Building Planning Capacity in the Offsite Construction Industry: Introducing the Theory of Constraints for Process Optimization

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ABSTRACT
Offsite construction (OSC) is a construction method that integrates two different paradigms, construction and manufacturing, and faces different challenges in production variability and demand synchronization. This study explores the application of the Theory of Constraints (TOC) as a strategic operation management framework to optimize manufacturing processes in the OSC industry. A five-step approach is presented to enhance production flow and reduce inefficiencies during the manufacturing stages. The study proposes a tailored framework incorporating TOC within the OSC environment, supported by metrics like cycle time and work-in-progress to detect and address bottlenecks. By emphasizing real-time data monitoring and continuous improvement, the framework highlights TOC's ability to streamline production, reduce waste, and adapt dynamically to changing conditions, making it a critical methodology for improving adaptability, resilience, and scalability in offsite and modular construction.

KEYWORDS
Planning capacity; Theory of Constraints (TOC); Process optimization; Adaptability

INTRODUCTION
Offsite construction (OSC) is a construction methodology that takes the building process from the site to the offsite factory setting. This change allows the OSC industry to achieve certainty in production costs, improve construction quality, and reduce construction time, amongst others. The change of location for construction activities provides a controlled environment for the fabrication of components, panels, or modules. This controlled environment is shielded from external elements such as weather conditions and onsite space availability. These external elements can drastically affect the execution of planned activities, the level of quality, and the overall performance of a project (Mahmoudi et al., 2021). This construction methodology introduces benefits such as greater operational efficiency, reduced waste, and less exposure to external factors that affect traditional construction, such as weather conditions or logistical constraints. However, being a hybrid model, OSC faces specific challenges, such as variability in demand, supply chain constraints, and the need for synchronization between manufacturing and assembly processes to maintain an ideal production level. Some of the key principles and tools employed in the OSC industry include dedicated production lines, highly standardized processes, product modularization, and the utilization of industrial automation for component fabrication.

The performance of construction projects heavily relies on the control and management of its resources as well as activity planning (Pourrahimian et al., 2024). Studies have proposed different mechanisms for production control through the use of lean production principles such as Last Planner System to improve planning reliability (González et al., 2010). In a study by Hamzeh et al. (2019), several performance metrics were introduced to evaluate the capacity levels of the resources assigned to planned activities with the actual needed demand. This consideration for production planning pondering capacity is crucial to provide early metrics and signals for early corrective actions during the execution of projects.

In the OSC industry, average production rates are often used to estimate production times and to build schedules; in some cases, this generates significant deviations from the actual production. To tackle those deviations and variability during production operations, an approach using historical data and real-time monitoring, and with the help of a digital-twin model was explored by Alsakka et al. (2024). Production control and management are crucial aspects to consider for the benefits offered by OSC to materialize. Without proper control of product quality, production times, and material utilization, amongst other things, the final output could not provide the expected benefits and could lead to over costs, rework, and product delays.

The inclusion of control theories in the OSC industry, especially during the fabrication stages, aims to improve process standardization, manage production control, and, in general, provide project managers with tools to plan, control, and manage projects in the most beneficial way for the stakeholders and project (Pourrahimian et al., 2024). Multiple studies have delved into the application of industrialized manufacturing concepts in the OSC industry. Operations management (OM) concepts have been used and proved to be beneficial for the OSC industry. In a study presented by Prado Lujan (2022), the relationship of offsite construction processes with production systems was presented. The findings indicated that the application of OM concepts with different control tools (use of control metrics for production such as cycle time, throughout, work-in-progress (WiP), % of fill rate) can help to understand and deal with variability, reduce risks, provide more reliable planning, and provide a *no-loss learning curve* for improvements and changes made in production processes.

The Theory of Constraints (TOC) is an OM practice widely used to evaluate and control constraints that can affect the production process. TOC was developed by Goldratt & Cox (2014), as a methodological framework based on the premise that every production system has at least one limiting element that restricts its overall performance. The identification and management of these constraints allows the improvement of operational efficiency and maximizes production flow. In the manufacturing sector, TOC has been used to optimize processes through the Drum-Buffer-Rope (DBR) approach, which regulates the workflow through the control of the main constraint (Liu et al., 2021). More recent studies have explored the application of TOC principles in digital manufacturing enterprises, where predictive analytics have been used to anticipate bottlenecks. In this regard, using spatial and temporal dependencies was crucial to extract correlations of tasks in a manufacturing system (Yin et al., 2025). Additionally, research has highlighted TOC’s ability to enhance speed and on-time delivery, as well as improve flexibility in responding to dynamic market conditions. By minimizing inventory levels and production downtime, TOC indirectly contributes to cost reduction and quality improvement, reinforcing its role as a strategic tool for manufacturing efficiency (Pacheco et al., 2021).

The effectiveness of TOC in manufacturing has been extensively studied in various industrial contexts. Kuo et al. (2021) conducted research in a semiconductor company in Taiwan, where TOC was implemented alongside a WiP monitoring system. This approach significantly reduced total processing time to 32.58 days and improved on-time delivery performance, with 68.5% of orders completed as scheduled. These findings highlight the potential of TOC in high-precision and technology-driven industries where efficiency and lead time optimization are critical. Beyond traditional manufacturing, TOC has also been successfully adopted in industries with make-to-order production models, which share similarities with OSC. These results underscore TOC's versatility and effectiveness in environments requiring high adaptability and synchronization, making it a compelling approach for OSC applications.

In the construction industry, TOC has been extrapolated to improve project management control and to reduce on-site execution times. Previous research has demonstrated that its application in this sector has enhanced activity scheduling efficiency and minimized non-productive time while also addressing unique challenges in construction projects to meet established deadlines. Identification of constraints helps to understand the causes of uncertainties during project execution and to improve planning reliability and project performance (Shen & Chua, 2005).

In this regard, Hammad et al. (2018) developed a schedule contingency management framework based on TOC to improve buffer control and stability in planning. Its application was evaluated across three types of construction projects with varying levels of complexity and nature: a bridge maintenance project, the construction of a residential building with 28 apartments, and a mixed-use project with commercial and residential units. The results demonstrated that proper buffer management in critical and non-critical activities reduced execution time variability, enhanced schedule stability, and optimized resource allocation. Similarly, Liu et al. (2021) conducted a simulation in a construction project for a hydroelectric plant, demonstrating that the application of DBR based on TOC reduced uncertainty by 25.64 days, significantly improving schedule reliability. Moreover, accurately identifying bottlenecks enabled better resource allocation and waste elimination, thereby increasing overall project efficiency.

In addition to TOC, Goldratt (2014) proposed Critical Chain Project Management (CCPM), a methodology developed to address the challenges of planning and controlling complex projects. CCPM focuses primarily on identifying the project's critical chain and protecting deadlines through the strategic insertion of buffers. While CCPM offers potential advantages in the context of OSC, it faces its own limitations, particularly in manufacturing environments where the focus is on continuous, synchronized production rather than discrete project milestones. The nature of OSC and the need for continuous optimization of manufacturing flows make TOC a more suitable approach for improving operational efficiency on the production floor. The justification for applying TOC in OSC lies in the need to streamline and enhance production processes within the factory environment. Unlike project-based approaches such as CCPM, TOC is better suited for environments where continuous production and elimination of bottlenecks are essential. By focusing on the physical and logistical constraints that directly impact manufacturing flow, TOC enables a more practical and targeted strategy for optimizing production processes. Appropriate definition of buffer size can be challenging, to avoid waste of resources (with big buffers), or not providing enough protection for uncertainties (with small buffers). Furthermore, Anastasiu et al. (2023) identified significant limitations in CCPM's application, such as its narrow focus on specific finishing tasks and its reliance on specialized teams that must work uninterruptedly to achieve the expected efficiency. These constraints make CCPM less adaptable to a manufacturing environment like OSC, where workflow optimization and process synchronization are fundamental. Therefore, TOC remains the most suitable methodology for managing constraints and improving operational efficiency in modular production environments.

However, despite its advances in traditional manufacturing and construction, the application of TOC in OSC has not been sufficiently explored. This study proposes that, due to the hybrid nature of OSC, which combines manufacturing principles with construction industry practices, TOC can provide an ideal framework for managing constraints within the controlled manufacturing environment of prefabricated modules and components.

RESEARCH METHODOLOGY

The proposed framework includes the application of TOC to optimize production processes within the OSC manufacturing environment, maximize operational efficiency, and mitigate the effects of critical constraints. Unlike previous studies that have addressed TOC in construction from a project management approach, this work focuses exclusively on its application within the manufacturing process, ensuring that the production of prefabricated modules and components reaches optimal performance before their integration into the construction site. For the application of TOC in the controlled OSC environment, the Five Steps of Targeting approach developed by Goldratt & Cox (2014), is used. The proposed methodology is presented in Figure 1, and displays the steps needed to allow the identification and elimination of restrictions within the production process. Their importance lies in the fact that they provide a logical sequence of continuous improvement, ensuring that resources are used efficiently and that production is not limited by unmanaged bottlenecks. Other typical constraints within the OSC manufacturing environment include limited skilled labor, machine availability, workspace limitations for storing WiP, and tool availability. These constraints directly affect throughput, even if they are not bottlenecks in the strict sense. Additionally, process capability, whether a workstation consistently produces quality output at the required rate can become a constraint if it fails to meet system demands.

To introduce TOC into an OSC environment, it is essential to consider a preparatory stage that precedes the traditional five focusing steps. This initial preparatory step sets the stage for a data-driven and goal-oriented implementation of TOC within a controlled production setting. Step zero involves defining the main operational objectives of the system, establishing a centralized performance monitoring platform, and enabling continuous data flows from real-time operations. These elements form the fundamental basis of an effective TOC strategy adoption in OSC, where modular workflows and frequent configuration changes demand accurate, timely information for decision-making.

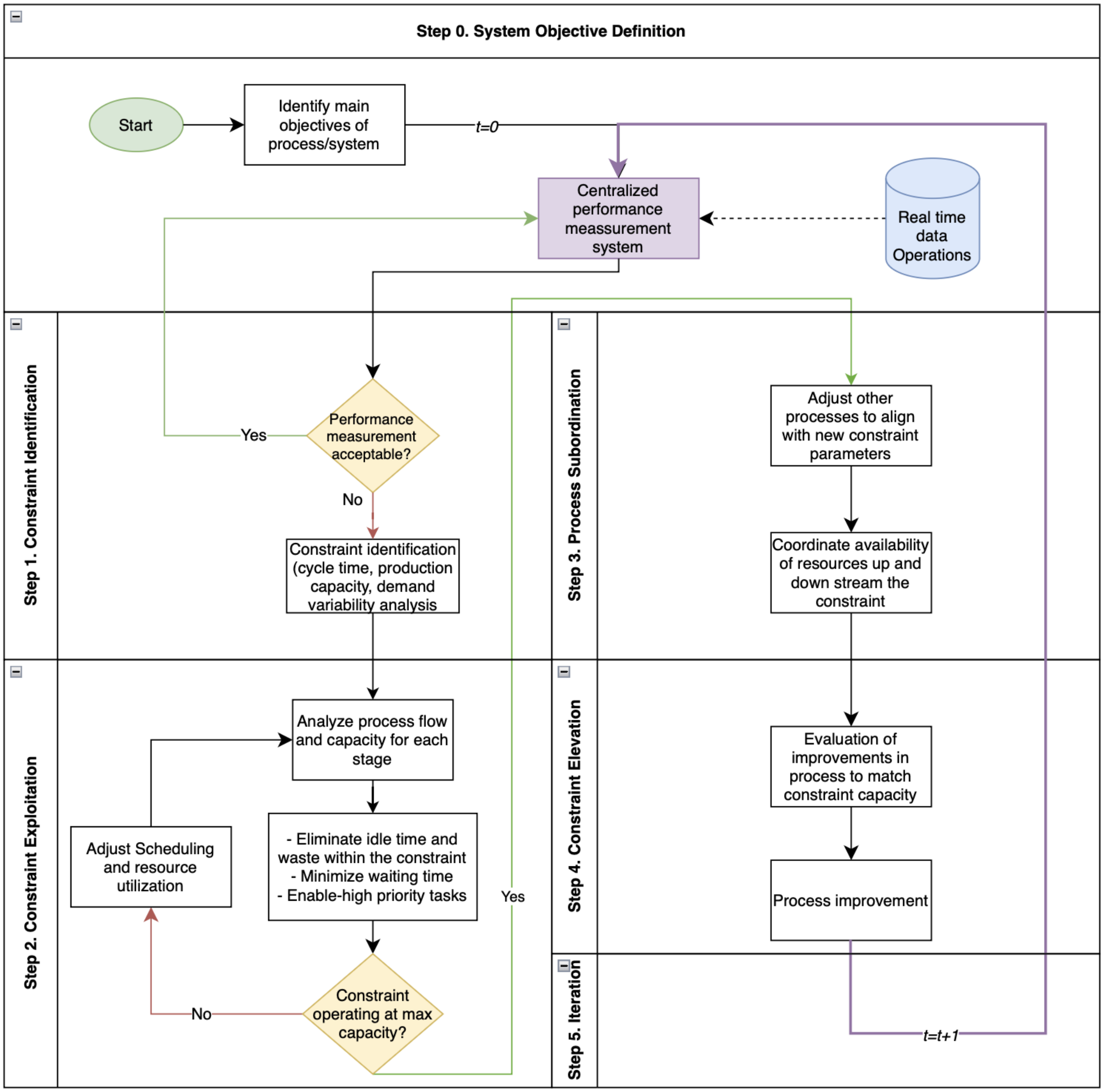

Figure 1. TOC framework for constraint and process optimization.

The first and most critical step involves identifying the constraint that limits the system's productive capacity. In controlled manufacturing environments, such as OSC, it is essential to detect the element that restricts production flow and, consequently, the overall efficiency of the system. A bottleneck in OSC is defined as the stage of the process with the lowest relative capacity compared to others, creating an imbalance in the production system. According to Yin et al. (2025), a productive constraint can be conceptualized as the activity or workstation with the lowest throughput, meaning the one that operates at the lowest frequency per unit of time relative to the rest of the system. This factor is critical because a bottleneck not only delays production flow but also directly affects the production rate and the ability to meet deadlines in industrialized construction projects. Furthermore, since OSC manufacturing involves the integration of multiple processes, the early identification of these bottlenecks is key to preventing excessive accumulation of WiP inventory and ensuring a continuous flow in the manufacturing of prefabricated components. The precise determination of the constraint within the OSC production process relies on quantitative metrics that evaluate the performance of each workstation. Among the most relevant metrics for identifying bottlenecks in OSC are Cycle Time (C/T), Throughput (TH), WiP, and Capacity Utilization (Urban, 2019). Limited resources such as specialized labor, production tools, raw materials, or plant space may not always be constraints; however, they become so when their limited availability directly restricts throughput. For example, if there is only one welding station for a critical module and it fails to meet demand, it becomes a constraint regardless of whether other stations operate efficiently.

The second step, exploiting the constraint, focuses on maximizing the efficiency of the limited resource without incurring additional investments. In the context of OSC, this involves optimizing task scheduling based on the actual capacity of the identified constraint. This entails minimizing waiting times, reducing unplanned stoppages, and ensuring that the constraint receives materials and resources continuously and promptly. The implementation of strategies such as workflow leveling seeks to distribute the workload evenly, preventing fluctuations that could lead to interruptions or excessive accumulation of WiP (Sims & Wan, 2017). The reduction of idle time through the use of the DBR approach from TOC is essential in this context. In OSC, where synchronization between workstations is essential to ensure continuous production without interruptions, the proper application of these strategies allows the system to operate at its maximum capacity without the need for additional investments.

The third step, subordinating everything else to the restriction, seeks to ensure that all activities in the production process are aligned with the main constraint. In the manufacture of prefabricated modules, this involves coordinating the availability of supplies, internal logistics, and the allocation of personnel in a way that does not generate additional delays. Constraint-based scheduling methodologies will be adopted, ensuring that downstream and upstream activities from the constraint operate in synchrony, avoiding inventory build-ups or downtime.

The fourth step, elevating the constraint, involves implementing improvements or investments that increase the capacity of the limited resource. In OSC, this step is crucial to ensure that the identified constraints do not become a permanent disruption to the growth and scalability of the production system. Elevating the constraint can be achieved by automating critical processes that reduce the reliance on manual tasks or significantly decrease cycle times. Additionally, optimizing plant layout to reduce transfer times between stations and incorporating advanced technologies for monitoring and controlling production can enhance operational efficiency and free up capacity in the constraint. Another strategy involves redistributing the workload or redesigning processes to better balance demand across different workstations. However, it is essential that any action aimed at increasing the constraint's capacity is carefully evaluated to avoid creating new bottlenecks in other parts of the system. Once the constraint has been elevated, it is necessary to monitor the impact of these actions on overall throughput and adjust the system to ensure that the improvements implemented generate a sustainable long-term effect.

The fifth and final step, repeating the process, establishes a mechanism for continuous improvement by constantly monitoring emerging constraints. In a dynamic production environment such as OSC, where demand and operating conditions can change constantly, it is critical to conduct regular evaluations to identify new constraints and adjust the strategy accordingly. The modular and customized nature of OSC projects implies that constraints may shift from one stage to another as the system configuration changes or new technologies or processes are introduced. Therefore, the implementation of a continuous cycle of identifying, exploiting, subordinating, and elevating constraints is essential to maintain an efficient and adaptable production system. Key performance indicators (KPIs) can be established to measure process efficiency, assess the impact of implemented improvements, and ensure that the system continues to operate optimally. This iterative approach allows for the timely detection of any changes in system constraints and the adjustment of corrective actions to maintain a constant and balanced workflow, ensuring the long-term sustainability and growth of the OSC production system. Step 5 is represented as an arrow that iterates back to Step 1, it underpins the entire methodology as an ongoing cycle of improvement. Once a new constraint is identified, the process iterates back to Step 1, forming a feedback loop driven by real-time data and continuous monitoring. This iterative approach is essential in OSC environments where production configurations and constraints may evolve frequently.

The TOC approach applied to OSC is aimed to optimize production through a continuous improvement cycle. First, the system's constraint is identified, then it is exploited to maximize its performance without additional investments. Next, all activities are aligned with the constraint, and its capacity is elevated to increase system performance. Finally, the process is repeated to identify and address new constraints, ensuring continuous and sustainable improvement in production.

DISCUSSION

The application of TOC in OSC has demonstrated significant benefits in optimizing production processes. One of the primary advantages is the improved efficiency achieved by identifying and managing the system's constraints. By focusing efforts on the constraint, production is better aligned with the available capacity, ensuring that resources are utilized more effectively, reducing waiting times, and minimizing WiP accumulation. This leads to smoother production flows, timely delivery of components, and, ultimately, higher throughput. Moreover, TOC's ability to synchronize operations across different stages of the production process reduces the occurrence of bottlenecks, which traditionally lead to delays and inefficiencies in OSC. The continuous monitoring and adaptation of the process contribute to long-term improvements in productivity, making OSC systems more resilient to disruptions and variabilities in demand and supply.

However, there are inherent limitations to the TOC approach, especially when it is not supported by real-time data collection systems. The lack of immediate data can result in late identification of emerging constraints, potentially leading to inefficiencies or interruptions in production. While real-time data is not strictly necessary for implementing TOC, it significantly enhances the responsiveness and adaptability of the system. In environments lacking real-time monitoring, historical data can still support constraint identification and scheduling through trend analysis. However, without real-time insights, there may be delays in detecting new constraints, which reduces the system’s agility and the timeliness of corrective actions. The reliance on manual tracking and static models can impede proper system’s adaptability, making it less responsive to changes in real-time conditions. In this regard, there is a technological disruption in OSC, as the traditional TOC approach does not fully capitalize on the potential of modern technologies like

IoT, sensors, and automation. These tools, if integrated with TOC, could provide real-time insights, enabling faster decision-making and more accurate constraint management. Without these technologies, the effectiveness of TOC could be compromised, particularly in dynamic environments where constraints evolve rapidly.

Future case studies exploring the application of TOC in OSC could provide valuable insights into its effectiveness and limitations. Additionally, the integration with optimization models could enhance TOC's flexibility, allowing it to manage more complex and dynamic constraints effectively. These models, capable of exploring diverse solutions, could be applied to adapt dynamically to changes in production conditions, offering a more robust framework for constraint management in OSC. This flexibility would allow activity planning to quickly adjust to the changing conditions of the identified constraints, ensuring that operations remain smooth despite fluctuations. Moreover, managing constraints efficiently also facilitates better handling of disruptions within the system, as it enables a proactive approach to mitigating delays and maintaining optimal workflow. The incorporation of real-time data management is critical, as it ensures that decisions are made based on current system conditions, reducing delays and improving responsiveness. The adoption of new technologies such as machine learning and Internet of Things could further refine the monitoring and optimization of manufacturing processes, enabling predictive analytics and proactive constraint management. By leveraging these technologies, future studies with TOC in OSC could enhance efficiency, adaptability, scalability, and resilience, paving the way for more intelligent and responsive production environments.

CONCLUSION

The application of TOC in OSC provides a structured methodology for identifying and managing the constraints in modular production systems. Through the five-step TOC process, OSC operations can systematically optimize workflows, reduce bottlenecks, and enhance overall production efficiency. Successful companies will skillfully merge the two paradigms, using manufacturing-inspired management systems that can allow the streamlining of processes while adapting them to the inherent variability and uncertainty driven by the construction industry's nature. As the industry evolves, TOC stands out as a key methodology for driving more agile, resilient, and sustainable operations for modular and OSC. Its ability to balance efficiency with flexibility makes it a valuable framework for companies looking to optimize production while navigating the challenges of a dynamic construction landscape.

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