The Role of Simulation in Digital Twin Construction

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Abstract. Fostered by advances in digital twin and onsite monitoring technologies, the paradigm of Digital Twin Construction (DTC) has emerged as a comprehensive mode of construction that proposes a data-driven lean production planning and control workflow, leveraging project status and design intent information to make proactive production system design changes. Simulation plays an essential role in the DTC paradigm as a provider of predictive situational awareness (SA), a mechanism for data-driven continuous improvement, and an enabler of future autonomous real-time production control systems in construction projects. In this paper, we outline these modes of use of simulation, discuss potential barriers to implementing simulation in DTC workflows, and propose a set of criteria to evaluate a simulation tool's applicability to DTC.

1. Introduction

Digital Twin Construction (DTC) is a new data-centric mode of construction management in which information and monitoring technologies are applied in a lean closed-loop planning and control system (Sacks et al., 2020). DTC leverages concepts and technologies from Building Information Modeling (BIM), Lean construction, Digital twins, and Artificial intelligence (AI) to capture project status and intent information in a digital twin information system (DTIS). As a result, the information system can provide production planners at all levels with accurate, comprehensive, and timely situational awareness of the past and present, as well as enabling projections of future status. Moreover, DTC-derived information systems may empower production planners to develop ongoing work with smoother and more reliable flows, less waste, enhanced safety, and lower risks.

Construction simulation is the discipline of building and experimenting with computer-based representations of construction systems to understand their primary behavior (AbouRizk 2010). Simulation applications range from earth-moving to high-rise construction. In production planning, simulation allows production planners to determine the potential range of impact of proposed changes before implementation. This aspect minimizes uncertainty during decision-making by providing production planners with insights about what may happen on site. In current practice, simulation provides information for the *Act* step of iterative planning and control cycles in line with the Plan-Do-Check-Act (PDCA) cycle (Deming, 2000).

As currently conceived, future DTC systems will automate the *Check* step of the PDCA cycle - monitoring of construction operations on and off site and interpretation of the resulting data streams to produce information that supports planners' situational awareness (SA). In DTC, simulation is applied on the basis of accurate and up-to-date project status information, enhancing its ability to support the *Act* step: predictive assessment and comparison of the likely outcomes and risks of the current baseline production plan to those of any possible alternative plans. The role of simulation in this context is to provide forward-projecting SA. However, it can also serve as a mechanism for data-driven continuous improvement and an enabler of future autonomous real-time production control systems in construction projects. In this paper, we outline these modes of use of simulation,

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discuss potential barriers to implementing simulation in DTC workflows, and propose a set of criteria to evaluate a simulation tool's applicability to DTC.

2. DTC Conceptual Model and Workflow

A DTC information system depicts the physical status of a building or infrastructure. DTC development requires holistic thinking about the ontological and epistemological dimensions of digital twins for construction, the information, technology, process and management elements, and the relationships among them.

DTC embodies the conceptual space of the information used in the DTC flow along three orthogonal conceptual axes (for details see Figure 3 in Sacks et al. 2020). The physical–virtual axis relates the physical information inherent in the building itself to its intended design and the process information (planning). The product and process axis distinguishes between the information stored in the design BIM model's objects, their properties, and their relationships, on one hand, and construction plans, on the other. The Intent -status axis relates future-looking design and plan information (what we plan to do) to past-looking project status information (what we have done). The information of the future state of a building is described in the design and in the construction plan for the components of the building that have not yet been built. This is called Project Intent Information (PII), representing the as-designed and as-planned aspects of the project. The information about the past states of a building and its construction process records what was done and how it was done. This as-built product and as-performed process information is called Project Status Information (PSI).

A DTC workflow involves all the system components, information stores, information processing functions, and monitoring technologies according to three concentric control workflow cycles: short-term production planning, medium-term production system design, and long-term continuous improvement. Figure 2 lays out the DTC workflow:

- At the start of a construction project, designers work from a project brief to design a building to fulfill the owner's functional requirements. This is closely followed, in an iterative fashion, with construction planning. The design product and the planning process are contained in the PII. Where designers and planners predict the likely performance of their designs and plans using the PII and codified design knowledge, the results obtained are knowledge about the behavior of the building and its project, collectively called Project Intent Knowledge (PIK).
- As construction progresses and data accumulate, the Interpret function uses complex event processing (CEP) to comprehend what was done and what resources were consumed during this process. The information that is generated describes the PSI. Events may be classified using diverse methods such as rule inferencing or machine learning algorithms.
- In the next step, an 'evaluate' function compares the actual to the intended, the PII to the PSI. The output of this function is called Project Status Knowledge (PSK). PSK supports decisions and actions that lead to value judgments about the current status. Appropriate data visualization tools are needed to communicate the project status, design intent or production plan deviations, and any other anomalies (not shown in the figure).
- At this stage, designers and planners can propose changes to the product design or the production plan in response to the status knowledge, and apply their decisions to update the PII, thus completing the PDCA cycle. The updated PII continues to govern operations in the

construction itself, and the planning and control cycle is repeated until the completion of the project. Finally, all the collected information and knowledge (PII, PIK, PSI, and PSK) are archived.

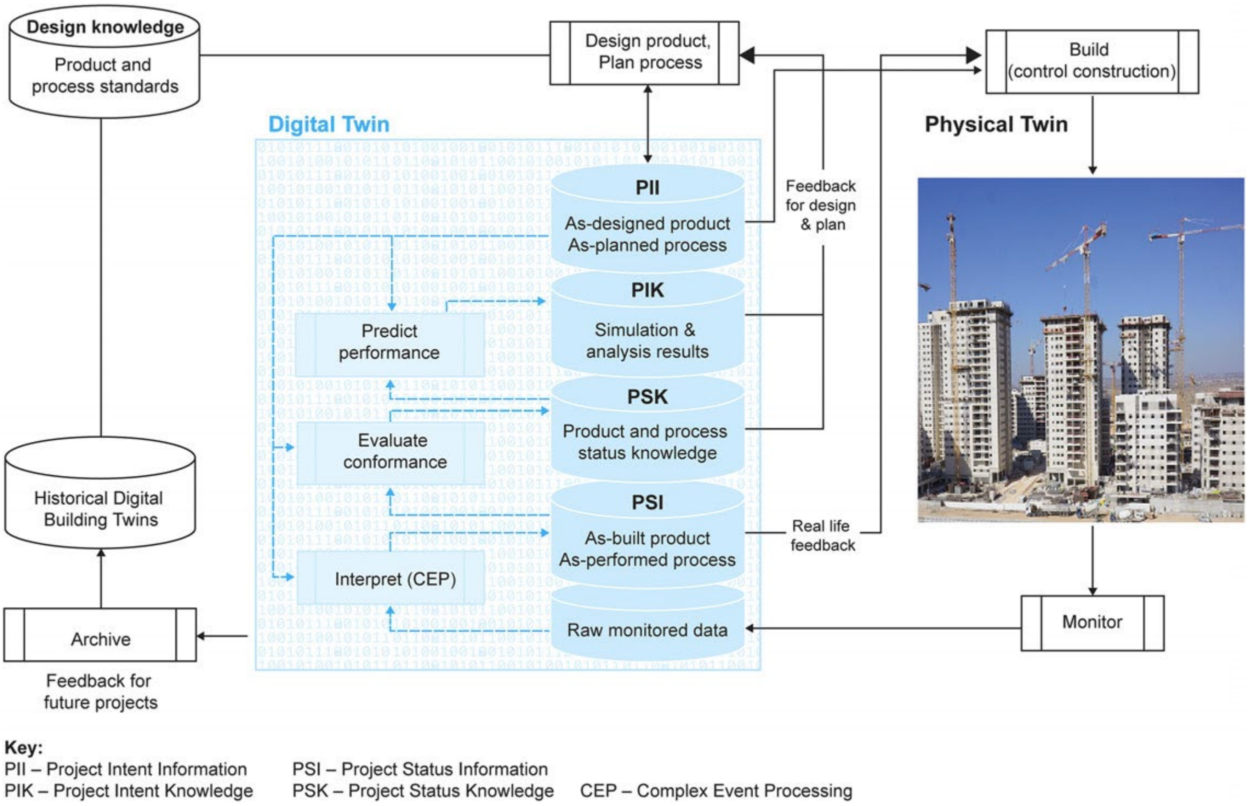

Figure 1: DTC workflow (from Sacks et al. 2020).

3. Role of Simulation in DTC

The previous section explained the fundamental role of a DTC information system in enhancing planners' situational awareness. This corresponds to the *Check* step of the PDCA cycle. The role of simulation in DTC is to help planners optimize their decisions concerning any necessary changes to the product design or to the process plans by leveraging a computer's capability to process the status data to predict how possible decisions might play out going forward. The goal is to provide what are sometimes termed 'actionable insights' (Thalheim et al., 2017) for the *Act* step of the PDCA cycle. In this section, we outline three ways that simulation can contribute to the DTC production planning and control workflow.

3.1. As a Provider of Predictive Situational Awareness

***Central Claim**: Simulation's basic role in DTC is to provide future-projecting situational awareness for proactive production planning and control.*

Predictive situational awareness (SA), or level 3 forward-projecting SA as proposed by Endsley (1995), grants planners the ability to project the future behaviours and risks of a production system. This is achieved through comprehension of the current situation and knowledge of the status and dynamics of the system. In the DTC workflow, simulation can work hand-in-hand with the DTIS to provide predictive SA. It can help planners understand the current trajectory of the project and explore what-if scenarios.

Figure 2 outlines a workflow in DTC where the information system can explore alternative production plans' outcomes and performances through simulation and provide recommendations to planners on the course of actions that can improve the outcome of the project. In large complex projects, simulation may offer the planner an alternative plan (AP) that they hadn't considered before. Grounded on PSI and PII, the system can generate alternative production plans from starting points that are within planners' degree of freedom in product and process changes (Martinez et al., 2022), while also leveraging knowledge from historical DT databases. An AP consists of the work breakdown schedule (a hierarchy of work packages, activities, tasks that capture the construction methods and group the building product element parts that are constructed in each one), the location breakdown schedule (a hierarchy of zones and locations in which work is assigned), a planned construction and material delivery time schedule, labor assignments, equipment utilization, product information requirements, and site safety information. The APs are then simulated to project the range of their probable outcomes, which are stored as PIK. APs' performances are assessed with respect to planners' objectives using multi-criteria evaluation methods. Planners may explore additional scenarios in a closed-loop optimization cycle. Finally, the system presents all simulated APs with probability distributions of their behaviors/characteristics (i.e. how safe, reliable, costly, fast, resilient, and/or lean they are). The APs that best meet the planners' objectives can be recommended to them. The chosen AP will be updated into the PII as the new baseline plan.

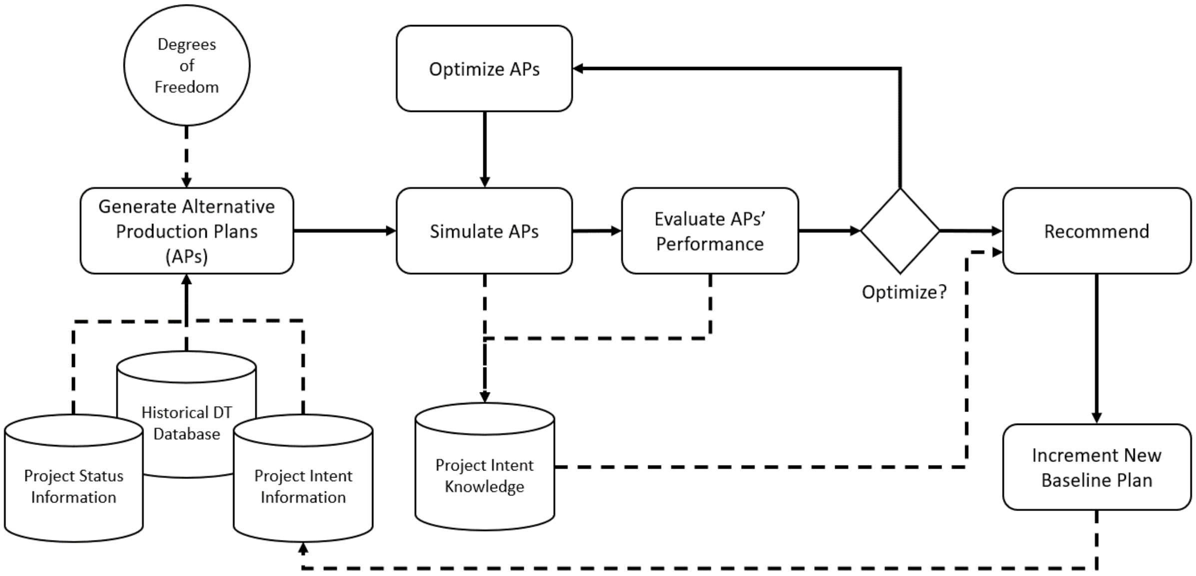

Figure 2: Generation of alternative production system designs and production plans, simulation, evaluation, and optimization.

3.2. As a Mechanism for Rapid Continuous Improvement

***Central Claim**: Simulation can enable continuous improvement by evaluating the outcomes of decisions made in Virtual Design and Construction (VDC) (product and process design) and in* *medium to long term lookahead planning (production system design) by enabling iterative optimization through virtual PDCA cycles.*

In the previous mode, simulation served to provide short-term predictions of a construction production system's function subject to a set of planning decisions made within the scope of planners' degrees of freedom of action. However, simulation can equally well evaluate possible alternatives that emerge from considerations of alternative product designs and alternative production system designs. These evaluations can be applied to enable continuous improvement, as comparisons between the outcomes of alternative choices can be used to guide medium- and long-term decisions within a current project or within future projects, where medium to long term planning concerns a three to six weeks lookahead, depending on the project type and size.

In the DTC paradigm, a virtual PDCA cycle can be created by using simulation as a validation mechanism that forecasts future behaviors and risks of a given production system over time. Product design changes are common throughout the construction process, whether due to customizations introduced by clients or due to engineering detailing conflicts. These changes can cause ripple effects to the production system and the production plan, and construction methods and sequences might need to be reconsidered.

In a conventional implementation of the PDCA cycle for a construction project (Figure 3), planners perform production planning and control and deliver the production plan as PII to the construction site as the *Plan* step of PDCA. The construction team executes the plan based on the given information as the *Do* step. Information about the as-built product and the as-performed processes that produced is collected from the site, typically through manual documentation, and in turn provides planners with level 2 SA, a comprehension of current situation (Endsley, 1995). Planners can use this SA to evaluate the performance of the production system (*Check*) and make management decisions, which are the appropriate changes to the product and production system design to improve project performance, as the *Act* step of PDCA.

Meanwhile, simulation coupled with the DTC information system supports a virtual PDCA optimization loop within the overall PDCA cycle (Figure 4). *Planning* and *acting* in the DTC workflow involves a closed-loop virtual PDCA cycle that begins with reacting to the project status through virtual prototyping of the construction project in VDC (Li et al., 2008), and production system design (*virtual* Act) followed by production planning and control (*virtual Plan*) to generate an alternative PII. This PII is simulated (*virtual Do*) to generate simulated PSI, which can be then be evaluated against the alternative PII to *check* whether the proposed changes are predicted to fulfill its intended goals. This understanding provides planners with level 3 predictive SA as PIK. They can build upon this newly discovered insight to perform multiple iterations of this virtual PDCA cycle to optimize their solution until they arrive at a satisfactory solution as the new PII for construction. PSI can be generated in the DTC information system through automated monitoring of the construction site and interpretation of the data streams. Then the DTC information system performs evaluation on the PSI and PII collectively to generate knowledge on the current status of the project (level 2 SA), which can be used as a basis for the next overall PDCA cycle.

Thanks to simulation as part of the virtual PDCA cycle, planners can learn and continuously improve their proposed systems and products without suffering real-world consequences of failure. They can test any building design, construction method, and production system from any point forward in time, understand how the production system would behave, what are the risks, where are the bottlenecks, where are the wastes, will the proposed changes have the intended effect?

While simulation can enable the virtual PDCA cycle in any standard production planning workflow, virtual PDCA cycles in DTC workflows offer significantly greater improvement opportunities. As discussed above, the DTC information system can provide planners with current information and knowledge on the as-built product and the as-performed processes that they can use as the basis for planning. In current planning workflows, planners predominantly rely on their expert experience to construct their initial solutions, often leading to misjudgment on the feasibility and effectiveness of their solutions. Meanwhile, planners in the DTC workflow are empowered to create more reliable plans by building upon the PSK provided by the DTC information system. Guided by an understanding of the project status from its inception to the current point in time, planners will be better equipped to create plans that address the quality, safety, and productivity issues occurring on the construction site while maintaining realistic expectations on the implementation feasibility.

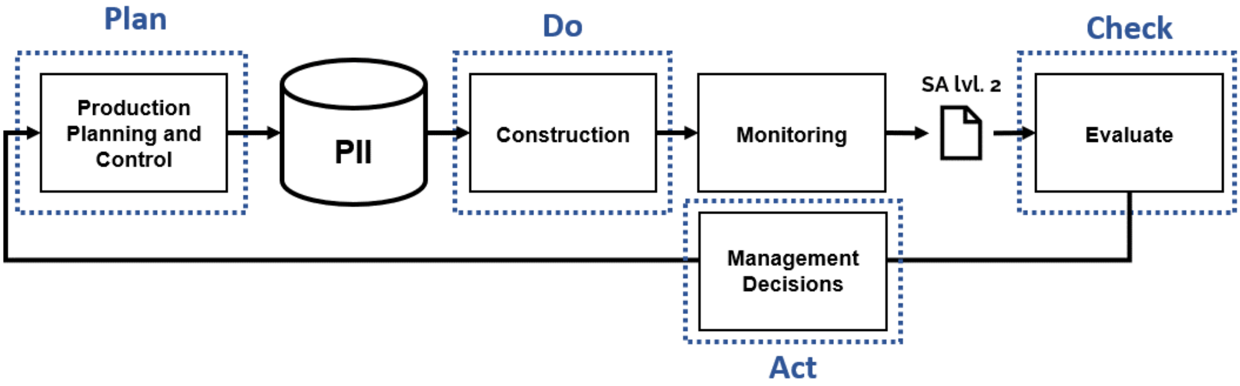

Figure 3: Conventional PDCA cycle

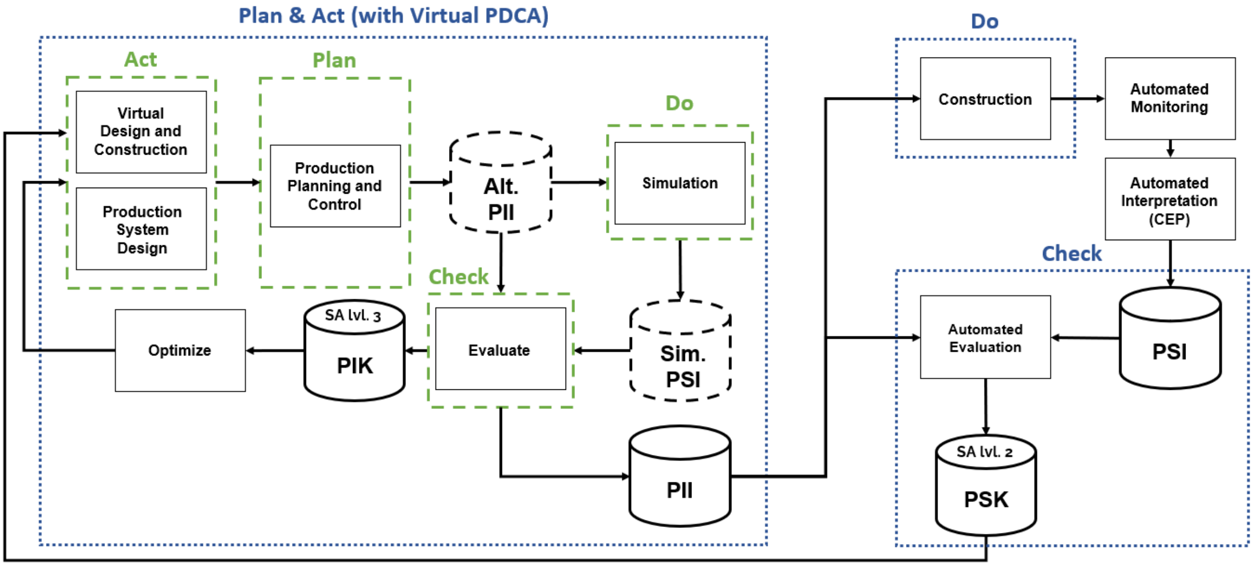

Figure 4: Virtual PDCA in DTC. The virtual cycle is iterated within the control cycle.

Within a typical planning window, planners can perform many iterations of VDC, explore many different alternative designs and construction plans, optimize them based on feedback from simulation results, and develop proactive strategies to mitigate uncertainty and risks that may arise in the solution that they choose. Without simulation, planners can at most consider the known-

known factors. With simulation, they can develop understanding of the potential impacts of known-unknown factors. In other words, simulation can serve as a virtual simulator of their specific construction site in the current control cycle, allowing them to iteratively optimize their solutions with validation feedback. The virtual PDCA workflow could potentially reduce the feedback cycle sufficiently to support continuous learning, thus maximizing learning opportunities and producing better planners in the long run.

Furthermore, by using archived project records for education and training, construction planners could be trained in much the same way as aircraft simulators are used to prepare pilots for the unexpected, making them more resilient when things do go wrong.

3.3. As an Enabler of Autonomous Real-Time Production Control Systems

Central Claim: *Predictive feedback provided by simulation is not only helpful for contemporary human-centric production planning and control workflows, it will also play an integral role in future autonomous real-time production control systems in construction projects.*

“The function of real-time production control is to adapt the production system to the changing environment, while preserving efficiency with respect to cost, time, and quality requirements. Real-time production control systems provide decisions for specific problems associated with part manufacturing, quality control, material provision, internal logistics, resource maintenance, and personnel allocation” (Pfeiffer et al., 2008).

In manufacturing, simulation has been used extensively as a component of real-time production control systems. As the DTC paradigm and its supporting technologies continue to evolve, we can contemplate a future construction site with features that may resemble manufacturing in terms of real-time production control.

Currently, production control remains a challenging task for construction planners. Not only are production managers struggling to consistently optimize their control decisions, their scale of “real-time” uses the units of days and/or weeks, far from the minute to minute, second to second real-time control in manufacturing. Three things are needed for autonomous real-time production control systems to work in construction: a) real-time status of the production system, b) a method to evaluate decisions/actions, and c) behavior models of production system components. Real-time status can be provided by the DTC information system, as conceived in the BIM2TWIN project (“BIM2TWIN,” 2022); evaluation and optimization of alternative decisions require simulation.

As discussed above, the predictive feedback provided by simulation within a DTC information system can be used to generate data defining forward-projecting situational awareness and stored within the PIK. This is not only useful for product and production system design in medium- and long-term planning, it is also beneficial to short-term production control. Given the complexity of construction projects and the large scales of their production systems, human planners find it challenging to perform proper, optimized production control in construction. Autonomous agents that are fully integrated with the information system and can execute simulations can achieve real-time production control with optimized decision-making based on full comprehension of the production system status and foreknowledge of the likely implications of their possible actions.

4. Evaluating Simulations for DTC

There is a wide range of computer simulation tools available for use in construction. The tools vary in their scope, input requirements, output information, modelling approaches, system compatibility, and intended workflows. Hence, it is not trivial for researchers and practitioners to judge a simulation tool's applicability to the DTC workflow, i.e., how well it can fulfil the roles outlined in the previous section. Evaluation requires a method that examines the fundamental characteristics of simulation tools relevant to the DTC planning and control workflow. To address this need, we propose a set of criteria as a basis for future evaluations.

Five primary criteria are defined in Table 1. These concern the elementary features of a simulation tool that characterize its general quality. In addition to the primary criteria, we define seven secondary criteria in Table 2 to evaluate how well a simulation tool can leverage the DTC information system and support simulation's three modes of use outlined in Section 3.

Table 1: Primary criteria for evaluating a simulation tool's applicability to DTC.

Criterion	Description
Relevance	How well the output of the tool satisfies the intended purposes, which, in the context of this paper, are the three modes of use in Section 3
Explainability	How well the results of the simulation can be interpreted by the user transparently and justifiably
Comprehensiveness	How thorough has the simulation taken into account the expected and unexpected events that can occur
Resolution	The level of decomposition of the production system and processes into their components
Fidelity	The extent to which the elements of the simulation faithfully imitate the characteristics and behaviors of their real-world counterpart
Reusability	How applicable the simulation is to different types of construction projects in different geographical locations

Table 2: Secondary Criteria for evaluating a simulation tool's applicability to DTC.

Criterion	Description
Flexibility	How capable the simulation is in changing its structure, i.e., how modular the simulation is
Extensibility	How easy it is to model new production system components (methods, products, and resources) into the simulation
Calibratability	The extent to which the simulation can be calibrated based on project status information, i.e., how many parameters can be calibrated in the simulation
Automatability	To what extent can the process of simulation model adjustment, calibration, extension, and alignment be automated
Stochasticity	The extent to which the simulation models events and behaviors stochastically with probability distributions
BIM Integration	How much BIM information is leveraged in the simulation

5. Potential Barriers in Implementing Simulation in DTC

DTC information system and workflows as outlined here require simulation functionalities capabilities beyond those common in state-of-the-art applications in construction. While computer simulation's value to production planning and control is well understood, its ability to integrate with the DTC information system to provide actionable insight for human planners and autonomous control systems remains to be demonstrated. Moreover, as Abdelmegid et al. (2020) pointed out, computer simulation has not gained widespread adoption by the construction industry, despite its usefulness having been proven by research efforts in the past four decades. Hence, it is reasonable to expect that simulation implementation in the DTC workflow will face many of the same barriers of simulation adoption in the industry today. Below, we discuss four major barriers shared by the DTC paradigm and ways to address these barriers.

The amount and nature of input and output data requirements – A significant quantity of data is required from the site to create an accurate model. Due to a lack of practical methods to provide updated and meaningful data during construction to capture changes in the production system, most construction simulations depend on historical data to overcome the information gap, affecting the reliability and credibility of the model. Moreover, data collection tools and workflows often vary from project to project, This inconsistency has led to missing, limited, or faulty data that causes difficulties in statistically characterizing construction processes through random distributions. DTC information systems, which integrate onsite monitoring technology with digital twin information processing, will support an automated data collection and processing framework that can replace the traditional manual and tedious process and boost simulation models' ability to maintain synchronization with the project status.

Sophisticated nature of simulation outputs – Statistical tables and charts are the typical outputs of a construction simulation model. These have been identified as unfit for current data management systems and visualization techniques for construction. For a simulation to make a meaningful contribution to planners' situational awareness, the explainability of the simulation output must be given adequate attention to avoid the "black-box effect" perception towards simulation that is prevalent among construction practitioners.

The long cycle time of simulation studies – The process of developing a construction simulation model from scratch is highly time-consuming for both modelers and construction stakeholders. Researchers such as (AbouRizk, 2010) have highlighted that the average time to construct a model in simulation studies is likely to exceed the duration of the construction project of interest, discouraging industry partners from adopting simulation as a decision-support tool. This barrier can potentially be overcome in DTC. Through a data schema that standardizes project status and intent information requirement, the DTC information system can support a modeling framework that automatically and parametrically constructs the simulation model according to the as-designed product and the as-planned production system, while project status knowledge can be used to calibrate the model to reflect system behaviors.

Limitations in construction simulation tools and methods – This barrier is the most frequently reported factor that hinders adoption of construction in simulation. Current simulation tools are reported to be incapable of capturing the reality of the construction systems (Leite et al., 2016). Modelers have made unrealistic assumptions and simplifications when adopting modeling strategies and tools from other disciplines (such as manufacturing). The complexity of modern construction systems increases the potential for inaccurate conceptualization of the construction operations and flows, further extending the gap between academic and industry. This barrier cannot be overcome by technology alone. Rather, it requires close collaborations between researchers and practitioners to model and validate behaviors of the production system guided by a robust and comprehensive framework that leverages information from the DTC information system and is supported by a lean understanding of the production system such as Transformation-Flow-Value views, variability, and waste.

6. Conclusion

The emerging DTC paradigm empowers human planners and future autonomous production control systems to make optimized decisions based on situational awareness of current project status and potential future states. Supported by onsite monitoring technologies and predictive simulation, planners in the DTC workflow can thoroughly explore alternative plans and designs and arrive at optimal solutions through virtual PDCA cycles. Simulation has three essential roles in the DTC workflow: as a provider of predictive situational awareness (SA), as a mechanism for data-driven continuous improvement, and as an enabler of future autonomous real-time production control systems in construction projects. We have proposed a set of criteria to evaluate a simulation tool's applicability to DTC and identified four potential barriers to implementing simulation in DTC. In ongoing work in the BIM2TWIN project, we are building a prototype tool to compile and run simulations as part of a virtual PDCA cycle.

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