A DIGITAL TWIN FRAMEWORK FOR EQUIPMENT EMISSIONS FROM CONSTRUCTION SITE OPERATIONS

Neeraj D. Bokde, Karsten W. Johansen, Søren Wandahl, Jochen Teizer

Department of Civil and Architectural Engineering, Aarhus University, Denmark

ABSTRACT: *The construction industry has been embracing digitization for several years to remove wasteful activities in its site operations. Construction sites generally offer dynamic workplaces that are rich of data but still lack in many applications the availability of suitable Internet of Things (IoT) solutions to gather and process data. The most recent trend towards deploying Digital Twins has further benefited the interest in intelligent site monitoring and decision-making technology to optimize its workflows. However, a unified framework and a cohesive approach towards tracking and reducing emissions from construction site operations have reached little attention in research to date. Besides, construction sites are known to cause a variety of emissions, for example, greenhouse gases, dust, noise, and vibrations. In total, construction sites contribute to a significant share in the world's total emissions. Our research aims to minimize emissions from construction equipment using digitization. A cohesive and unified Digital Twin framework is desired that guides as a stepping stone in the process of transforming an industry towards greener operations. In this paper, we propose the concept of a Digital Twin framework to track, monitor, predict, and reduce construction emissions (DTCE). While we discuss the components of the DTCE in depth, early results from a case study implementation add a promising outlook of using sensor technology that generate the required data sets that will be needed.*

KEYWORDS: *Digital twin, construction sites, emissions, equipment, planning, monitoring, analysis, prediction.*

1. INTRODUCTION

In the growing industrial societies including agriculture, transportation, forestry, manufacturing, and construction human activities are responsible fora large number of emissions (Lamb et al. 2021). Examples of emissions are Greenhouse Gases (GHG), dust, and noise. A significant amount of GHG emissions (around 10%) originates from construction site activities, which cover emissions from heavy equipment (for now, still reliant on the use of fossil fuels), power tools, lighting, heating, and several other activities (Akan et al. 2017). In the general trend towards greener industries, sustainable building standards, guidelines, and policies have been implemented worldwide to improve the building sector's energy utilization and reduce emissions. In 2015, for example, the Nationally Determined Contribution (UNFCC 2021) was established under the Paris Agreement committee and the United Nations Sustainable Development Goals. It intends to reduce the carbon footprint of the building sector.

In the era of Construction 4.0, many construction sites are today dynamic workplaces and rich in sensors and IoT data. This makes the construction sector one of the few which can heavily benefit from information-driven knowledge management. Numerous activities are foreseeable for implementation regarding site monitoring, data analytics, decision-making, and other processing to reduce waste, optimize the construction flow, and reduce emissions. However, these actions lack a unified and cohesiveness framework to integrate information-driven processes. The outcomes are inefficient construction site operations and unleashed potential for efficient and sustainable construction (Sacks et al. 2020).

In order to utilize the full potential of digitization in the construction sites and interface it with the physical construction site with cohesive and unified framework, the Digital Building Twin (DBT) technology can be a practical solution. In this paper, we have propose a conceptual digital twin framework to track and monitor emissions from construction site operations. We introduce and discuss our Digital Twin for Construction Emissions (DTCE) concept as it adds value to various users and stakeholders and helps in tracking and monitoring emission levels in construction equipment operations. We are introduction several components of DTCE in detail and demonstrated its application with a preliminary case study.

For common understanding, we define the term Digital Twin. In the evolution of Construction 4.0 sites with data-centric operations, the "Digital Twin" concept is generally seen as an up-to-date digital representation of the physical work with functional properties of a system that support rapid decision making, for example, by predicting and analyzing potential future scenarios (Tao et al. 2019). For the domain of construction:

- the "physical twin" includes construction site events, activities, workers, vehicles, and artifacts in the real world (e.g., the emissions from equipment).

- the "digital twin" is the digital counterpart (e.g., a virtual model of the construction site events, activities, etc.) used to generate simulations for predicting, e.g., areas or activities with excessive emissions).
- the "digital twin platform" provides the formal connection between the two twins (e.g., data, information, and knowledge exchange)

2. BACKGROUND

2.1 Current state of emissions reduction process and level of information technology

Emissions tracking, monitoring, and reduction at a construction site are part of any successful sustainable agenda in construction, like, e.g., the fossil-free construction site. These steps, in combination, fulfill important roles in making construction site operations greener. Over the years, planners, public authorities, and governments have established and implemented approaches for reducing emissions from construction operations (e.g., demanding construction fleet managers to change to biofuels or even electric-powered construction machines) (EPA 2021, European Commission 2021). However, very few of these approaches target the practical reasons and processes responsible for emissions at the construction sites. Managing construction emissions is more difficult due to the highly dynamic nature of construction operations. For instance, these operations consist of several processes such as a frequent change in construction site layouts and plans; update in production schedule; variability in machine availability, size, type; uncertain and changing weather conditions; diversity in the kind of construction activities (e.g., pile driving, excavation, etc.). These processes are typical construction management issues where Lean Construction is adapted to reduce waste, improve flow, and make construction more sustainable in general (Wandahl et al. 2021). Moreover, these reasons make it challenging to formulate solid practical policies to reduce the emissions in constructions significantly.

With the advancement in analytical and modeling tools, simulative approaches have been utilized by the construction industry for optimizing and improving operation and process, such as finding a trade-off between crew size and on-site winter heating or improving choices of construction material (Mohamed & AbouRizk 2005, Iddon & Firth 2013). However, such studies have not discussed and addressed the actual sources and operations responsible for construction emissions. Long back, it has been predicted that construction equipment and processes will be responsible for significant emissions (Winther & Nielsen 2006), and several precaution measures and policies have been proposed and implemented. However, the existing construction emissions reduction approaches are labor-intensive, time-consuming, and error-prone (Li et al. 2017). Even with the emergence of Building Information Modeling (BIM) methods, investments, and present strategies for construction emission, reductions follow manual, time-consuming, and error-prone processes (Cheng et al. 2020).

2.2 Digital Twins and data acquisition within typical construction project constraints

Construction is often referred to as one-of-a-kind products with being highly unique dynamic. However, construction tasks, methods, and associated risks are fairly well-defined at a decomposed level and, thus, predictable. However, the large number of subcontractors, suppliers, and stakeholders in general, work with or generate their own information about products and construction processes. Under current conditions, few stakeholders are motivated to collaborate intensively, which often leads to a fragmented 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 essential to understanding and optimizing construction workflow. These building information models often include planning (4D) and cost (5D) information. To make matters worse, construction sustainability (possible 6D) is far behind and often not included in BIM. Likewise, numerous data acquisition technologies that support sustainability goals are rarely implemented on construction sites.

There is a significant opportunity for Digital Twins that are explicitly tailored for reducing emission from construction site operations to provide new kinds of decision support to key stakeholders. Primary stakeholders are the contractor and sub-contractors but include all others responsible for making construction greener (e.g., engineers, planners, construction managers, workers, and even the client). This potential has slowly stimulated construction engineering and management research, 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 reducing construction-related emissions (Teizer & Wandahl 2022). Therefore, this paper aims to create a thorough workflow for planning, monitoring, reducing, and learning for construction emission 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). Furthermore, a preliminary case study performs a proof of concept.

3. DIGITAL TWIN FOR CONSTRUCTION EMISSIONS

This section describes how a Digital Twin for Construction Emissions (DTCE) can be created and utilized to track, monitor, and reduce emissions from construction site operations.

Figure 1 shows the overview of our Digital Twin for Construction Emissions (DTCE) (shown in the lower-left corner of the diagram). The DTCE is dependent on other DTs, and those should be interconnected in a network that lets them exchange information and knowledge of interest. The DT should also be able to perform tasks for each other. For example, we envision that the Digital Twin for Production Planning (DTPP) requests DTCE to enable emissions (e.g., GHG, noise, dust) reductions and assessments to an alternative production plan or a batch of those. It is chosen to concentrate mainly on the DTCE, which means 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 DTCE.

3.1 Construction Site (CS)

The construction site refers to the actual workplace (i.e., the physical twin), either planned, under construction, or constructed. It contains the production factors used to transform input to output. These factors are mainly; (1) equipment, machines, power tools, and other tangible fixed assets; (2) labors, e.g., construction workers, operators, site managers, HSE and BIM coordinators, etc.; (3) energy use for equipment, lighting, heating, dehumidifying, etc.; (4) construction materials; (5) services and information like construction schedule, site layout, work descriptions, etc.

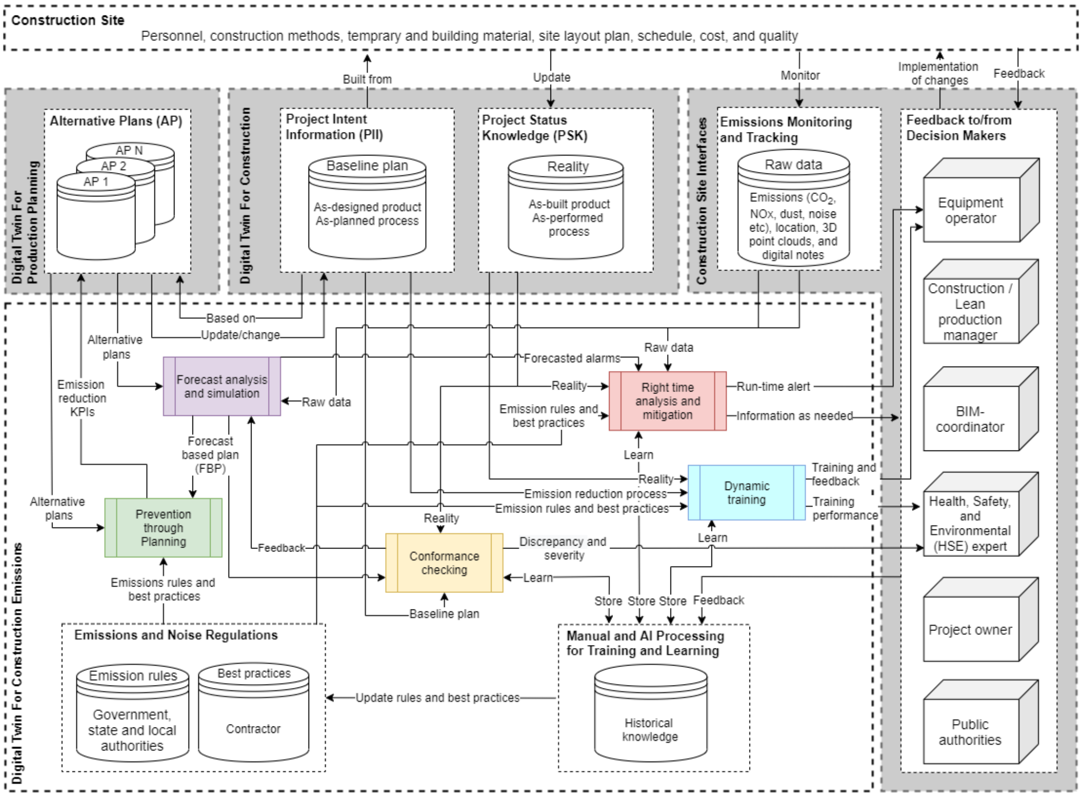

Fig. 1: Overview of the Digital Twin for Construction Emissions (DTCE) and relationship and interaction with the other important Digital Twins (e.g., production planning), physical construction site, and construction site interfaces (e.g., monitoring and decision-makers), education and training (e.g., operator behavior).

3.2 Digital Twin for Construction (DTC)

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 product's design. An example of the state is the set of the equipment or machines that have already been in operation and information on whether they have been operating correctly compared 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. Comparing 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.

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

3.3 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 maker's 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 DTCE to enhance and assess emissions and noise reduction policies. The KPI facilitates the selection of the AP. The decision-makers should be presented with the APs (including the related KPIs), from which the decision-makers select an AP on an as-needed basis that aligns with their overall goal and vision. This may happen daily (i.e., morning meetings), weekly, or as otherwise defined in the planning method. 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.

3.4 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, thus including different interfaces. The interfaces are illustrated as different boxes for the individual decision-makers, although some may overlap or extend. The emission and dust monitoring components provide the DTCE with raw data that 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 an equipment operator interface that would be different from the ones the construction management uses. The equipment operator can be alarmed if emission or noise levels exceed the permitted thresholds. It would not be sufficient if the operator needs to interpret a comprehensive emission report first before being notified of excessive emissions or unbearable noise generated on the construction site. The vision is to rather give a (run time) alert through sound or light emitters. Likewise, construction management and/or HSE can be informed via an application, a daily e-mail notification, or a live dashboard available online. If needed and in case to understand how to react correctly, a push notification allows the user to see alternative plans or corrective measures. Likewise, historical data can be processed and predict potential strategies to avoid such situations in the future. The solution can be the creation of new alternative plans for the equipment of operations.

3.5 Digital Twin for Construction Emissions (DTCE)

With the components mentioned above, we are now ready to describe what happened in the DT for construction emissions in greater detail. The DTCE consists of three main components, i.e., Prevention through Planning (PtP), 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 their contents. The alternative plans are received from the DTPP for emissions and noise reductions, which means the new policies are added to the model. There may exist more than one way to make a better plan, which will result in an answer set of different solutions. The solutions are created based on the rules and regulations (government and local authorities), which holds information about emission thresholds provided by the government, the state, and local authorities (e.g., EU regulation 2016/1628 for Non-Road Mobile Machinery) (Europea Commisssion 2016). Another component of the emissions and noise regulations is best practice, which should hold the decision maker's preferences (e.g., the contractor's own rules might be stricter than government/local regulations. Or, the client may require more stringent policies than regulation requires). Each AP is given a collection of KPIs informing the HSE about the cumbersomeness of, among others, a new plan for site logistics and construction schedules. The rules and regulation data storage should be updated based on the actual performance of the chosen AP and the decision-makers' feedback stored in the historical knowledge database.

Based on a conformance checking of the new plan and the actual construction site's reality, it should be possible to locate discrepancies. These are classified into three levels of severity (i.e., high, medium, and low), provided to the project manager and responsible actors, and *stored* in the historical knowledge database. The project manager should then act appropriately to the severity, solve the flagged rise in emissions or noise, and implement changes to the physical construction site. When an event has been solved, the project manager should provide feedback to the system (comparable to data labeling) for future improvement, i.e., *learning* from the output (both information & classification) and recommendations.

Right-time analysis and mitigation provide two kinds of output, i.e., the run-time alerts for the equipment operator and information as needed for the remaining decision-makers. It is envisioned that an equipment operator in the construction site should be alerted as soon as possible through an appropriate user 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, the equipment has exceeded the emissions or/and noise level above a hazardous level. Hence, the equipment operator and all other employees available on the construction site should be aware of the exceeded emissions or/and noise 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 a better execution plan for equipment usage and better coordination between several types of equipment on the construction site. 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.

3.5.1 Prevention through planning (PtP)

The left side of Figure 2 illustrates in brief how the alternative plans are generated based on the decision maker's preferences and the current baseline model. The APs are handed to the PtP component of the DTCE (right side of Figure 2) and enhanced with emission measures (e.g., schedule changes) based on the emissions regulation that applies to the construction site. The system analyses the emissions-prone spaces in construction sites and processes identified responsible for excessive emissions. The APs are returned to the DTPP for decision-maker selection, consequently updating the baseline plan from which the construction site is built.

3.5.2 Conformance checking

The conformance checking should find and classify discrepancies between the plan (created in PtP-module) and reality (captured by sensors) (Figure 3). For example, a diesel engine-driven equipment producing excessive emissions than the regulated thresholds would result in a relatively high severity. This information is stored, and when the HSE personnel knows about the problem, they can provide new information on the correctness of the output (in terms of both understanding reasons and its severity). This information provided by the HSE should be used to reduce chances of future occurrences and to update the best practice.

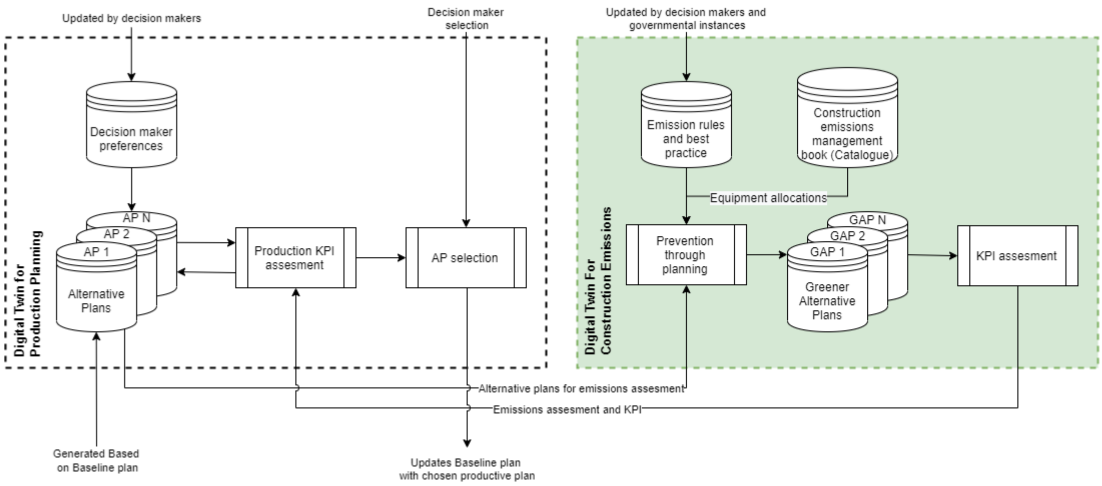

Fig. 2: Internal operation of the prevention through planning component. As the in- and outputs are highly connected to the Digital Building Twin for production planning, it is chosen to include these in the diagram.

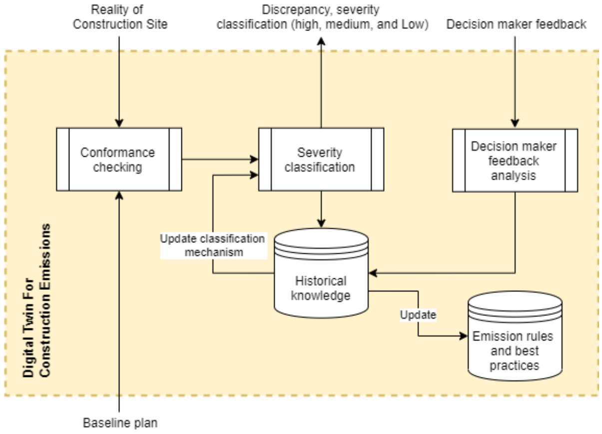

Fig. 3: Internal operation of the conformance-checking component.

3.5.3 Right time analysis and mitigation

Based on the reality of the construction site, the raw emissions monitoring data, historical knowledge, and emission regulation module perform complex event processing, from which the equipment drivers and construction managers are alerted to prevent emissions-oriented alarming situations (Figure 4). The module subsequently performs an investigation, where the incident's root cause can be determined and prevented in the future. In addition, in this module, the feedback to and from the decision-makers are stored and used in processing and investigation mechanisms. The new rules are also included in this diagram. These are updated and used in the prevention through planning module (i.e., the first component of the DTCE), conceptually closing the loop of the digital twin for construction emissions.

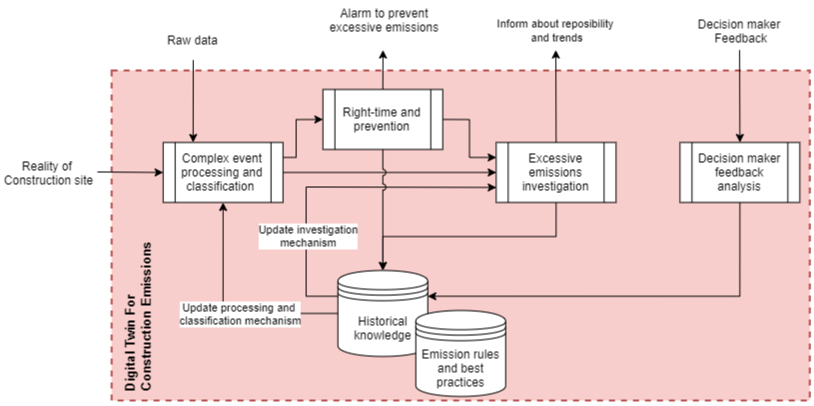

Fig. 4: Internal operation of the right time analysis and mitigation component.

3.5.4 Forecast analysis and simulation (FAS)

The FAS component (Figure 5) is dedicated to emissions forecasting (time series analysis) and simulating greener construction plans for future construction operations based on the forecasted emissions. The components of DTCE discussed so far are related to the real-time operations on the construction site. Whereas the FAS component works in the back-end and simulates plans (based on the forecasted emissions, baseline and alternative plans, and other available resources (e.g., equipment history)) that can help explore the possible emission severity in the near future at the construction site. For instance, we have historical CO_2 emissions time-series from the construction site for the last two weeks; the emission history and schedule of all equipment; and baseline and alternative plans for tomorrow's construction activities. The FAS will explore all resources, and based on this analysis, it will simulate different plans (from baseline and/or alternative plans) and estimate the possible emissions in the following days (near future). The simulated plans with the lesser emissions potential will be noted as 'Forecast Based Plans (FBP).'

The FBPs will help prioritize the available plans along with their information about emission reduction potentials. Besides, the FAS will be able to track high severity events corresponding to all FBPs, and preventive measures can be thought of accordingly in advance. The FAS component can enable DTCE to look at the future and plan in real-time to reduce the chances of high severity events at the construction sites.

The FAS component will coordinate with other DTCE components for different purposes. It provides FBPs to the PtP component and helps to prioritize the alternate plans. The FAS will share FBPs with the conformance checking component, which compares the discrepancies between reality and FBPs and return the feedback (e.g., the accuracy of FBPs) to FAS. The FAS will interact with the 'right time analysis and mitigation' component whenever it predicts a chance of possible high emissions event (based on FBPs) in the near future.

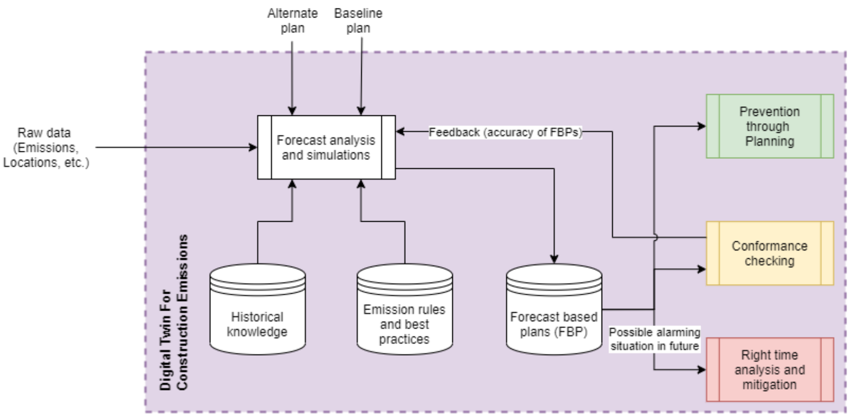

Fig. 5: Internal operation of the forecast analysis and simulations component.

3.5.5 Dynamic Training

The dynamic training module (Figure 6) includes periodic training of workers using the latest information from the DTCE. By feeding the model with the emissions and noise incidents and the area, the DTCE can produce relevant scenarios for each incident fed into the system. This will be done based on the location and type of alerts. Both the workforce and the digital twin benefit from this. The worker receives training, and the digital twin receives knowledge that can be utilized when other prevention approaches are used. Besides, this knowledge can be utilized when the Key Performance Indicators (KPI) are assessed for a plan.

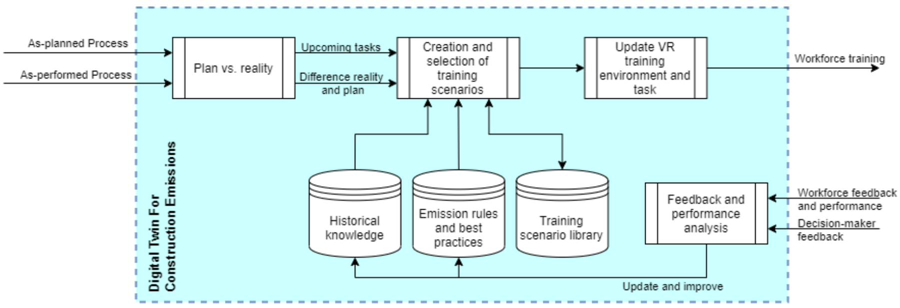

Fig. 6: Internal operation of the dynamic training component.

4. PRELIMINARY IMPLEMENTATION AND RESULTS

The proposed DTCE concept can be implemented with several technologies, including sensor networks, digital building twin tools, building information model (BIM), data analytics, and user interfaces (visualizations). The possible features and responsibilities of these technologies are briefly discussed below:

4.1 Technologies

4.1.1 Sensor Networks

Raw data is one of the essential requirements for DTCE to be functional and can be collected through a sensor network. At the selected construction site, a dense network of sensors will be set up in the construction sites and construction vehicles to monitor emissions, air quality, noise, vibrations, positions, patterns for the use of construction machinery, and real-time energy consumption. The sensor network will be arranged modularly, and its most relevant elements can thus later be transferred to other construction sites. Sensor output will be collected and stored on an ongoing basis, both before and after implementing technical and organizational measures. The systematic collection of data will be a prerequisite for carefully quantifying the effect of the individual measures. In addition, this data can serve several other purposes, such as visualization of environmental effects, assessment, modeling, and improvement of logistics. Besides, communication and data assimilation are the important aspects associated with the sensor networks. Communication protocols such as GSM can be employed for the collection of sensor data.

4.1.2 Digital Building Twin (DBT)

Digital Building Twin will be one of the challenging technologies in this case study. The actual construction site will be replicated digitally with the concept of Digital Twin technology. This digital twin will be based on building information modeling (BIM), site layout plan, schedule, and construction cost. Collectively, it can be represented by a 5D structure. Also, this twin will be integrated with the real-time sensor networks installed in the construction site. The task of this digital twin will be to evaluate and reduce the energy consumption and emissions related to the construction sites, their equipment, and transport vehicles. However, it will be crucial to identify the parameters to be considered while designing the digital tool for the construction site and to decide the nature of the digital twin (simulation-based or data-driven).

4.1.3 Building Information Model (BIM)

A Digital Building Twin developed in this project will be based on the BIM information such as construction site layout plan, construction schedule, costs, and other parameters such as equipment list. The higher resolutions and precise formation of BIM information can lead to developing an accurate Digital Building Twin for the targeted construction site.

4.1.4 Data analytics

The major task in data analytics will include developing and implementing new predictive algorithms to estimate reduced energy consumption and emission of exhaust gases based on improved construction site logistics. Further, the data analytics will help compare real-time construction sites with the digital model. Finally, the analysis and optimization of workflows can be enhanced with the data analysis strategies and the digital twin model.

4.1.5 User Interface

Visualization supports the dissemination of the digital building twin's activities and results, and that data visualization will be an important management instrument in the short-term planning of the construction site's processes. Internally, visualization is a key element in involving employees on the construction site. By showing current results on an ongoing basis, the project will inform the residents in the local area in a new way and thereby provide public knowledge about the emissions at the construction site of the future. An interactive dashboard can be used as the front-end user interface. Numerous plots and visuals can be provided through the dashboard, which will be based on the actual sensors data, data through digital twin models, and conclusions derived through the data analytics.

4.2 Case study

4.2.1 Conformance Checking

A field test was conducted with two pieces of heavy construction equipment. The laydown yard, located in an industrial area of Aarhus, Denmark, provided a safe test environment where typical machine operations can occur. The details of machine 1 and 2 are shown in Table 1. Both machines were wheel loaders and manufactured by Volvo Construction Equipment AB. The first machine was a wheel loader L90G, built in 2013 with a Stage III B (incl. particle filter) engine and a net power of 173 hp (129 kW), whereas the second machine 2 was the wheel loader L350F, manufactured in 2015 with a 528 hp (394 kW) powered Stage III A engine. Both machines had a cold start (defined as low temperature relative to its operating temperature) at an ambient temperature of approximately 23 °C). According to the European Union (EU) standards, the permitted NO_X limit values for Machine 1 and Machine 2 are 2.00 and 3.81 g/kWh, respectively (DieselNet 2021). In our case study, we followed the same standards for conformance control.

A Smart Emissions Measurement Systems (SEMS) module was mounted on the machines before they operated in the laydown yard. The SEMS module (Teizer and Wandahl 2022) is an Internet of Things (IoT) based sensory device which measures several emission parameters (e.g., NO_X, CO_2, O_2, particulate matters (PM)) that are emitted by the equipment engine. The particular SEMS also measures its (and the machine's) position details using Global Navigation Satellite System (GNSS) information, resulting in latitude, longitude, and vehicle speed data. The emissions data are further communicated from both machines to a cloud server platform where data is prepared to supply it to the DBT, finally processed and visualized in near run-time. The gathered data relates to several observed activities such as driving behavior and constriction operations as noted in Table 1 in more detail. Figure 7 shows the trajectories of Machines 1 and 2 along with their NO_X emissions generated while different activities were observed. The color coding of these trajectories represents the NO_X emissions from the respective machines. A benchmark was set with respect to the applicable EU standard. A performance comparison between both machines is possible, since the same color coding is used for representing the NO_X emissions.

The forthcoming text explains some of the main functionalities of the proposed DBT based on the concept of the proposed DTCE.

Table 1: Details of equipment used in the case study.

Machine	1	2
Model image		
Manufacturer	Volvo Construction Equipment AB	Volvo Construction Equipment AB
Equipment model	WHEEL LOADER L90G	WHEEL LOADER L350F
Year built	2013	2015
Engine net power	173 hp (129 kW)	528 hp (394 kW)
Engine type	Stage III B	Stage III A
Particle filter	Yes	No
Cold start	Yes	Yes
Observed activities (numbers refer to locations as seen in Figure 7)	Start of engine (1), Changing tool, excavation/loading on ground surface (2), idling (2), and driving at slow (3) and fast (4) vehicle speeds in laydown yard	Driving one slow round and one fast round in laydown yard

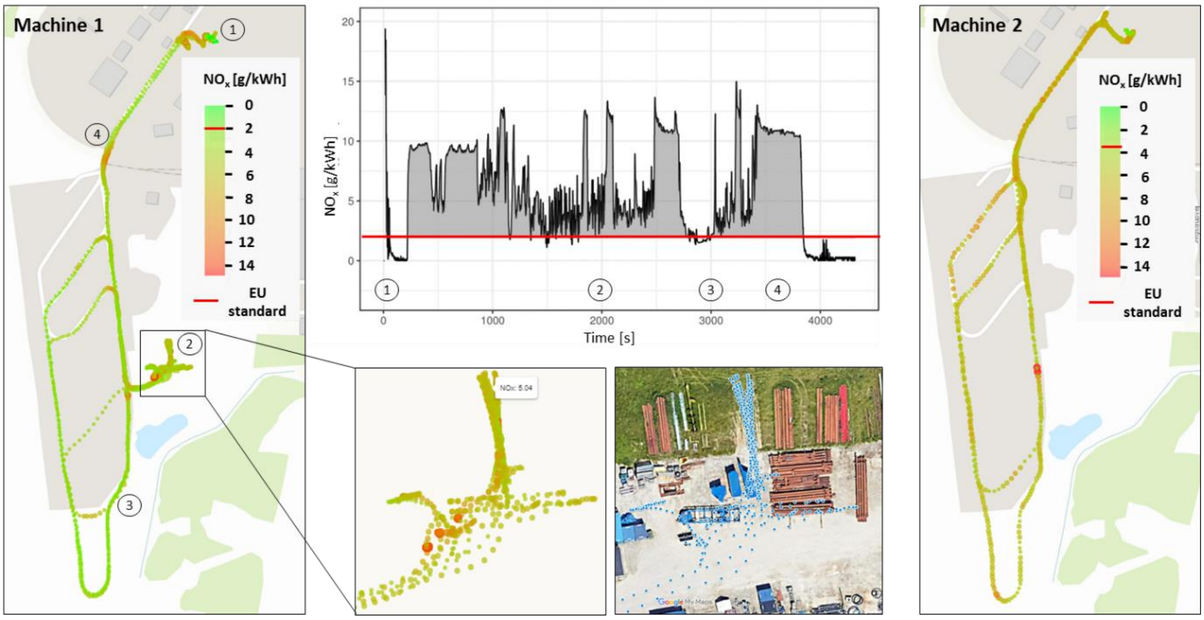

Fig. 7: Trajectories of equipment with NO_X emission levels.

4.2.2 Right-time Analysis and Mitigation

The purpose of DTCE is to track and monitor construction equipment emissions. The intent of the DTCE is to continuously perform right-time analysis on the collected data (Teizer 2016). In the performed case study, the DTCE had continuously monitored the emissions from the individual machines only. Additional data may come from the overall collective emissions at the construction site. For test purposes, a hypothetical alarm threshold is set according to the ED standard or the user's best practice. Latter might be, depending on the project owner's and/or contractor's own ambitions, tighter than governed by regulations. Figure 8 (left image) displays a heat map where emissions from Machine 2 cross a user-defined threshold (i.e., 14 g/kWh). Upon the occurrence of such events, the DTCE attempts to mitigate it by sending such information to the respective personnel, e.g., equipment operator, construction site manager, or HSE responsible staff. Given the early type of our DTCE work and as shown, right-time data analysis was implemented and successfully tested, however, the impact of corrective means neither deployed nor measured. This is believed to be part of future work, e.g. longer-term test that withstand rigorous scientific testing.

4.2.3 Forecast Analysis and Simulations (FAS)

The FAS component is not implemented in the present version of DTCE; however, the conceptual stage of its main functionalities are documented in this sub-section. While the DTCE is continuously in operation, it collects large amounts of time series data. These include several events information, containing underlying root causes being used in historic evaluations. Besides, the DTCE is equipped with information to alternative construction site layout planning (dynamically generated as BIM updates) that can be selected as an alternative future. The FAS component will use all available data resources to attempt the most likely event predicting with least possible impact of emissions. For example, time series data related to specific work activities or generated alarm events can accordingly calibrate the accuracy of the FAS component.

4.2.4 Dynamic Training

The proposed DTCE allows feeding the model with other important emission values that typically are present in construction sites, for example excessive noise, dust, and vibration incidents. The DTCE is capable of storing such data while making it available in personalized training scenarios as shown in Figure 8 (right image). According to research in HSE (Teizer 2016), it is believed that human operator training has one of the most significant impacts in reducing equipment-related emissions. The DTCE therefore serves as an ideal to develop several preventive approaches not related to technology but to human skills.

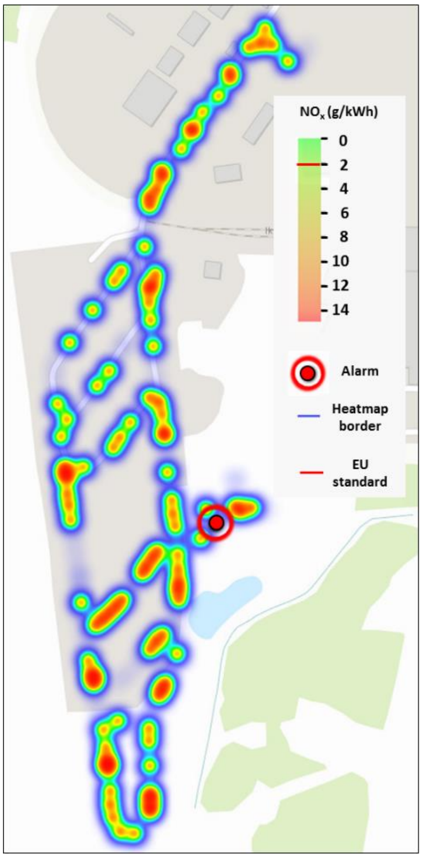

Fig. 8: Image to the left: DTCE dashboard showing an emissions heat map and an alarm pointing to levels that may surpass standard or user defined limits. Image to the right: Self-guided learning of earthmoving operations using an equipment simulator at a vocational school. Note: training operator behavior to reduce emissions is not part of the current learning objectives of equipment simulators, except that excessive use of fossil fuel consumption is part of the personalized feedback at the end of a training session. However, this provides user little to no answers which parts of the operations can be improved to lower the emissions or impact thereof.

5. CONCLUSION

This paper demonstrated the initial concept of a Digital Twin for Construction Emissions (DTCE), including the core information and control elements. Following the more general definition of a Digital Twin, the proposed concept of a DTCE represent models for information-driven management and control of physical systems including equipment operators and construction staff, operational processes, and sensor as well as data processing and communication technology and user interfaces. The DTCE targeted equipment emissions tracking, monitoring, and reduction from site operations by four vital steps: (1) emission prevention through detailed planning and scheduling; (2) proactive forecasting, focusing on excessive emission warnings; (3) continuous performance evaluations and improvements with personalized as well as project-based feedbacks; and (4) mitigation of situation with alarms and too high emissions. Based on these core elements, we advocated and demonstrated a DTCE information system workflow, including information models and rule sets, monitoring technologies, and performance feedback, in a preliminary implementation of digital twins for construction emissions. Since not all of the proposed elements were implemented, further research and evaluation thereof are needed.

ACKNOWLEDGEMNT

The authors gratefully acknowledge the Ministry of Environment of Denmark (Danish Environmental Protection Agency) for their financial support of the project “Green Construction Site of the Future” (MUDP Sags nr.: 2020-37291). Furthermore, they thank Aarsleff Rørteknik and Techno-Matic A/S for their support.

REFERENCES

Akan, M.Ö.A., Dhavale, D. G. and Sarkis, J. (2017). Greenhouse gas emissions in the construction industry: An analysis and evaluation of a concrete supply chain. *Journal of Cleaner Production*, 167, 1195-1207.

Beaney, M. (2018). Analysis, The Stanford Encyclopedia of Philosophy (Summer 2018 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/sum2018/entries/analysis/.

Cheng, B., Li, J., Tam, V. W., Yang, M. and Chen, D. (2020). A BIM-LCA approach for estimating the greenhouse gas emissions of large-scale public buildings: a case study. *Sustainability*, 12(2), 685.

DieselNet (2021). "EU: Nonraod Engines." Revision 2016.11, ECOpoint Inc., https://dieselnet.com/standards/eu/nonroad.php. Accessed: October 12, 2021.

EPA, 2021. https://www.epa.gov/dera/reducing-diesel-emissions-construction-and-agriculture. Accessed August 18, 2021.

European Commission (2016). Regulation (EU) 2016/1628. https://ec.europa.eu/growth/ sectors/automotive/environment-protection/non-road-mobile-machinery_en, Accessed: October 12, 2021.

European Commission (2021). Internal Market, Industry, Entrepreneurship and SMEs, https://ec.europa.eu/growth/industry/sustainability/built-environment_en. Accessed: August 18, 2021.

Iddon, C.R. and Firth, S.K. (2013). Embodied and operational energy for new-build housing: A case study of construction methods in the UK. *Energy and Buildings*, 67, 479-488.

Lamb, W.F. et al. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*. 16(7), 073005.

Laudan, L. (1978). Progress and Its Problems: Towards a Theory of Scientific Growth, Vol. 282. *University of California Press*, Berkeley, California, USA.

Li, H.X., Zhang, L., Mah, D. and Yu, H. (2017). An integrated simulation and optimization approach for reducing CO2 emissions from on-site construction process in cold regions. *Energy and Buildings*, 138, 666-675.

Mohamed, Y., and AbouRizk, S.M. (2005). Framework for building intelligent simulation models of construction operations. *Journal of Computing in Civil Engineering*, 19(3), 277-291.

Sacks, R., Brilakis, I., Pikas, E., Xie, H. S. and Girolami, M. (2020). Construction with digital twin information systems. *Data-Centric Engineering*, 1.

Tao F., Zhang M. and Nee A.Y.C. (2019). Digital Twin Driven Smart Manufacturing. *Academic Press,* London, UK.

Teizer, J. (2016). Right-time vs. Real-time Pro-active Construction Safety and Health System Architecture, *Construction Innovation: Information, Process, Management, Emerald*, 16(3), 253-280, http://dx.doi.org/10.1108/CI-10-2015-0049.

Teizer, J. and Wandahl, S. (2022). Simplified Emissions Measurement System for Construction Equipment, *CI & CRC Joint Conference*, Arlington, Virginia, USA (in press).

UNFCC, 2021. https://tinyurl.com/3wuzztwz. Accessed: August 18, 2021.

Wandahl, S., Pérez, C. T., Salling, S., Neve, H. H., Lerche, J. and Petersen, S. (2021). The Impact of Construction Labour Productivity on the Renovation Wave. *Construction Economics and Building*, 21(3), http://dx.doi.org/10.5130/AJCEB.v21i3.7688.

Winther, M. and Nielsen, O. K. (2006). Fuel use and emissions from non-road machinery in Denmark from 1985-2004 and projections from 2005-2030. *The Danish Environmental Protection Agency. Environmental Project*, 1092, http://mst.dk/86392.