Digital Twin for Construction Safety Modules in the Plan-Do-Check-Act Cycle of Events and Information Exchange

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Abstract
Industries like construction have recently been making significant investments in information-driven management and control of physical systems. Such models are commonly referred to "Digital Twins". However, in the construction safety domain, a digital twin (DT) remains vastly undefined. No consensus exists on two essential aspects: (a) the connection between the physical reality of a construction site (the "physical" twin) and the corresponding computer model (the "digital" twin) and (b) the most effective selection and exploitation of real-life data for supporting the safe design, planning, and execution of construction. This paper outlines the concept for a Digital Twin for Construction Safety (DTCS), defining four essential steps in a DT workflow: (1) safe workplace design and planning for hazard prevention, (2) conformance checking for ensuring compliance, (3) risk monitoring and control for proactive prediction and alerting, and (4) continuous performance improvement for personalized- or project-based learning. DTCS should be viewed as a system-based approach enhancing the overall performance rather than exclusively integrating sensing information or generating knowledge in Building Information Modeling (BIM) for safety purposes. Our result is a DTCS including the description of its modules.

Keywords: Construction safety, hazard prevention, proactive personalized feedback and control

1 Introduction

Construction is one of the many industries in the world that would greatly benefit from introducing information- and knowledge-driven management of the physical system (e.g., about people, processes, and technology) to run its operations more efficiently and safely. Its dynamic workplaces are diverse and rich for (sensor) data collection. 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 (Teizer et al., 2020). 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). Example consequences of construction safety are the added cost of poor planning and uninformed decision-making, increased risk of a project being temporarily shut down, the loss in the owner's or contractor's reputation, a worker suffering from injury and being forced into absenteeism from work (of which all are preventable) (Garrett and Teizer, 2009).

As construction sites turn to data-centric operations, the "Digital Twin" (DT) concept is seen as up-to-date digital representations of the physical and functional properties of a system that support decision-making by predicting and analyzing potential future scenarios (Lu et al., 2019). For 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, its virtual model that generates simulations for predicting hazardous regions (as detailed by Johansen et al. (2023); and
- the "digital twin platform" (DTP) 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). Eliminating hazardous pedestrian worker and equipment interactions is one of the applications that would benefit from the emergence of DTs in construction. A need exists to merge the largely independent domains in the construction of safety planning, engineering, management, computing, site monitoring, 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) (Toole and Gambatese, 2008), Job Hazard Analysis (JHA) with Building Information Modeling (BIM) (Zhang et al., 2015), safe and lean project production systems and thinking (Teizer and Melzner, 2018), automated data acquisition, processing, and mitigation frameworks in construction operations (Golovina et al., 2021). These are integrated through the DT concept, in combination with Artificial Intelligence (AI) methods, to achieve closed-loop control systems for construction safety, which extends the regular BIM-based project design and planning approach that has been utilized until now. The next section provides a review on existing construction safety processes, the importance of data acquisition technologies to monitor physical operations, the emergence of DTs, and the difference to existing information modeling approaches. Thereafter, we introduce the digital twin for construction safety which we call DTCS.

2 Related work

2.1 Current state of construction safety and level of information technology

Thorough Job Hazard Analysis (JHA), careful monitoring, and subsequent control are parts of any successful safety process and management (Zhang et al., 2015). 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 makes managing the processes involved in 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 (Teizer and Melzner, 2018). 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) (Zhang et al., 2015). 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 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).

2.2 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. The literature also states that several cases have been reported on DTs where there are actually none (Sacks et al., 2020). As they point out, in the effort to establish DT information systems, federated building models that represent as-designed and as-planned states of a project are not DTs. As such, building information models as the digital representation of buildings or infrastructure lack the frequent as-built and as-performed states essential to understanding construction processes and continuously improving 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 a significant opportunity for DTs that are tailored specifically for construction safety to provide new kinds of decision support to key stakeholders. Primary stakeholders are the HSE coordinators but include others with 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 like Teizer et al. (2022). have shown for DTCS. Therefore, this paper extends their work and aims to create a more thorough workflow for planning, controlling, and learning for construction safety using DT information systems. Certain aspects concerning user interfaces are reflected in the research as well. Our method is 'conceptual analysis' (Luadan, 1980) to establish the foundation of a concept that is based on elementary parts and interdependencies (Beaney, 2018).

2.3 Digital twin vs. digital shadow and digital model

Digitalization comes in different flavors that are useful for construction safety and the construction industry in general. Overall, there are three levels of digitalization: digital model, digital shadow, and digital twin, and their degree of automation and complexity increases according to the sequence that they are mentioned. Even though the manufacturing industry is ahead with digitalization and research of digital twins, there still exists misconceptions about separating them from digital shadows (Bergs et al., 2021). The manufacturing industry is more advanced in digital twin research due to the fragmented supply chains, dynamic environments, and complex data recording in the construction industry, making it harder to capture the state and equally hard to impact it directly (Opoku et al., 2023). Therefore, misconceptions of digital twins are also reported in the construction domain (Arowoiya et al., 2024; Feng et al., 2021; Radzi et al., 2023; and Sacks et al., 2020). The illustration shown in Figure 1 captures the differences between the digital model, digital shadow, and digital twins (Yildiz et al., 2020). All three consist of a physical and a digital object. In the context of construction, the physical object refers to the construction site and project, and the digital object is the digital capture of it.

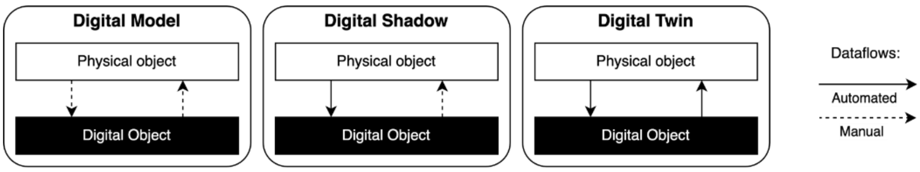

Figure 1. Differences between digital model, shadow, and twin (modified, after Yildiz et al. (2020))

In the digital model, both data flows are manual, meaning that when the physical object progresses, the digital object will only be updated based on manual efforts and vice versa. The digital shadow is automated in the data flow going from the physical object towards the digital, which means that the change in the physical object will automatically appear on the digital object. However, the changes to the digital object will still not automatically appear on the physical object. In the DT context, both directions must happen automatically, which means that the status (progress, both planned and unplanned) should replicated in the digital object automatically, and updates to the digital object should appear automatically on the physical twin (constructions project and site). However, the automatic appearance of changes in the digital object still requires humans in the loop, which means that the physical object in current practices will still be a construction plan; the work orders should be updated to compensate for events such as delays, quality issues, or safety compliance issues (Sacks et al., 2020).

The issues can be identified in the checking phase of the Plan, Do, Check, Act (PDCA) cycle (also known as the Shewhart cycle) (Lodgaard and Aasland, 2011; Patel and Deshpande, 2017), which is used to describe an iterative process in which repetitions of the four phases are used to complete a project. Each iteration is initiated by planning a portion of the work, which in construction is referred to as the look ahead, then the work is performed in the do phase, and the checking phase makes sure that everything went as planned; otherwise, eventual discrepancies are handled and compensated in the acting phase. The automated dataflows allow the DT to automatically capture the performed state of the project and carry out the checking. If any discrepancies are identified, eventually with the use of AI, recommendations are given to the Construction Management (CM) team for implementing change. If these are accepted, they should automatically be considered in the next iteration (i.e., look ahead) (Sacks et al., 2020).

2.4 Data to information to knowledge

The differences between data, information, knowledge, and wisdom were established by (Ackoff, 1989), and later described in the context of construction (Borrmann et al., 2024). Data can, for example, be images and data that is acquired on the construction site. Information refers to something that is useful and has a direct meaning for the end user. Knowledge refers to a higher level of abstraction, which, based on combinations of information, brings additional insight beyond the available information to the end user (Borrmann et al., 2024). The process of transforming data into knowledge can be automated through the application of AI, which for images can extract detected objects (Seo et al., 2015), or even track objects (Bügler et al. 2017, Pfitzner et al., 2024). For localization data the transformation can consist of extracting safety incidents, (Johansen et al., 2024a; Teizer and Cheng, 2015), or progress estimations (Johansen et al., 2021). Progress can also be extracted from point cloud data (Braun et al., 2020) and further be used for quality assessments depending on the resolution (Zhang and Zou, 2023).

2.5 Digital Twin for Construction Safety

Our previously established concept for a DTCS has been published originally in Teizer et al. (2022) and was further extended and validated in Teizer et al. (2024). Both works describe a DTCS which is envisioned to work in close collaboration with a Digital Twin for Production Planning (DTPP). The DTPP requests DTCS to do a safety enhancement and assessment to an alternative production plan or, alternatively, a batch of those. Furthermore, the works highlight specific details that readers of this paper should consult before continuing. These papers present for four submodules of the DTCS, their inputs, interactions, and outputs. The four modules are: (1) Prevention through Design and Planning (PtD/P) that eliminates hazards before they appear in the real workplace, (2) Conformance Checking (CC) that finds and classifies discrepancies between the plan (created in PtD/P-module) and the reality (captured by sensors), (3) Right-time Analysis and Mitigation (RAM) that performs runtime safety analysis based on raw safety monitoring data, historical knowledge, and safety regulations to identify and inform about incidents, and (4) Personalized Learning (PL) that provides an enhanced experience through a realistic Virtual Training Environment (VTE) for construction personnel for the purposes of hazard recognition and safety awareness training.

3 PDCA in DTCS

While the PDCA cycle has already been described in relation to the general execution of a construction project, how the DTCS modules can be integrated into the PDCA cycle remains undescribed. Figure 2 visualizes the PDCA cycle, and the individual DTCS modules are placed within the cycle. Their placement represents their relation to the stages of the original cycle.

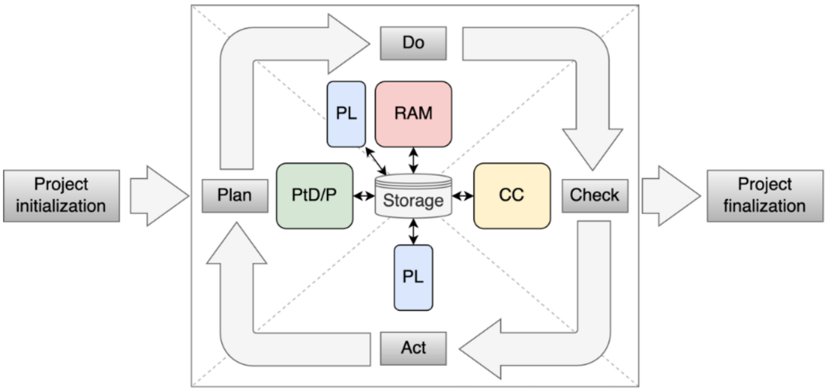

Figure 2. Proposed DTCS modules in the Plan-Do-Check-Act (PDCA) cycle (extended Patel and Deshpande, 2017)

The cycle starts out at the planning stage. The planning stage covers coming up with an approach to carry out the construction in the form of a schedule and a description of the involved processes, which is performed upon project initiation. Regarding safety, the PtD/P module will run in the planning stage, where the building design is made safe based on the planned activities and the geometry of the building, as described in the previous section. The doing stage of the cycle represents the stage where the construction workers perform the plan to make progress on the construction project. The PL module was placed just before this stage to show that some tasks may need training before they are carried out in reality. This can, for example, be if a work crew has not yet experienced a similar task before or if a new kind of measure is needed to perform the task safely. In other words, this is the preventative training, which is based on safety challenges that are foreseen in the planning stage. The RAM module is placed parallel to the doing stage, as its purpose is to identify incidents where the workers are not acting according to the training. However, it is also responsible for identifying incidents that were not foreseen in the planning stage or not yet part of the training scenarios. After some duration of doing, the resulting progress and execution must be checked. This activity is performed in the checking stage of the cycle, which covers progress and quality checking, as well as determining if the safety protection equipment on site has been installed to fulfill the safety plan and if it is complying with the regulation. The acting stage is where the potential discrepancies are acted upon; in the general flow, this, for example, covers schedule delays or quality assessments not meeting the requirements. in relation to it also means that workers can be trained further in specific details such as identifying hazards and mitigating them, acting safer in specific scenarios, or repairing/replacing safety protective equipment as the construction goes on. This part of the PL can also be referred to as post-incident training and can be based on the incidents found in the RAM and CC modules.

The PDCA cycle is performed with a fixed frequency, which is based on the project's lookahead duration, and continues until the checking stage finds that the construction project has been completed to a satisfying quality, which will allow it to stop and exit the cycle. The storage in the middle represents an entity, which is used by the individual modules to exchange information about their findings and feedback from the stakeholders, which is further described in the following section.

4 Flow of events and information

While the previous section describes the overall relationship between the DTCS modules and the PDCA cycle, it remains unclear how the modules interact and trigger each other to perform analysis and provide their contribution to a safer work environment. Figure 3 provides an overview of the interaction and events that flow through the DTCS modules and how the decisionmakers check their outputs before they are implemented on the construction site. Starting from the left of the figure, both internal (DTCS) and external (DTC, DTPP, Authorities, Sensor data, and Construction site). Most of the inputs relate to a stamped arrow annotated Decision making" representing that the stakeholders can check, select, and refine recommendations before those are included and considered in the next iteration. Similarly, there is a chance for the stakeholder to assess the outputs of the DTCS modules before these are implemented on the construction site (captured in the stamped arrow in the top annotated "check output and act").

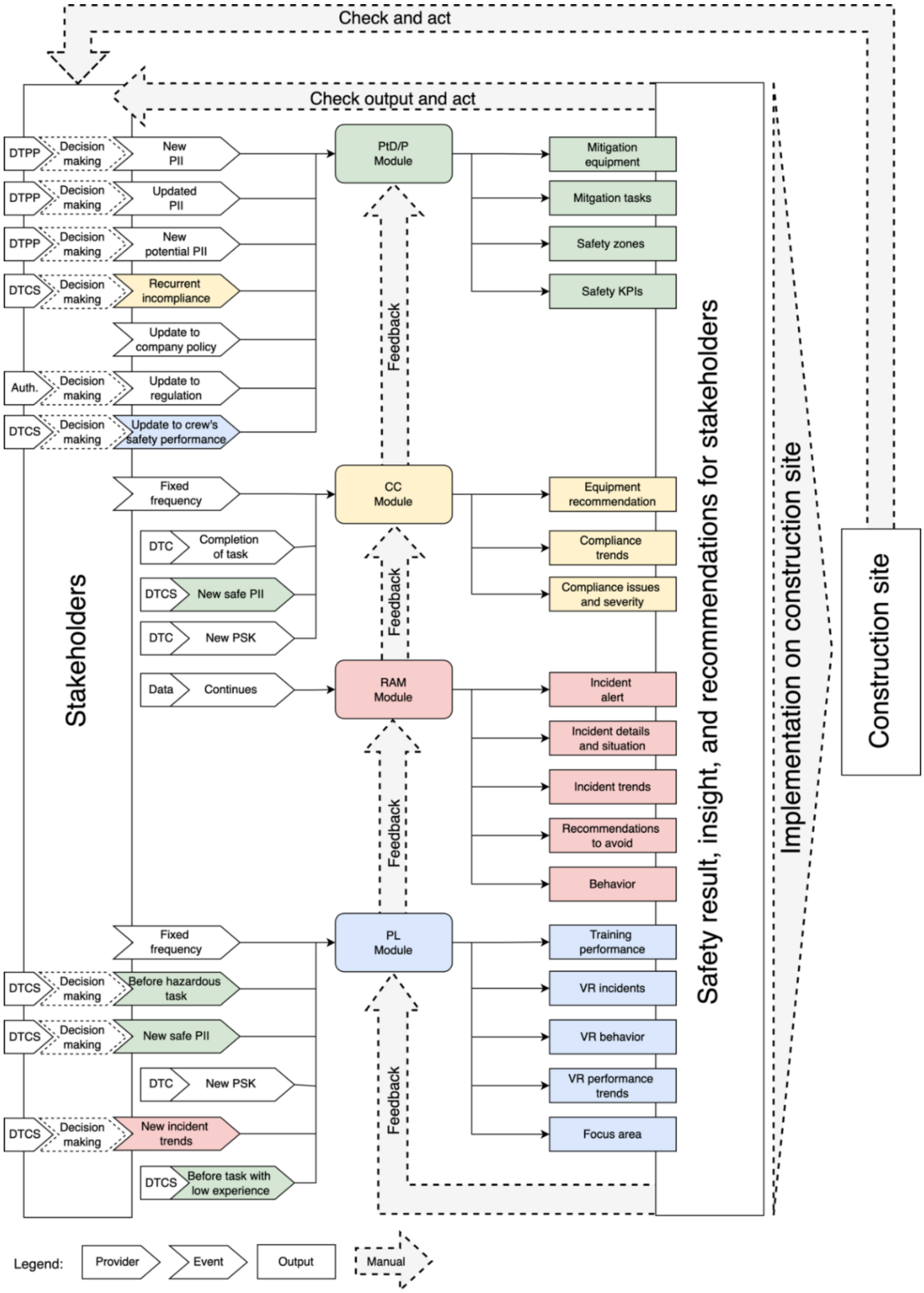

Figure 3. Overview of events and information exchange in the modules of DTCS

4.1 Events to trigger PtD/P

The three first events that make the PtD/P module run are new PII, which represents (1) that a new project has been initiated; (2) updated PII, which represents that an update has happened to the PII for example, representing a schedule change, and the new potential PII is representing that the stakeholder wants a safety assessment on potential alternative construction approaches generated by the DTPP. The next event that can result in the PtD/P modules running again is if there is a recurrent identification of incompliance in the CC module. This can be, e.g., if a piece of railing equipment is recurrently removed or worn out due to the delivery of materials. In this case, the decision maker would be suggested to change the equipment type to something more durable or something that cannot be removed without permission. Similarly, it can be chosen to change the company policy based on combinations of observations. Depending on the change, the module may need to run again to ensure that these are represented fully in the safe PII. Lastly, it can be identified in the training that one crew is performing well in ensuring the installation of safety equipment, which should result in them entering the workspace before their colleagues, and that change should be reflected in the schedule.

Each of these events will make the PtD/P module run, which results in a new safePII containing (1) the mitigation equipment needed to ensure a safe work environment for the workers, (2) the tasks to install the equipment, (3) the zones that were identified in the safety analysis, and (4) the safety KPIs, which represents how well the incoming PII performs in terms safety. The safety KPIs describe information such as the amount of hazard exposure, the amount of mitigation equipment, and the time it takes to install the equipment.

4.2 Events to Trigger CC Module

The first type of event that can trigger the CC module is based on a fixed frequency set by the stakeholders. The fixed frequency can be based on company policies or requirements stated in the regulations. Besides the fixed frequency, it can also be based on the event of completing specific kinds of tasks or milestones. The configuration should be based on historical information where completion often results in unprotected areas or incompliant protective equipment. Alternatively, it can be based on the postcondition of a task, e.g., if the completion of the task introduces a fall from height hazard. Similarly, the creation of a new safePII triggers an update to ensure that the changes are also considered in reality.

As the CC module is running, it creates a compliance report consisting of compliance issues, their severity, and recommendations to improve the overall safety situation, such as changing a piece of mitigation equipment from one type to another non-removable type. The module should also compile a compliance trend report, which the stakeholders can use to get an understanding of the long-term effects of selecting different mitigation approaches.

4.3 RAM Module

The RAM module is not envisioned to be started by specific events, as it needs to run continuously as long as there is a stream of, for example, incoming real-time location sensor data. However, there can also be other data sources that can be used to identify incidents, such as video, where object detection is used to identify unsafe behaviors (Hong and Teizer, 2023). As this module identifies incidents, it is envisioned to alert the involved parties, but only if it can be done in a way that does not remove their focus from identifying the incident themselves in reality. Otherwise, the identified incidents need to be shared with the parties through a feedback user interface. The feedback needs to be specific for the user who requests the information to comply with data privacy concerns, and only the user can access detailed information about their incidents. However, overviews and anonymized insight should be accessible to the construction site's stakeholders, allowing them to identify areas of the construction site that need additional efforts in safety planning and if incident trends of specific hazard types occurrence increase and need further training. The outputted behavior is a capture of how the tracked assets are moving around, which can be used to create behavior templates that can be used in training scenarios and for later advancements of analysis modules.

4.4 PL Module

There are different reasons for the PL to be used and updated. While the previous modules run when data becomes available, the events in the PL module symbolize that the module and the training environment can be updated as the new inputs are available. Additionally, they symbolize suggestions on when workers can be trained in the updated environment. Firstly, the update of the environment and the training can be performed with a fixed frequency. The frequency can be influenced by regulations or company policies. Besides the fixed frequency, the training suggestion can also be based on an upcoming hazardous task, which, based on hazard statistics, is known for creating unsafe situations. Likewise, a new SafePII can result in the need for training if it is decided to use another approach, which changes the sequence of tasks, and thereby the situation that the workers will experience in reality, but also if it is decided to use another form of protective equipment (e.g., safety nets instead of guardrails, or installing wires that are installed through holes of the precast columns to prevent falls from heights hazards. Another parameter to consider in the training is the overall construction site progress, which is captured in the PSK. Especially if the progress means that different type of equipment is used on the site to perform the construction tasks, for example, the need for a tower crane and excavators, which are introducing new situations that the workers need to be aware of. The training scenario needs, by all means, to be updated to reflect reality and prepare the workers in the best possible way, and the training scenario selection should be impacted by the incident trends that are also extracted in the RAM module (Speiser and Teizer, 2023).

The PL module will collect information on how the trainee acts in different situations and compile the participant's safety performance support. The performance report is used both as input to the safety planning module and also for the safety trainer to assess whether or not there should be additional focus on specific kinds of incidents or situations. Besides the direct assessment, it also needs to be possible to collect the incidents that happen in the training environment, which can be correlated with the ones that are found to validate the realism of the PL module and its capability to improve the workers' safety awareness and behavior.

4.5 Stakeholders' Feedback to the DTCS Modules

While the modules should operate autonomously, they should still include the practitioners in the loop. It is still far from reality to expect that the modules would always be able to create perfect output, which means that all the output should be captured as recommendations that the human domain experts can decide to follow or ignore. The purpose of the modules is not to remove the humans from the equation but rather to assist them in some of the monotonous, tedious, and time-consuming tasks so that they can focus on the critical matters where their experience and domain knowledge are indispensable. The modules should, however, collect feedback from the stakeholders to improve over time, allowing them to improve their recommendations to fit practices, regulations, and statistics better over time. Figure 3 contains an arrow, annotated feedback from the right box of stakeholder interaction towards each module. The arrows symbolize that the modules should compile the feedback from the stakeholders. For the PtD/P module, an example of the envisioned feedback can be stricter requirements for the elevation that requires fall protection (i.e., stricter than the regulation), preferences on the type of protective equipment for specific situations, or general. For the CC module, the feedback can consist of confirmation of the correctness of the classification both in terms of false positives and false negatives but also with respect to allowable margins of angles and openings. The RAM module should consider feedback about the relevance of the identified incidents to ensure that these are actual incidents and that the workers are not fatigued from notifications. This should also consider the severity and whether the output should be accumulated in a dashboard to avoid notifications that can potentially steal the workers' awareness of reality and the chance to identify the hazard themselves. The feedback to the PL module can consist of relevance and realism parameters where both the trainer and trainee can suggest changes that will improve the scenarios and the resulting safety awareness.

The above describes a non-exhaustive list of examples where feedback is collected for the four modules. The feedback content ranges over different kinds and formats, where it is envisioned that some can be integrated directly, and some takes additional development efforts. The feedback capture and processing will, therefore, need to be capable of handling a broad variety of input and transforming that into valuable information that is stored or configurations that are changed directly in the tools, which need to be broken down and investigated further.

5 Conclusion

This article presented the most recent work in progress on DTCS modules in the PDCA cycle of events and information exchange. The presented DTCS focuses on the overall holistic approach of transforming BIM into DT in the construction phase, including safe construction operations. Like other DTs that represent models for information-driven management and control of physical systems (with respect to people, processes, and technology), four essential modules in the process of construction safety were found and defined: (1) safe design and planning for hazard prevention, (2) conformance checking for ensuring compliance, (3) risk monitoring and control for proactive prediction and alerting, and (4) continuous performance improvement for personalized- or project-based learning. Working from these four core modules, we advocated for a DTCS information system workflow, including information models, rule sets, and monitoring and information visualization technologies that assist in effortless construction site data collection and analysis, and objective performance-based prediction and personalized feedback. We emphasized that the DTCS deserves future work, for example, extensive validation studies that measure its impact on essential safety applications (Johansen et al., 2024b).

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