The Concept of Digital Twin for Construction Safety

J. Teizer\textsuperscript{1}; K. W. Johansen\textsuperscript{2}; and C. Schultz\textsuperscript{3}

\textsuperscript{1}Dept. of Civil and Architectural Engineering, Aarhus Univ., Denmark (corresponding author). ORCID: https://orcid.org/0000-0001-8071-895X. Email: teizer@cae.au.dk
\textsuperscript{2}Dept. of Civil and Architectural Engineering, Aarhus Univ., Denmark. ORCID: https://orcid.org/0000-0002-1828-3833. Email: kwj@cae.au.dk
\textsuperscript{3}Dept. of Electrical and Computer Engineering, Aarhus Univ., Denmark. ORCID: https://orcid.org/0000-0001-7334-6617. Email: cschultz@ece.au.dk

ABSTRACT

“Digital twins” as models for information-driven management and control of physical systems have emerged over the past years in multiple industrial sectors and recently also in construction. However, in the domain of construction safety, a digital twin remains undefined, with little or no consensus among researchers and practitioners of two essential aspects: (1) the connection between the physical reality of a construction site (the “physical” twin) and the corresponding computer model (the “digital” twin), and (2) the most effective selection and exploitation of real-life data for supporting safe design, planning, and execution of construction. This paper outlines the concept for a Digital Twin for Construction Safety (DTCS), defining three essential steps in the digital twin workflow: (1) safe design and planning for hazard prevention, (2) risk monitoring and control for proactive prediction and warning, and (3) continuous performance improvement for personalized- or project-based learning. DTCS should be viewed as a system-based approach enhancing the overall safety performance rather than exclusively integrating sensing information or safety knowledge in Building Information Modeling (BIM) for safety purposes. The result is an outline of our vision of the DTCS and a description of its components. Additionally, we point toward future research on the topic.

INTRODUCTION

Construction is one among the many industries in the world that would greatly benefit from introducing information-driven management of the physical system (e.g., people, processes, technology) to run its operations more efficiently and more safely. Its dynamic workplaces are diverse and rich in sensor data. However, the wide variety of site monitoring and data processing technologies employed, and the subsequent decision making drawn from this data, are yet to be properly integrated within a uniform framework. The problem with this lack of a cohesive, unified framework that integrates the breadth of sensor data, processing technologies and decision-making services, is it results in significant inefficiencies in the operational, physical work environment, as others have documented, e.g. (Sacks et al. 2010). The typical consequences in the case of construction safety are, for example, the cost of poor planning and uninformed decision making is an increased risk of a project being temporarily shut down, a loss in the owner’s or contractor’s reputation, a worker being forced into absenteeism from work, or of a worker suffering injuries (of which all are preventable) (Garret and Teizer 2009).

In the evolution of construction sites becoming data-centric operations, the "Digital Twin" concept is generally seen as up-to-date digital representations of the physical and functional
properties of a system that support decision making, for example, by predicting and analyzing potential future scenarios (Tao et al. 2019). For domains like safety in construction:

- the "physical twin" includes construction site events, activities, workers, vehicles and artefacts in the real world (e.g., the placement of a guardrail);
- the "digital twin" is the digital counterpart (e.g., a virtual model of the construction site events, activities etc. that is used to generate simulations for predicting hazardous regions);
- the "digital twin platform" provides the formal connection between the two twins (e.g., data, information, and knowledge exchange)

Therefore, construction safety digital twins and their accompanying platforms are needed in the value-creating chain of gathering raw data, processing it to derive safety information, and smart decision making at the right-time (Teizer 2016). The emergence of digital twins in construction is motivating the need to merge the largely independent domains of construction safety engineering and management, computing in construction, site monitoring technologies, and control methods.

This paper develops the core concepts for developing and implementing an information-driven workflow for safety in the planning and operation of building and civil infrastructure construction. It builds upon existing concepts of Design for Safety (DfS), Building Information Modeling (BIM), lean project production systems and thinking, automated data acquisition and processing in construction operations (Tool and Gambatese 2008, Zhang et al. 2015, Rozenfeld et al. 2010). These are integrated through the digital twin concept, in combination with artificial intelligence methods, to achieve closed-loop control systems for construction safety, which extends the regular BIM-approach that has been utilized until now. The next section provides a brief state-of-the-art on existing construction safety processes, the importance of data acquisition technologies to monitor physical operations, the emergence of digital twins, and the difference to existing information modeling approaches. The subsequent section introduces the digital twin for construction safety which we call DTCS.

BACKGROUND

Current state of safety management process and level of information technology - Good Job Hazard Analysis (JHA), monitoring, and control are part of any successful safety process and management. Combined, these steps fulfill important roles in the hierarchy of controls that make workplaces safer. Over the years, JHA has been established as a well-known practical method for identifying, evaluating, and controlling risk in many industrial sectors. However, the highly dynamic component of construction operations make managing construction site-safety more difficult than managing safety elsewhere. For instance, construction operations are typically comprised of unique factors such as: changing site layout conditions; multiple and often temporary work crews; differing in sizes or numbers of machines competing for the same workspace; or rapidly alternating weather conditions. Particularly in construction, a different approach is needed to identify hazards and risks, increase safety, and prevent accidents.

JHA in construction is still a labor-intensive, error-prone, and thus time-consuming process (Zhang et al. 2015). For determining the priority order of mitigation that needs to be implemented to make workplaces safe, the hazardous component of tasks involved in an activity are analyzed by a safety engineer. Safety engineers are typically trained in workspace planning and health, safety, and environment (HSE), and they evaluate the category of each incident risk by assessing the incident's probability of occurrence and its expected outcome (the level of injury) (Rozenfeld 2010). Those two measures rank the potential risk in a scale from most negligible to the most
severe outcome. According to Chao and Henshaw (2002) the process of job site safety analysis is divided into three tasks: (a) loss-of-control identification associated job or activity, (b) assessment of the level of risk for the identified incidents, and (c) action controlling the risk to reduce or eliminate it. However, even with the emergence of Building Information Modeling (BIM) methods, the current strategy and investment in construction safety planning, monitoring, and controlling follows manual, time-consuming, and error-prone processes (Li et al. 2020).

**Digital twins and data acquisition under typical construction project constraints** - Although construction projects as a whole are highly unique and dynamic, individual construction tasks, methods, and associated risks are fairly well-defined and expected. However, its numerous stakeholders work with, or generate, their own sets of information about products and the process of executing construction works. Under current conditions, few stakeholders are motivated to collaborate intensively with each other which often leads to the use of digital tools with multiple data formats that are not exchangeable.

As Sacks et al. (2020) point out in the effort to establish digital twin information systems, federated building models that represent as-designed and as-planned states of a project are not digital twins. As such, building information models as the digital representation of buildings or infrastructure lack the frequent as-built and as-performed states that are essential to understand construction workflow and to continuously improve this workflow. To make matters worse, construction safety is far behind other disciplines in BIM for which somewhat structured processes and tools exist, for example, estimating construction costs and schedules (Teizer 2016). Likewise, numerous data acquisition technologies exist that hardly touch the world of construction safety.

There is significant opportunity for digital twins that are tailored specifically for construction safety to provide new kinds of decision support to key stakeholders. Primary stakeholders are the health, safety, and environmental (HSE) coordinators but include all others who have the same responsibility in their job profile (e.g., engineers, planners, construction managers, workers). This potential has greatly stimulated construction safety research and development, although many research efforts often only target the use of a singular technology, without integrating the technology and subsequent analysis into a broader, more comprehensive framework for identifying and preventing hazards (Teizer 2019). Therefore, this paper aims to create a thorough workflow for planning, controlling, and learning for construction safety using digital twin information systems. Certain aspects concerning user interfaces are reflected in the research as well. The method is conceptual analysis (Laudan 1978) as a way to establish the foundation of a concept that is based on elementary parts and interdependencies (Beany 2018).

**DIGITAL TWIN FOR CONSTRUCTION SAFETY**

In this section, we describe how a Digital Twin for Construction Safety (DTCS) can be created and utilized to actually be a Digital Twin. Several cases have reported on "Digital Twins" where there are actually none (Sacks et al. 2020).

Figure 1 shows the overview of our DTCS (shown in the lower-left corner of the diagram). The DTCS is, as shown, dependent on other DTs, and those should be interconnected in a network that lets them exchange information and knowledge of interest. The digital twin should also be able to perform tasks for each other. For example, we envision that the Digital Twin for Production Planning (DTPP) requests DTCS to do a safety enhancement and assessment to an alternative production plan or, alternatively, a batch of those. It is chosen to concentrate mainly on the DTCS, which means that some details are missing from some of the surrounding components, e.g., the
greatly simplified DTPP, where user interaction, creation, and simulation have been kept out of
the diagram. In the following, we will elaborate on the inputs, interactions, and outputs of the
individual components of the DTCS. The prevention through design and planning (denoted in
green) is presented in a more detailed version in Figure 2, conformance checking (yellow) in Figure
3, and the Right time analysis and mitigation (red) in Figure 4.

Figure 1. Overview of the Digital Twin for Construction Safety (DTCS) and relationship
and interaction with the other important Digital Twins (e.g., production planning), physical
construction site, and construction site interfaces (e.g., monitoring and decision makers).

Construction Site (CS) - The construction site refers to the physical workplace (i.e., the
physical twin), which is either being planned, under construction, or constructed. It contains the
personnel (e.g., workers, construction management (CM), health and safety expert (HSE), and lean
production/planning experts), construction methods (e.g., consideration of equipment
alternatives), temporary resources (e.g., scaffolds and safety equipment), building materials (e.g.,
drywall, concrete slabs, and windows), and construction plan (e.g., site layout plan, schedule, cost,
and quality). The personnel (later referred to as decision-makers) have responsibilities, that need
to be considered from a broader perspective to facilitate a productive, safe, and high-quality result.
Digital Twin for Construction (DTC) - The DTC is a digital representation of the construction site (i.e., the "digital twin" of the physical world, where the physical world itself is referred to as the "physical twin"), which contains both the future potential reality, called Project Intent Information (PII), the past reality, and the present reality, captured in the Project Status Knowledge (PSK) (Sacks et al. 2020). The construction is built from the PII, namely the Baseline Plan (BP), containing both the as-designed product (how it should be) and the as-planned process (how, and in which sequence, it should be constructed). The PSK is then updated from the physical world (e.g., semi- or fully automated through a combination of raw and processed field data, i.e. real-time location sensing and three-dimensional point cloud data of resources or structures, respectively, of which both are present or appear on the construction site). The PSK also captures the state of the product (as-built product), which is tightly coupled to the design of the product. An example of the state is: the set of walls that have already been placed, and information on whether they have been placed correctly in comparison to the as-designed product. Furthermore, the PSK captures the performed process of the construction (as-performed process) that can be compared to the as-planned process. The comparison of the two sets of information (i.e., as-designed vs. as-built and as-planned vs. as-performed) generates knowledge about the discrepancy that may be avoided through different planning strategies in future projects.

Through information gathering of historical decision-maker feedback and preferences, and the information from the comparison of planned activity vs. reality, the digital twin gives knowledge that can be applied to future planned construction activities and projects. For example, this knowledge can facilitate optimized construction safety in terms of task-specific coordination in schedules, budget associated cost in more detail than available before, and ensure higher quality.

Digital Twin for Production Planning (DTPP) - As mentioned, the Digital Twin for Construction (DTC) contains a Baseline Plan (BP) used to build the physical construction. The DTPP also generates Alternative Plans (APs) with the BP as a starting point, along with the decision-makers' preferences (i.e., based on experiences or internal guidelines). It creates some number, \( N \), of APs, that slightly differ in the process, cost, quality, etc. The measures, aka. Key Performance Indicators (KPIs), of the individual plans, are gathered through simulation affected by the historical knowledge that is a part of the digital twin. Each of the APs is given to the DTCS for enhance- and assessment of safety equipment along with the creation of Safety Key Performance Indicators (SKPI). The KPI and SKPI facilitates the selection of the AP, thus the APs become Safe Alternative Plans (SAPs). The decision makers should be presented with the SAPs (including the related KPIs and SKPIs), from which the decision-makers select an SAP, on an as-needed basis, that aligns with their overall goal and vision. This may happen daily (i.e., for preparing toolbox meetings), weekly, or as otherwise defined in look-ahead schedules. Through this process, the BP is updated/changed continuously with newly collected knowledge. This may well be integrated with ongoing look-ahead scheduling used in construction production planning.

Construction Site Interface (CSI) - The CSI serves to provide, get feedback from, and give feedback to, the different decision-makers present on the construction site, and thus includes different interfaces. The interfaces are illustrated as different boxes for the individual decision-makers, although some may overlap or extend. The safety monitoring components provide the DTCS with raw data that first must be interpreted into information that can then generate knowledge. It is envisioned that the raw data can contain different sensor data, which can be used in collaboration to create information that is not visible in one sensor output exclusively (aka. data fusion). Here, digital interfaces (i.e., wearables) that are simple to use for personnel on the construction site may provide an additional means to record data or receive communication.
An example is an interface for a construction worker interface which would be different from the one for construction management. The worker should be alarmed if being in danger and it would not be sufficient if the worker needs to interpret a comprehensive accident investigation report first before being hit by a nearby piece of equipment or load, but rather is given the (run-time) alert through sound and light emitters. To understand how to act correctly to prevent the accident, the alerting sound can be accompanied by a push notification on an easy to carry device (e.g., smartphone) stating (in short) to leave the area as crane activity is being carried out. The notification can also inform the worker how to leave the area safely. The crane operator should also be notified. The digital twin for the crane stops the activity automatically, or the operator does this and waits until the worker has left the operation space. The HSE should be informed about the accident and provide feedback to the system, informing the HSE about potential strategies to avoid this hazard in the future. The solution can both be the usage of signs, the addition of virtual spaces (temporal restricted areas), training, or most likely, a combination of these.

**Digital Twin for Construction Safety (DTCS)** - With the components mentioned above, we are now ready to describe what happened in the digital twin for construction safety in greater detail. The DTCS consists of three main components, i.e., Prevention through design and planning (PtD/P), Conformance Checking (CC), and Right-time Analysis and Mitigation (RAM). First, we introduce the overall interaction of these with their surroundings, and subsequently, we describe the contents of these. The alternative plans are received from the DTPP for safety enhancement and assessment, which means that the protective safety equipment is added to the model. There may exist more than one way to make a safe plan, which will result in an answer set of different solutions. The solutions are created based on the safety regulation, which holds information about safety rules provided by the government, the state, and local authorities (e.g., BG BAU 2019, OSHA 2020). Another component of the safety regulation instance is best practice, which should hold the decision-makers' preferences (e.g., guardrails over safety net). Each SAP (i.e., a safe version of an alternative plan) is given a collection of SKPIs informing the HSE about the cumbersomeness of, among others, safety equipment installation, protection capabilities, risk analysis. The Safety regulation data storage should be updated based on the actual performance of the chosen SAP and the decision-makers' feedback stored in the historical knowledge database.

Based on a conformance checking of the safe plan and the reality representing the actual construction site, it should be possible to locate discrepancies. These are classified into three levels of severity (i.e., High, Medium, and Low), provided to the HSE, and stored at the historical knowledge database. The HSE should then act appropriately to the severity, solve the flagged accident, and implement changes to the physical construction site. When an accident has been solved, the HSE should provide feedback to the system (comparable to labeling of data) for future improvement, i.e. learning from output (both information & classification) and recommendations.

Right-time analysis and mitigation provide two kinds of output, i.e., the run-time alerts for the worker, and information as needed for the remaining decision-makers. It is envisioned that a worker in danger should be alerted as soon as possible through an appropriate interface. The information as needed is more elaborated information and includes appropriate mitigation strategies, where further analysis has been performed. This is envisioned as there may not necessarily be time, or necessity, for elaborate mitigation actions in a close call situation, for example, a worker being located in the blind spot of construction machinery. Hence the machinery operator and walking worker should both be aware of the hazardous situation and solve the issue collaboratively. Information and mitigation proposals can be compiled and handed to the HSE and
BIM-coordinator for future avoidance of similar occasions. For example, avoidance measures may consist of better signage, a cleaner separation of walk paths and machinery roads, or construction site cleaning, as walk paths may be obscured with construction materials or waste. Once again, it is envisioned that the output is *stored* along with the decision-maker feedback, from which the component can *learn* to provide better information and mitigation actions.

Figure 2. Internal operation of the prevention through design and planning component. As the in- and output is highly connected to the Digital Twin for production planning it is chosen to include it in the diagram.

Figure 3. Internal operation of the conformance checking component.

**Prevention through design and planning (PtD/P)** – The left side of Figure 2 illustrates in brief how the alternative plans are generated based on the decision-makers' preferences and the current baseline model. The APs are handed to the PtD/P component of the DTCS (right side of Figure 2).
and enhanced with safety measures (e.g., guardrails, safety nets, pedestrian walk paths, schedule changes) based on the safety regulation that applies to the construction site. This may, as mentioned, result in more than one SAP for each AP. The system analyses the hazard spaces identified in the design, and hazard spaces identified in the process (e.g., work crews working simultaneously on different stories, creating hazard zones in terms of being struck by an object from above). The SAPs are returned to the DTPP for decision-maker selection, consequently updating the baseline plan from which the construction site is built.

![Figure 4. Internal operation of the right time analysis and mitigation component.](image)

**Conformance checking** – The conformance checking should find and classify discrepancies between the plan (created in PtD/P-module) and reality (captured by sensors) (Figure 3). For example, an incorrectly installed or removed guardrail would result in a relatively high severity. This information is stored, and when the HSE personnel has visited the problem, they can provide new information on the correctness of the output (in terms of both incident classification and its severity). This information provided by the HSE should be used to improve the classification of future occurrences and to update the best practice. An example of an updated best practice could be to use a safety net in some situations to avoid the repeated removal of, e.g., a guardrail.

**Right time analysis and mitigation** – Based on the reality of the construction site, the raw safety monitoring data, historical knowledge, and safety regulation module performs complex event processing and classification, from which the workers are alerted to prevent both accidents (i.e., fatalities, serious injury, and minor injury) and incidents (i.e., close calls and unsafe acts) (Figure 4). The module subsequently performs an accident investigation, where the root cause of the incident or accident can be determined and prevented in the future. Also, in this module the feedback to, and from, the decision-makers are stored and used in processing/classification- and investigation mechanisms. The safety rules are also included in this diagram. These are updated and used in the prevention through design and planning module (i.e., the first component of the DTCS), conceptually closing the loop of the digital twin for construction safety.

**CONCLUSION**

This paper presented the new concept of Digital Twins for Construction Safety (DTCS), and a set of three core information elements and control elements. Like other digital twins that represent
models for information-driven management and control of physical systems (e.g., people, processes, technology), three essential steps in the workflow of construction safety were defined: (1) safe design and planning for hazard prevention, (2) risk monitoring and control for proactive prediction and warning, and (3) continuous performance improvement for personalized- or project-based learning. Working from these core elements, we advocate a DTCS information system workflow, including information models and rule sets, monitoring technologies, and performance feedback, in the implementation of digital twins for construction safety. Additionally, we outlined components of the DTCS that are still to be investigated, which can be performed in individual studies and afterwards connected to the DTCS. The DTCS is as part of a EU funded project that focusses on the overall holistic approach of transforming BIM into DT in construction operations.

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