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TOWARDS INTEGRATED DIGITAL TWINS FOR CONSTRUCTION AND MANUFACTURING

Irfan Čustović[1], Ranjith K. Soman[2], Pieter Pauwels[3], Daniel M. Hall[1]
[1] Department of Management in the Built Environment, Delft University of Technology, The Netherlands
[2] Institute of Construction and Infrastructure Management, ETH Zurich, Switzerland
[3] Department of the Built Environment, Eindhoven University of Technology, The Netherlands

Abstract

A digital twin (DT) can enhance construction management with comprehensive real-time simulations. However, research rarely considers prefabrication factories, whose processes have a significant impact on cost and duration. It remains unclear how construction DTs can achieve their expected benefits without dynamically interacting with the DTs of manufacturing facilities. To address this, a DT integration model is proposed. It builds upon systems theory and describes integration across the three layers *objectives*, *processes*, and *data & tools*. A theoretical example demonstrates potential benefits of integrated DTs. This work can assist researchers and practitioners who are focusing on DTs in the execution phase.

Introduction

For projects to be completed on time and within budget, it is crucial to efficiently execute and synchronize upstream production steps with the on-site work. However, this is a challenging task as these activities are carried out in complex environments with different business objectives and strategies. Fabrication of building elements in controlled stationary production facilities is subject to the management principles of manufacturing. Therein, production planning and control (PPC) tries to maintain high efficiency by ensuring steady production volumes with repetitive production requirements (Slack, Brandon-Jones and Johnston, 2013). In contrast, on-site work consists of various one-off activities, whose execution outdoors is vulnerable to uncertain weather conditions (Dallasega, Marengo and Revolti, 2021). This very nature of construction projects requires managers to perform short-term adjustments to work scheduling and delivery dates for ensuring efficiency (Ballard *et al.*, 2007).

In the manufacturing domain, previous research indicates that the physical-virtual synchronicity enabled by DTs enhances operations management. Bi-directional DTs can provide real-time insight into the fabrication process and allow for optimized instructions to be fed back to the shopfloor (Tao and Zhang, 2017). Barkokebas et al. (2022) demonstrate how operating digital twins of these factories enables simulations and optimized allocation of manufacturing resources for ensuring efficiency.

It is only recently that DTs have also been considered for managing on-site works in the execution phase. For example, Sacks et al. (2020) present a DT construction mode, in which established management principles are combined with the physical-virtual synchronization of DTs to make construction management more proactive. However, these approaches are primarily focused on objectives relevant to on-site execution and material delivery. They do not yet consider the interaction with prefabrication factories and their management systems.

It is unclear how construction DTs will achieve their promised benefits if they do not consider the upstream manufacturing systems and their DT-based modes of operation. There is need to align objectives and optimize production between the construction site and the supply chain. To date, there is not yet an approach to integrate goals, simulations, and information between DTs for construction and DTs for manufacturing.

This paper addresses this gap by proposing a three-layered integration model based on systems theory. The remainder of the paper is divided into four sections: The following section explains the concept of DT and its application in manufacturing and construction. It also describes the use of this concept for PPC in these two fields. Next, the integration model is presented in detail. The potential benefits of integration are illustrated through a theoretical example. Finally, the discussion section summarizes three ways that integrating DTs can improve construction management and points to future work needed.

Point of departure

Digital Twins

A DT is a virtual representation of a physical object, process, or system created with bi-directional communication and operated for specific use cases. The basic principle is the synchronization of a physical state and a virtual state using data transmission technologies (Grieves, 2014). Synchronization is achieved by capturing the characteristics of the entity in one realm and replicating them as an identical entity in the other realm (see Figure 1). In contrast to digital models (no twinning) and digital shadows (physical-virtual twinning only), the DT automates the data exchange between physical and virtual entities in both directions (Kritzinger *et al.*, 2018).

This creates a highly interconnected, bi-directional system where both entities can communicate and affect one another's states.

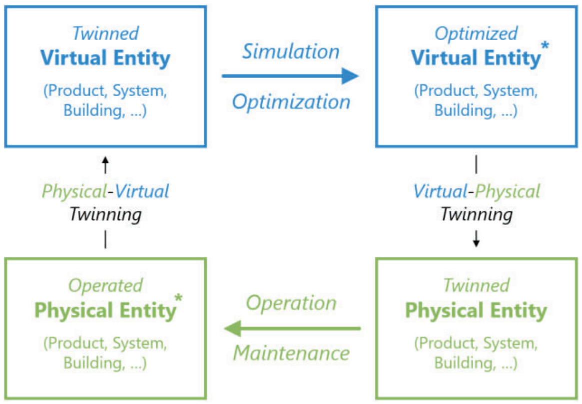

Figure 1: Digital twin concept, adapted from Jones et al. (2020)

DTs complement the perception and decision-making of human operators. Since the virtual system reflects a majority of properties of the physical system in real-time, operators can gain a better insight into complex matters (Whyte *et al.*, 2019). In case of deviations from the plan during runtime, operators can perform analyses and simulations with accurate data from the virtual models. Subsequently, they can quickly and inexpensively compare different possibilities for mitigation before applying the most efficient one to the physical entity. DTs allow for sending the optimizations seamlessly to the physical systems and manipulating their operation. Moreover, analyses can be performed based on time-series big data. This accumulated information allows for long-term evaluation of a system's performance and improved prediction of future behavior (Thelen *et al.*, 2022).

Digital twins for production planning and control in manufacturing

Ensuring efficiency under real-time factory operations is a complex task. This dynamic (operational) complexity originates from the uncertainties of events in manufacturing systems (ElMaraghy *et al.*, 2012). They are caused by deviations from the normal way of operation due to equipment breakdowns and maintenance or due to variations induced by external factors such as delayed deliveries from suppliers.

DTs are useful for tackling this operational complexity. Tao and Zhang (2017) introduce a bi-directional shopfloor DT that interconnects the physical machines, and corresponding virtual models alongside a shopfloor service system. An underlying database allows for linking a variety of information in real time and for quick identification of deviations from the planned progress. The service system can recalibrate the manufacturing process model via sensor inputs, compare the actual state with the planned state, perform optimization algorithms, and communicate improvements to the physical shop floor. Task scheduling and resource allocation (i.e. *planning*) is enhanced as it is provided with comprehensive data representing the actual performance of the system alongside simulation results (Tao *et al.*, 2018). Similarly, *controlling* is enhanced by performing profound comparisons of expected and actual progress in the virtual models and proposing adjusted production strategies in real-time (Tao *et al.*, 2018). An important enabling technology for both planning and controlling is the Internet of Things (IoT), which allows for automated, real-time capture of the current machinery status (Čolaković and Hadžialić, 2018).

So far, there is relatively little attention paid to the application of DTs for prefabrication. Lee and Lee (2021) use DTs of building modules to optimize the logistics from the factory to the installation site and Kosse et al. (2022) propose a data structure for DTs of precast concrete elements. An investigation of DTs specific to prefabrication factories operations is done by Barkokebas et al. (2022). Their bi-directional DT uses real-time information from the shop floor provided by IoT to determine efficient workstation occupancy through discrete event simulation and make this information available to the workers. The lack of research in this area is likely a missed opportunity, because DTs can address the need for simulations of different scenarios and process control in industrialized construction (Correa, 2022).

Digital twins for production planning and control in construction

When looking into DTs for planning and control in the execution phase of construction projects, Zhang et al. (2022) examine how construction site DTs can be used for progress monitoring, equipment maintenance, energy efficiency control, and accident prevention. The concept consists of construction site objects in the physical domain (facility, equipment, landscape, material), databases with project information (time, cost) as well as visualization and simulation engines in the virtual domain, and lastly IoT technologies for data transfer. Similarly, using the Unity game engine, Jiang et al. (2022) realize DTs of construction objects, including workers, equipment, and resources, to monitor and control the assembly of prefabricated elements on the construction site.

Sacks et al. (2020) go a step further, describing new procedural ways in which real-time synchronization of virtual planning and physical execution can reshape construction management. They first review established lean PPC approaches in construction. Then, they elaborate on how combining them with automated site monitoring, situational awareness, and production knowledge has the potential to make construction more proactive. By aligning DT information systems with lean management principles, more extensive simulations for production planning can be facilitated (Yeung *et al.*, 2022). A data model developed by Schlenger et al. (2022) for this purpose considers processes, products, and resources as relevant elements - similar to manufacturing - and adds zones to them that are also relevant for planning construction site activities, as the authors argue.

Lacking integration of digital twins

A prerequisite for DTs to perform successfully under a wide range of conditions is the large-scale aggregation of data from a multitude of systems (Thelen *et al.*, 2022). If large amounts and high-quality data about the physical system are available, DT simulations that base on this information can predict its future behavior more accurately. However, if the physical system is only twinned partially or with a significant time delay, the results become less accurate and the actual behavior evolves in a different way than predicted. Thus, integrating the product DTs and DTs of the manufacturing system in which products are fabricated is an important topic to be addressed by research (Grieves, 2022). For construction projects, this refers to the building's DT (*product*) and the DT of the prefabrication factory (*process*). Here, the process dimension comprises both bespoke stationery manufacturing facilities and future mobile factories temporarily set up close to the site as proposed by Rauch, Matt and Dallasega (2015) and Wagner et al. (2020).

Previous research on DTs in the construction phase does not address the interactions between products and processes properly. Construction DTs mainly focus on in-situ activities and do not consider preceding work performed in manufacturing facilities. If the DTs are applied separately and do not exchange information about their physical systems in real-time, incompatible optimization strategies may result. This would in turn hamper the decision-making process of construction managers. DTs might fail in fulfilling the original purpose of the application – enhanced controlling and optimization. Consequently, there is a need to formalize ways of integrating construction DTs and manufacturing DTs.

Model for integrating digital twins

A good integration ideally builds on a conceptually aligned modeling of the systems (Jonker and Karapetrovic, 2004). Systems theory is suitable for describing entities and their interactions that influence the complex behavior of the system. In this light, a factory is a continuous manufacturing system in which elements are used and arranged to produce physical or informational products with quantifiable properties (Suh *et al.*, 1998). Similarly, a construction project can be viewed as a temporary system in which measurable customer requirements (e.g. function, time, cost) are to be achieved through formalized allocation of project resources (e.g. crews, materials, tools) (Love *et al.*, 2002). Both systems require management that ensures the fulfillment of their particular purpose in the presence of dynamic uncertainties.

The DT concept is applicable to systems and supports managing their operations (Jones et al., 2020). The physical-virtual synchronization can be realized on varying hierarchical levels: individual units, subsystems, or system of systems (Reiche *et al.*, 2021). Replicating a manufacturing system or a construction project in the virtual realm likewise resembles a system in which twinned materials and twinned operations provide insights. Hence, DT management systems make it possible to analyze and manage their operation to meet the set goals.

Integration of management systems in organizations is a much-researched field and its principles appear supportive in achieving the envisaged fusion of DTs. In the wake of the emerging standardization of systems through international standards, Karapetrovic and Willborn (1998) have introduced a conceptual model suitable for describing management systems to be integrated. In their pioneering work, the system is characterized by the three elements objectives, processes, and resources along with their interactions to formalize easier collaboration.

Deriving from these concepts, we introduce a model system that formalizes the integration between construction DTs and manufacturing DTs (see Figure 2). These management systems are depicted on three levels:

(1) Objectives are quantifiable requirements about the product's characteristics and processes' performance that the DT is managing. Factory objectives can be to maintain high utilization rates and have little work in progress accumulated. The plausible objectives of the construction system are a speedy completion of the project alongside a good flow of activities. Integration of objectives allows for simultaneous consideration of management objectives for finding holistic optimal solutions.

(2) Processes are the sequence of activities that are performed to support the achievement of the DT's objectives. Examples of processes in the virtual factory are machine allocation planning, efficiency analyses, or future-state simulations for optimization. The construction management system includes processes such as activity planning with resource allocation, as-planned & as-is comparisons, and simulations of optimized construction procedures. Integration of processes allows for comprehensive analyses and simulations provided by extensive time series and real-time data.

(3) Data & tools encompass information carriers and software tools in virtual systems. This data is used by processes as inputs, processed using the virtual tools, and provided as outputs with optionally modified properties. Important data of the virtual factory are real-time information about machines and equipment in the form of an up-to-date manufacturing process model alongside a time series data storage. Relevant virtual tools are enterprise resource planning (ERP) and manufacturing execution system (MES) software alongside evaluation and simulation algorithms. Data necessary for virtual construction are up-to-date BIM models that describe the product and all its subassemblies, schedules that indicate the sequence of on-site works to be performed alongside budgets. Relevant virtual tools are scheduling and estimation software, simulation algorithms or game engines suitable for data visualization via dashboards, tables, and extended reality. Integration of data & tools provides profound insight into the current status of physical systems and their evolution over time.

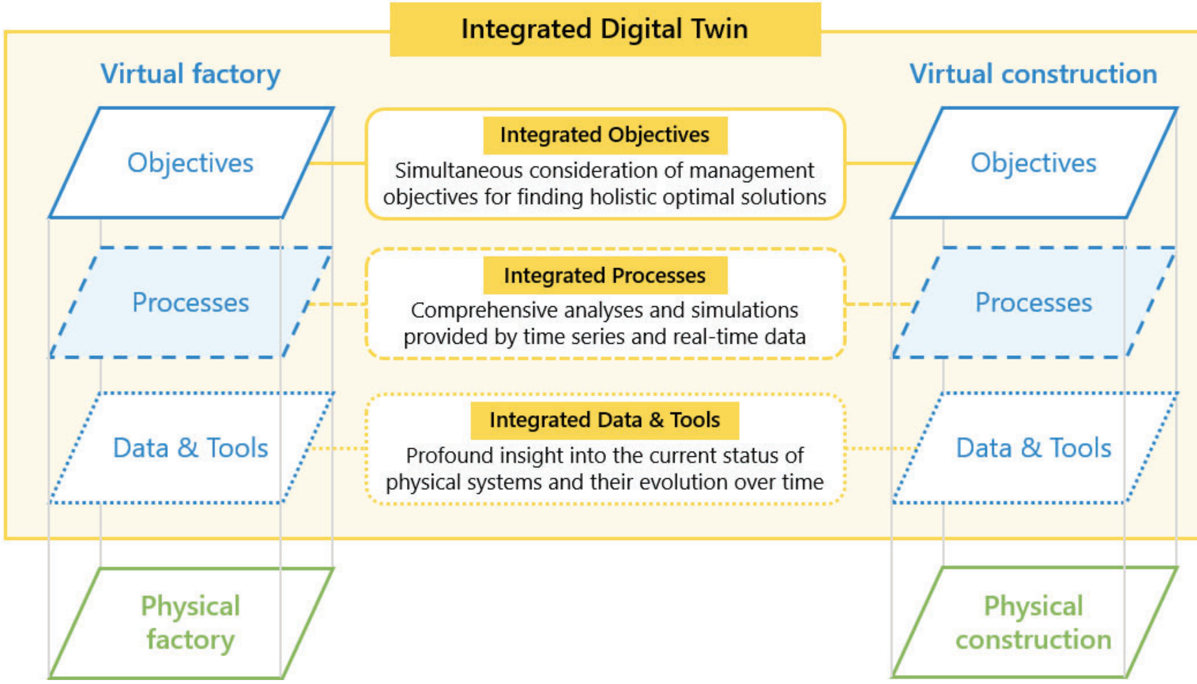

Figure 2: Three-layered model for integrating construction digital twins and manufacturing digital twins

Theoretical example of integrated digital twin

Use case – digital twins with conflicting objectives

A theoretical, yet-to-be-implemented example is introduced to illustrate how the proposed model can support the integration of DTs with opposing optimization targets (see Figure 3). One objective of the factory's DT may be to have machines keep producing the same products for as long as possible to take advantage of learning effects and reduce unproductive changeover times. The construction DT, in contrast, may target schedule adherence with short monitoring and control cycles while reducing on-site storage space.

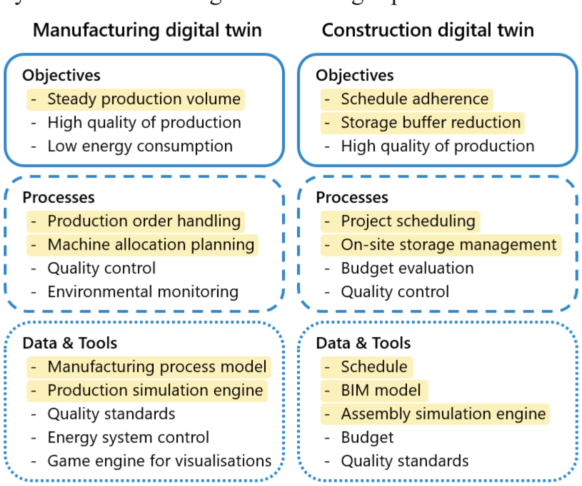

Figure 3: Example application of the model for formalizing the integration of digital twins. The yellow highlighting indicates the elements to be integrated.

To realize horizontal integration across DTs, vertical mapping within the individual DTs is required to identify the processes relevant to these objectives. In this case, order handling and subsequent machine allocation planning in the factory are concerned. Additionally, relevant processes in construction can be project scheduling alongside on-site storage management. Then, the data & tools used by processes as inputs are to be defined. Here, the factory DT uses the process model of the manufacturing line as it provides up-to-date information about the machinery. The scheduling process of the construction DT has the overall project schedule, a BIM model with site geometry, and the resource pool as information inputs. Moreover, both DTs rely on dedicated simulation algorithms as inputs to generate desired machine orders and assembly sequences.

Integrated bi-directional workflow

The procedure depicted in Figure 4 illustrates how this integrated DT can in theory be useful to achieve holistic goals when uncertainties lead to deviations from the planned project execution.

Step 1 – The starting point is a delayed completion of in-situ preparation work. This requires the re-planning of element production in the factory and their assembly on the construction site. Due to the intrinsic complexity of both systems, it is challenging for planners to immediately develop possible adjustments and assess their impact on the construction and factory objectives.

Step 2 – Physical-virtual twinning captures the progress in both construction and factory in real-time. This is represented in the up-to-date data & tools of the DT that are synchronized with the as-is state of their physical counterparts. The project schedule contains – in addition

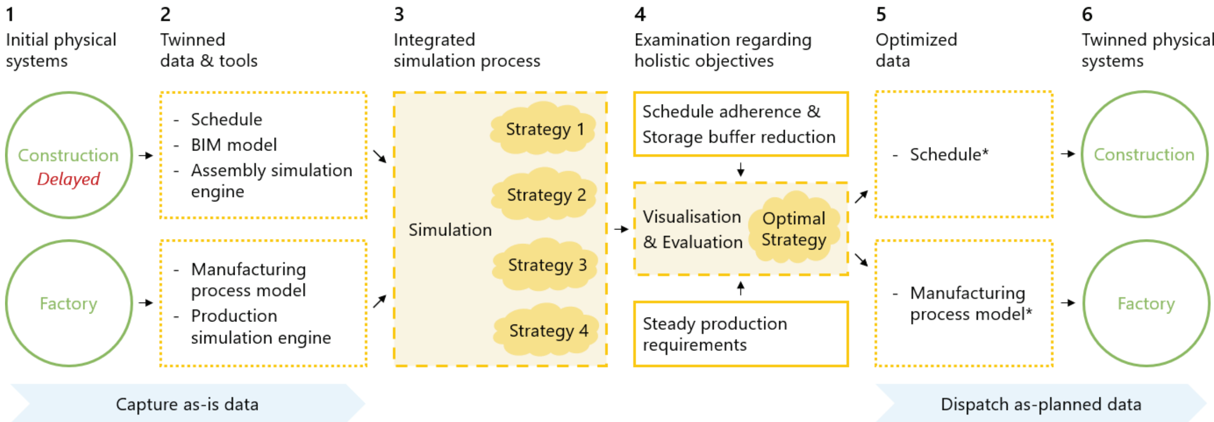

Figure 4: Operation example of the bi-directional integrated digital twin. In case of unforeseen events, the real-time physical-virtual twinning of both systems (steps 1 & 2) allows for production control and re-planning that considers holistic objectives (steps 3 & 4). Virtual-physical twinning transfers the optimization results back to construction and factory (steps 5 & 6).

to the planned durations – information on the actual duration of currently performed and already completed activities. Comparison of these values allows for detecting the delay and affected downstream activities. The BIM model contains the geometry and number of building elements still to be manufactured. Here too, both planned and actual properties like the exact dimensions or amount of material used are stored. Furthermore, different work zone definitions can be derived from the BIM model. The manufacturing process model from the factory reflects the sequence of activities and contains precise information about the current availability, the efficiency over time, and upcoming maintenance intervals of machinery. Besides these information carriers, the integrated DT has access to the simulation engines of both environments.

Step 3 – Using this real-time integrated information, the DT supports speedy production re-planning. An integrated simulation engine quickly performs multiple what-if analyses. Discrete event simulation is used to vary system operation parameters within their feasible range and determine their impact on performance metrics. Parameters can include the number of machines operated, crews assigned to the job site, or quantities of materials ordered. The result is a list of possible strategies that are uniquely described by a particular combination of process and product parameters and resulting metrics. Relevant metrics for the factory can be the utilization rate of the machines, the amount of WIP, or expected scrap. Metrics relevant to construction include adherence to schedule and space required for storing building elements on site.

The strategies generated by the integrated DT in this example differ regarding the achievement of holistic objectives. One strategy may involve pausing production to prevent the accumulation of completed parts (construction objective). However, this would lead to downtimes of the machinery. Another strategy can envisage continued production in the factory at full load, which ensures steady capacity utilization (factory objective). Yet, this carries the risk of piling up a lot of building elements. In both cases, only the specific objective of each system would be considered. Yet, there might be a strategy that provides a feasible solution for both systems. This could involve a partial shutdown of production by stopping individual machines. This time could be used for maintenance intervals to be brought forward and at the same reduce production output and the risk of large extents of work in progress accumulated. Despite not meeting both objectives individually, it can be the best mitigation strategy from a holistic perspective.

Step 4 – The results of the simulations are visualized by the DT to assist the operators in decision-making. It is important to make the selected parameters and the resulting performance metrics for each strategy clear to them. Simple metrics such as machine efficiency or cost per time unit can be displayed in dashboards or reports. Changes to the manufacturing process or site infrastructure, by contrast, can be displayed using extended reality visualizations provided by game engines. Here, there is also the opportunity to provide additional context to the data displayed owing to the integration of process and product information in the DT and thereby reduce complexity. Operators can assess which downstream activities are affected by which strategy. They can then simultaneously explore how options will impact the efficiency metrics in the factory. Based on these visualizations, decision-makers select an optimal mitigation strategy.

Step 5 – Once a strategy has been defined, intended optimizations to the operation are modeled in the virtual realm to represent the as-planned state. On the one hand, the schedule contains updated resource allocations alongside new dates for the delivery and assembly of the building elements. On the other hand, the manufacturing process model defines new machine allocations for the factory.

Step 6 – Finally, virtual-physical twinning is done by sending optimized data automatically to the construction and factory. The new version of the schedule, which has been updated with the latest knowledge, replaces the previous schedule and is now used for planning the construction works. This data coming from the virtual realm can be represented visually to instruct workers on the physical site or be digitally sent to actuators such as excavators or cranes to direct their operation. Likewise, the old process model in the factory is automatically replaced so that all further work instructions for the machines and workers on the shopfloor are obtained from this updated model. Thereby, on-site activities and factory operations are automatically supplied with the most current information, making the overall physical execution more efficient and completing the integrated bi-directional DT loop.

Discussion

The presented model makes it possible for formalizing the integration of DTs in manufacturing and construction in terms of *objectives*, *processes*, and *data & tools*. It reveals the specific elements of the separate digital twins that need to be aligned horizontally to achieve holistic objectives. At the same time, it allows for mapping elements vertically within individual DTs. The three-layered model is derived from proven approaches to management system integration and is based on systems theory (Karapetrovic and Willborn, 1998). Therefore, it can be extended with additional layers to cover further aspects of integration.

Integrating DTs has the potential to enhance construction management in three ways. First, it allows for aligning the divergent strategies and objectives that govern manufacturing and construction (Ballard *et al.*, 2007; Slack, Brandon-Jones and Johnston, 2013). In addition to previously studied benefits of DTs for mono-dimensional optimization, the integration model elaborates on use cases and benefits for decision-making on a more holistic scale. This synchronization of construction and manufacturing seems particularly relevant for projects involving mobile factories that are installed temporarily close to the construction site to supply the necessary building elements at short notice (Rauch, Matt and Dallasega, 2015). Second, the integration of data & tools between the DTs allows more real-time information to be available for management in the execution phase. If unexpected events occur on-site, this information is immediately available in the factory and vice versa. Rather than relying on inaccurate estimates, integrated DTs can take advantage of this up-to-date information and support construction management with relevant simulations covering both systems. Third, collecting information across factory and construction site facilitates more in-depth big data analytics and fine-tuning of forecast models. Particularly noteworthy about an integrated DT is that the necessary data aggregation does not take place retrospectively, but continuously at the exact moment when the data is generated in the respective systems.

Future research is necessary to facilitate the realization of an integrated DT for construction and manufacturing. As such, more detailed objectives, processes, and data & tools of an integrated DT should be determined. These will differ depending on the focus of the optimization, like for instance quality assurance, budget adherence, or sustainability. On the one hand, the DTs proposed in research so far should be considered here. On the other hand, data about the needs and established procedures of industry stakeholders should be collected. In this way, a detailed operational concept for an integrated DT could be developed from the view of different users. Furthermore, the technical aspect of integration must be examined in more detail. Data integration is an essential issue to be solved for DTs (Farghaly and Soman, 2022; Merino *et al.*, 2022). More specifically, for the integrated processes to be executed, it is necessary to manage and share information across diverse sources like manufacturing execution systems or construction scheduling software. Since these processes must be performed in real-time, current file-based exchange formats between manufacturing and construction do not seem to be appropriate. Here, solutions based on semantic web technologies and linked data technologies appear to be more promising (Pauwels, Zhang and Lee, 2017). Lastly, the expected benefits of integrated DT are to be confirmed by means of a real-world implementation. Following the theoretical example presented, this could be limited to one to two major objectives in the first prototypical development. This would allow metrics to be captured that quantitatively prove the advantage of using integrated DTs for management over separate DTs.

Conclusions

In this paper, we have investigated the integration of construction DTs and manufacturing DTs. As they are operated in different business environments, their simulations will be guided by different objectives. For them to properly consider all relevant aspects of the physical systems and to help managers in decision-making with feasible optimization strategies, a joint consideration is necessary. The integration of DTs can be formalized with a three-layered model that describes them with respect to their objectives, the processes they perform, and the data & tools they employ. A theoretical example illustrates how such an integrated DT with bi-directional information flow might improve optimizations in case of unexpected delays during project execution.

However, this is only initial conceptual work that needs to be expanded upon in the future. Forthcoming research should elaborate on precise operation concepts of integrated DTs. Further, the technical integration of data & tools must be investigated in terms of interoperability. Finally, real-world implementation of an integrated DT for construction and manufacturing should validate the expected benefits.

This work is relevant to researchers as it introduces a well-established modeling approach from management systems integration to the emerging research on DTs in the operational phase of construction projects. Applying the presented model, research can describe both theoretical studies and practical implementations of DTs using a formal approach. This promotes comparability of the solutions developed and opens the possibility for the integrations of separate works. At the same time, practitioners can use this model to formally outline planned DT implementations. Starting from this model, they can conceptualize integrations with other DTs present within their supply chains to jointly increase the payoff of the investments made for each separate DT.

Acknowledgments

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References

Ballard, G., Tommelein, I., Koskela, L. and Howell, G. (2007) 'Lean construction tools and techniques', in *Design and construction*. Routledge, pp. 251–279.

Barkokebas, B., Alsakka, F., Hamzeh, F. and Al-Hussein, M. (2022) 'Digital Twins to Enable Flexibility in Off-Site Construction', in *Lean Construction 4.0: Driving a Digital Revolution of Production Management in the AEC Industry*. 1st edn. London: Routledge. doi: 10.1201/9781003150930.

Čolaković, A. and Hadžialić, M. (2018) 'Internet of Things (IoT): A review of enabling technologies, challenges, and open research issues', *Computer Networks*, 144, pp. 17–39. doi: 10.1016/j.comnet.2018.07.017.

Correa, F.R. (2022) 'BIM, Twin and Between: Conceptual Engineering Approach to Formalize Digital Twins in Construction', in *Proceedings of the 39th International Symposium on Automation and Robotics in Construction*. Bogotá, Colombia, p. 8. doi: 10.22260/ISARC2022/0065.

Dallasega, P., Marengo, E. and Revolti, A. (2021) 'Strengths and shortcomings of methodologies for production planning and control of construction projects: a systematic literature review and future perspectives', *Production Planning & Control*, 32(4), pp. 257–282. doi: 10.1080/09537287.2020.1725170.

ElMaraghy, W., ElMaraghy, H., Tomiyama, T. and Monostori, L. (2012) 'Complexity in engineering design and manufacturing', *CIRP Annals*, 61(2), pp. 793–814. doi: 10.1016/j.cirp.2012.05.001.

Farghaly, K. and Soman, R. (2022) 'Construction Programme & Production Control (CPPC) ontology : a required integration for construction digital twin', in *Proceedings of the 2022 European Conference on Computing in Construction*. doi: 10.35490/EC3.2022.159.

Grieves, M. (2022) 'Intelligent digital twins and the development and management of complex systems', *Digital Twin*, 2, p. 8. doi: 10.12688/digitaltwin.17574.1.

Jiang, Y., Li, M., Guo, D., Wu, W., Zhong, R.Y. and Huang, G.Q. (2022) 'Digital twin-enabled smart modular integrated construction system for on-site assembly', *Computers in Industry*, 136, p. 103594. doi: 10.1016/j.compind.2021.103594.

Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. (2020) 'Characterising the Digital Twin: A systematic literature review', *CIRP Journal of Manufacturing Science and Technology*, 29, pp. 36–52. doi: 10.1016/j.cirpj.2020.02.002.

Jonker, J. and Karapetrovic, S. (2004) 'Systems thinking for the integration of management systems', *Business Process Management Journal*, 10(6), pp. 608–615. doi: 10.1108/14637150410567839.

Karapetrovic, S. and Willborn, W. (1998) 'The system's view for clarification of quality vocabulary', *International Journal of Quality & Reliability Management*, 15(1), pp. 99–120. doi: 10.1108/02656719810198601.

Kosse, S., Vogt, O., Wolf, M., König, M. and Gerhard, D. (2022) 'Digital Twin Framework for Enabling Serial Construction', *Frontiers in Built Environment*, 8, p. 20. doi: 10.3389/fbuil.2022.864722.

Kritzinger, W., Karner, M., Traar, G., Henjes, J. and Sihn, W. (2018) 'Digital Twin in manufacturing: A categorical literature review and classification', *IFAC-PapersOnLine*, 51(11), pp. 1016–1022. doi: 10.1016/j.ifacol.2018.08.474.

Lee, D. and Lee, S. (2021) 'Digital Twin for Supply Chain Coordination in Modular Construction', *Applied Sciences*, 11(13), p. 5909. doi: 10.3390/app11135909.

Love, P.E.D., Holt, G.D., Shen, L.Y., Li, H. and Irani, Z. (2002) 'Using systems dynamics to better understand change and rework in construction project management systems', *International Journal of Project Management*, 20(6), pp. 425–436. doi: 10.1016/S0263-7863(01)00039-4.

Merino, J., Xie, X., Moretti, N., Chang, J.Y. and Parlikad, A.K. (2022) 'Data integration for digital twins in the built environment', in *Proceedings of the 2022 European Conference on Computing in Construction*. doi: 10.35490/EC3.2022.172.

Pauwels, P., Zhang, S. and Lee, Y.-C. (2017) 'Semantic web technologies in AEC industry: A literature overview', *Automation in Construction*, 73, pp. 145–165. doi: 10.1016/j.autcon.2016.10.003.

Rauch, E., Matt, D.T. and Dallasega, P. (2015) 'Mobile On-site Factories – Scalable and distributed manufacturing systems for the construction industry', in *Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management (IEOM)*. Dubai: IEEE, pp. 1–10. doi: 10.1109/IEOM.2015.7093746.

Reiche, L.-T., Gundlach, C.S., Mewes, G.F. and Fay, A. (2021) 'The Digital Twin of a System: A Structure for Networks of Digital Twins', in *Proceedings of the 2021 IEEE 26th International Conference on Emerging Technologies and Factory Automation (ETFA)*. Vasteras, Sweden: IEEE, pp. 1–8. doi: 10.1109/ETFA45728.2021.9613594.

Sacks, R., Brilakis, I., Pikas, E., Xie, H.S. and Girolami, M. (2020) 'Construction with digital twin information systems', *Data-Centric Engineering*, 1, p. e14. doi: 10.1017/dce.2020.16.

Schlenger, J., Yeung, T., Vilgertshofer, S., Martinez, J., Sacks, R. and Borrmann, A. (2022) 'A Comprehensive Data Schema for Digital Twin Construction', in *Proceedings of the 29th EG-ICE International Workshop on Intelligent Computing in Engineering*. EG-ICE, pp. 34–44. doi: 10.7146/aul.455.c194.

Slack, N., Brandon-Jones, A. and Johnston, R. (2013) *Operations management*. Seventh edition. Boston: Pearson.

Suh, N.P., Cochran, D.S., Lima, P.C. and Cambridge, M.I.T. (1998) 'Manufacturing System Design', *CIRP Annals*, 47(2), pp. 627–639.

Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H. and Sui, F. (2018) 'Digital twin-driven product design, manufacturing and service with big data', *The International Journal of Advanced Manufacturing Technology*, 94(9–12), pp. 3563–3576. doi: 10.1007/s00170-017-0233-1.

Tao, F. and Zhang, M. (2017) 'Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing', *IEEE Access*, 5, pp. 20418–20427. doi: 10.1109/ACCESS.2017.2756069.

Thelen, A., Zhang, X., Fink, O., Lu, Y., Ghosh, S., Youn, B.D., Todd, M.D., Mahadevan, S., Hu, C. and Hu, Z. (2022) 'A comprehensive review of digital twin — part 1: modeling and twinning enabling technologies', *Structural and Multidisciplinary Optimization*, 65(12), p. 354. doi: 10.1007/s00158-022-03425-4.

Wagner, H.J., Alvarez, M., Kyjanek, O., Bhiri, Z., Buck, M. and Menges, A. (2020) 'Flexible and transportable robotic timber construction platform – TIM', *Automation in Construction*, 120, p. 103400. doi: 10.1016/j.autcon.2020.103400.

Whyte, J., Chen, L., Gamble, C., Genes, C., Pierce, K., Fitzgerald, J., Coca, D., Mayfield, M., Babovic, F., Pedro, A. and Shah, N. (2019) *Analysing Systems Interdependencies Using a Digital Twin*. London: Centre for Digital Built Britain.

Yeung, T., Martinez, J., Sharoni, L. and Sacks, R. (2022) 'The Role of Simulation in Digital Twin Construction', in *Proceedings of the 29th EG-ICE International Workshop on Intelligent Computing in Engineering*. EG-ICE, pp. 248–258. doi: 10.7146/aul.455.c215.

Zhang, J., Cheng, J.C.P., Chen, W. and Chen, K. (2022) 'Digital Twins for Construction Sites: Concepts, LoD Definition, and Applications', *Journal of Management in Engineering*, 38(2), p. 04021094. doi: 10.1061/(ASCE)ME.1943-5479.0000948.