ready at core-wall mid-height as shown in Figure 6. Third, columns and slabs construction are streamlined with the possibility of independent progress.

WASTE REDUCTION

Advanced formwork systems target several aspects of waste usually encountered on construction sites. The system reduces the amount of material wasted to follow design standards as in the case of steel splices (or couplers) that are used once every second floor (in the case of double jump system). Nonetheless, material idle time is expected to decrease due to improvements observed in material delivery and inventory management. Moreover, the trailing platform allows the early occupation of core-wall shafts by lifts' crews; a working space wasted in the case of regular core-wall formwork. Advanced formwork systems also reduce unnecessary movements. In this regard, lifting crews and material which is usually performed by external hoists and cranes, which take longer time with increasing building height, is now boosted by the early use of building service elevators. Beyond the mentioned wastes, advanced formwork systems provide a well-organized working environment that reveal the sources of waste and brings them to surface. As the system pushes towards continuous flow of activities alongside smaller work batches, project managers can better detect wastes taking place and act proactively against them.

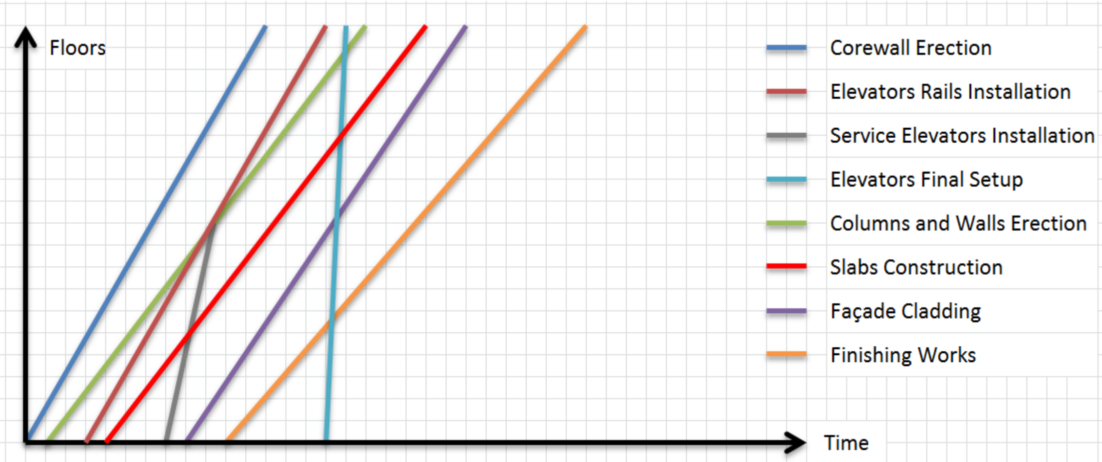

Figure 6: Schematic LOB schedule using advanced formwork

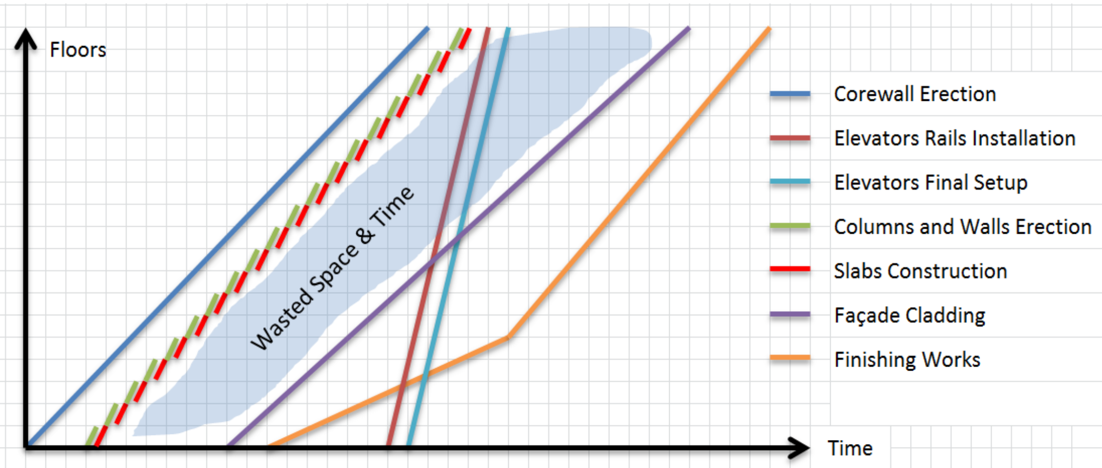

Figure 7: Schematic LOB schedule using regular formwork

REDUCED VARIABILITY AND INCREASED FLEXIBILITY

The repetitive nature of high-rise construction endorses the application of lean ideals. Repetitive tasks help stabilize the construction workflow and promote standardization and modularization. On the other hand, location based scheduling allows for continuous resource utilization and prevents spatial clashes where production rates of crews are adjusted and optimized. However, a clash free schedule and streamlined tasks are not enough to ensure smooth construction workflows on site. In reality, labor and material delivery to work areas is a major challenge on high-rise construction where hoisting speed and capacity decreases with increasing building height and involvement of multiple trades. In this context, the role of advanced formwork systems goes beyond just enhancing construction flows, but also improving labor and material flow on site. By releasing the constraints on the crane schedule and early use of service elevators, advanced systems contribute to increasing site flexibility and reducing batch sizes. As labor and material are efficiently moved to work areas, required batch sizes can be more accurately calculated with less variability, which is an important factor to stabilize the production on site as mentioned by Alarcon and Ashley (1999). Thus, the increased site flexibility is translated into more adequate logistics and inventory management potentially leading to smaller inventory sizes. This fact, along with tighter tolerances provided by advanced systems, empowers the use of prefabrication and off-site production which can boost construction speed, decrease cost, and increase site safety.

SAFER WORKING ENVIRONMENT

Advanced formwork systems provide innovative safety features. The core-wall formwork is totally isolated by cladding, protecting workers from falling and external weather conditions. The cladded formwork also waives the risk attributed to height changes that affects workers perception of danger and could disturb their response under hazardous situations (Hsu et al., 2008). Access to core-wall formwork on the top deck is provided by an internal isolated lift which is also raised by the system at each cycle giving safe access for workers. The perimeter system is also equipped with safety screens that cover several levels; providing edge to edge protection.

CONCLUSION

The role of formwork systems in high-rise construction goes beyond building the concrete core. The choice of the system shapes construction workflows and affects the planning of logistics, site inventory, and labor and material delivery to work areas. From a lean perspective, advanced systems are expected to streamline construction workflows, increase production rates, reduce wastes, decrease batch and inventory sizes, reduce variability and increase flexibility. This comprehensive understanding of the role of formwork systems is necessary to compare formwork options, and essential to reap full benefits when selecting one system or another. Further investigations are needed to quantify the paper findings, and to address other aspects of lean principles related to formwork design such as quality at bay and error proofing. Future studies also can link the selection of formwork systems to takt time calculation, and the use of pull systems and kanban cards.

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