Adaptive BIM/CIM for Digital Twining of Automated Shotcreting Process

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Abstract. The development of digital twins (DT) for construction processes requires adequate replication of real-world spaces. Therefore, the use of Building/Civil-Construction Information Modeling (BIM/CIM) for the creation of a digital representation of the physical process and asset plays a vital role. The construction process considered for this research study is shotcrete application and surface finishing during the construction and finishing phases. The research presents the role of adaptive BIM/CIM models for the digital replication of automated shotcreting of civil infrastructure projects. For a digital twin, simulations, and visualizations are essential for the process monitoring and diagnostics alongside the control of the physical asset in real-time through real-world data synchronization. Hence this paper proposes adaptive modeling of civil infrastructures (physical assets) and their associated requirements to facilitate the simulations and visualizations during the digital twining of the related asset and process. The proposed approach takes into account the creation of adaptive BIM/CIM models at the initial stage such as modeling in parts instead of a single element to facilitate the purpose of the visualizations of the digital model in the later stages of the creation of DT. Additionally, the use of an IFC-based hierarchy is prioritized for the purpose of linking the 3D object elements to the corresponding sensor data and simulations. Other aspects taken into consideration are the registration of robots with GIS measurements and the integration of IoT sensors.

Keywords: BIM · Shotcreting · Digital Twin

1 Introduction

Shotcrete (sprayed concrete) is used for pneumatic projection at high velocity onto a receiving surface where concrete vibration is not possible, mostly being used in underground mining, tunnel construction, and surface rehabilitation of infrastructures [1]. As per the Sika Sprayed Concrete Handbook [2] the current shotcrete methods depend on operators endangering themselves to un-secured shotcrete to manually examine optimal shotcrete thickness resulting in unreliable examination. Thus, the digitalization of shotcrete application would result in the process being more environmental-friendly, safe, with better quality, and with high cost-effectiveness.

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Effective construction digitalization requires appropriate planning synchronization and optimization of technological and logistic elements of construction. Hence, Digital Twin (DT) as an analog-based planning and optimization concept has started to impact the construction industry in recent years [3]. Digital twin uses machine learning, data analytics, and multi-physics simulation to study the dynamics of a given system and therefore the appropriate digital representation of the physical asset or process is essential for DT development [4]. Building Information Modeling (BIM) models are interactive 3D design models of a building or other built infrastructure assets. BIM models primarily encapsulate design intent information [5]. Whereas Civil/Construction information modeling (CIM) is a term commonly used in the AEC industry to refer to the application of BIM for civil infrastructure facilities also called horizontal projects, such as bridges, tunnels, railways, etc. [6]. Thus, BIM models as the digital representation of a construction object or process, contain detailed information about an object such as geometry, function, and visual description which can be used to create the digital replica for the DT. Extensive research by [7] and [8] provides an overview of the application of DT's in the construction industry with the purpose of reducing risk, cost and improving safety and resource efficiency.

Therefore, a construction DT for real-time shotcrete visualization and cognitive simulation of shotcrete application realizes a platform for construction process diagnostics, planning & monitoring. The absence of BIM/CIM models without appropriate digital representation in case of aging infrastructure that requires to be maintained/repaired or for new constructions cause hindrance in developing holistic solutions for automating shotcrete application. Consequently, this article presents an overview of the importance of adaptive BIM as an underlying representation for the digital twining of automated shotcrete application. Since this paper delves into both BIM and CIM for the sake of reference BIM will be used as a reference for both modeling methodologies in the subsequent text of the paper.

2 State of the Art

2.1 BIM in Digital Twins

A digital twin is a virtual replica of a physical asset, such as a building or infrastructure, that is used to monitor and simulate its behavior and performance. Thus, BIM models are essential to DT's as they are used to create a digital representation of the physical asset, including its geometry, materials, and other important characteristics [9]. The digital twin is then created by linking the BIM model to real-time data from sensors and other sources.

The importance of BIM models for digital twins can be summarized as follows: Accurate representation: BIM models provide an accurate representation of the physical asset, which is necessary for creating an effective digital twin, Improved monitoring: The integration of BIM models with real-time data from sensors allows for improved monitoring of the asset's performance and behavior, Simulation: BIM models can be used to create simulations that allow for better understanding of the asset's behavior under different conditions and scenarios, Optimization: By analyzing data from the digital twin, improvements can be made to the physical asset to optimize its performance, Maintenance: BIM models can be used to create a maintenance plan for the physical asset, which can help to prevent costly downtime and repairs [10]. A research study [11] demonstrated the use of BIM with a geographic information system to develop a web-based DT application for real-time visualization of the asset in an interactive 3D map connected to analytical dashboards to support decision-making. Researchers [12] demonstrated the use of BIM on DT's to simulate, visualize and analyze the construction process to support intelligent building construction management by formulating a reliable construction management plan.

In summary, state-of-the-art research on the importance of BIM models for digital twins has focused on the integration of BIM with other technologies, the use of BIM for more accurate and detailed digital twins, and the application of machine learning and artificial intelligence to analyze data from digital twins.

2.2 Shotcrete Digitalization

Shotcrete is a method of applying concrete using a high-pressure hose to shoot concrete onto a surface, often used in construction for building walls, retaining walls, and tunnels. The research study in this section explores and summarizes the most likely application of digital solutions that can help improve the efficiency and accuracy of shotcrete processes. Some digital solutions for shotcrete include:

1. Laser Scanning: Laser scanning can be used to create a 3D model of the surface to be covered with shotcrete, which can be used to plan the shotcrete process and ensure accurate coverage, alongside tracking of sprayed concrete.
2. Augmented Reality: Augmented reality (AR) can be used to overlay digital information onto the physical surface, allowing the shotcrete operator to see a virtual representation of the surface and ensuring accurate and consistent coverage.
3. Automated Control Systems: Automated control systems can be used to control the shotcrete spraying process, ensuring consistent thickness and coverage. These systems use sensors to monitor the thickness of the shotcrete and adjust the spraying process accordingly.
4. Virtual Reality Training: Virtual reality (VR) training can be used to simulate the shotcrete process in a safe and controlled environment, allowing operators to practice and improve their skills without the risk of damaging the physical surface.
5. Digital Documentation: Digital documentation can be used to track the shotcrete process, including the amount of material used, the thickness of the shotcrete, and other important metrics. This information can be used to improve the shotcrete process and ensure quality control.

The subsequent section presents the application of digital technologies for shotcreting and the proposed method to automate shotcrete application using digital twins as an enabler.

3 Proposed Shotcrete Automation

RoBétArmé project aims to automate laborious construction tasks during shotcrete application. Thus, the project work will deliver collaborative construction mobile manipulators, consisting of an (I) Inspection-Reconnaissance mobile manipulator (IRR) to address fast, high precision modeling and rebar reinforcement through metal additive manufacturing in the preparatory phase and (II) a Shotcrete and Finishing mobile manipulator (SFR) to address autonomous shotcrete application and surface finishing during the construction and finishing phase, respectively.

To this end, RoBétArmé will provide a Digital Twin with advanced simulation tools tailored to the BIM/CIM models used as the basis for representing the physical asset and combining information from robot scanning for an up-to-date model of the construction environment, thus propelling the implementation of the automated construction activities. Thus, the next section describes the role of modeling in the development of shotcrete application DT's.

4 Adaptive BIM/CIM Models

Adaptive modeling of BIM models during the initial project stage is necessary to support dynamic simulations and visualizations during the digital twinning stage of shotcreting. Previous studies have explored the aspects of adaptive BIM. The approach of adaptive and parametrized 3D BIM model for linear infrastructure: tunnels was explored by developing Revit families that can be instantiated and adaptively placed along the tunnel alignment to attain a high degree of automation in modeling such as changing shape or attributed values [13]. Another study introduced the concept of Fabrication Information Modeling (FIM), to integrate digital manufacturing in digital design through a combination of additive manufacturing (AM) and BIM methods [14]. The parameters considered to be modeled include material, process, and machine parameters enabling FIM to digitize construction processes that can be executed through AM. Thus, this paper focuses on the role of such BIM models to expedite shotcrete automation.

In the subsequent sections, the requirements for such models from the shotcrete application perspective are presented, followed by the different modeling considerations to make the BIM model adaptive for digital twinning.

4.1 Requirements

From the perspective of BIM/CIM models, the processing of modeling itself and then the integration in the DT to develop a digital twin for supporting the automated construction process during the shotcrete application will have some requirements as shown in Table 1. The different ID's mainly define the different requirements that contribute to the development of the digital representation in the DT application. Additionally, the technical requirements represent what a component expects from other components for successful implementation within the scope of the whole research project.

4.2 Adaptive Modeling and Interoperability Considerations

This section describes in detail how the different established requirements were considered in the modeling of adaptive BIM models for creating the digital replica of DT's for automated shotcreting on construction sites. For this study, the focus is on shotcrete application on service tunnels, thus the adaptive modeling and its application are done

Table 1. Technical requirements

ID	Requirement	Originating Component	Related Parameters	Context
TR-01	3D Geometric model	Design Plan	IFC	3D BIM/CIM model for representing the construction site
TR-02	Reinforcement detailing	Reinforcement plan	Type, location, arrangement	Visualization of reinforcement bar and mesh to facilitate shotcrete simulation
TR-03	IoT sensor 3D model	IoT sensors	Type, shape, connection & location	Modeling of IoT sensors in the BIM model based on their actual site installation
TR-04	Robot simulation specification	Robot coordinates	Robot localization and navigation path	Possibility to support robot platform navigation using elements of the BIM model

for the 3D BIM model of a tunnel. As per this study an '*adaptive model' would adequately include all relevant DT representations that can be changed through a modular approach as per the desired DT requirements for simulation and visualization of the construction process (shotcreting) based on an end-user centered approach.*

Adaptive Simulation-Oriented Object Modeling

From the DT perspective, adaptive modeling of the infrastructure is essentially aimed to facilitate visualization and simulation. The study by [15], based on practical experience developed parametric and adaptive components to model segment systems for tunnel structures using component families on Revit. In addition, [13] presented a case study to advocate the use of 3D BIM models over traditional 2D design for improving data handling in the tender phase to avoid data loss and adequately represent all the tunnel services that can not be represented in 2D plans.

The adaptive modeling approach adopted in this paper essentially aims to represent established technical requirements in the model that would support simulating and visualizing shotcreting activities on the DT platform. Figure 1 shows the tunnel BIM model wherein different elements are modeled with a segmental approach and a lower level of geometrical detailing. The adopted simulation-oriented modeling approach is primarily based on the use of the IFC data schema and the level of geometric detailing as per the digital model requirements of the DT.

Tunnels can be classified as per their function and their construction method; therefore, the modelling is aimed to be done as per the IFC-Tunnel data model [16] to describe the geometry and semantics of different elements. Shotcrete is often sprayed onto the rock surface immediately after a blast to secure the work environment. The shotcrete could sometimes have conventional mesh reinforcement or contain fibres. Thus, as per the data model geometry representation of the shotcrete could be modeled as a 3D representation of the shotcrete surface with thickness and the shotcrete area sprayed on the tunnel rock surface called as developed geometry. The IFC classification and hierarchy are vital for the DT representation as they can be used as a point of reference to generate specific simulations and visualizations such as resulting heat maps from sprayed concrete, generation of near real-time meshes to represent the thickness of shotcrete sprayed on the existing surface in the model and 4D planning of shotcrete activities. Additionally, IFC as an open data format can improve information sharing throughout the lifecycle of the digital twin.

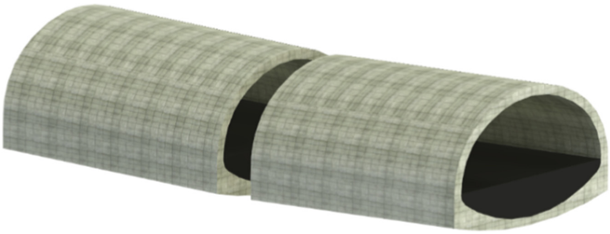

Fig. 1. Adaptive modeling (segment-wise) for service tunnels.

Subsequently, another modeling approach adopted is to model the entire tunnel structure based on a higher degree of level of geometry (LoG). LoG defines the degree/level of geometrical detail that occurs in the tunnel model [17]. The components include (reinforcement, inner lining, waterproofing membrane, and outer segmental lining) that were modeled as individual objects, as represented in Fig. 2. Therefore, the use of LoG while developing the model is linked to the level of DT development as per the user's requirement with a higher LoG resulting in a more accurate DT representation.

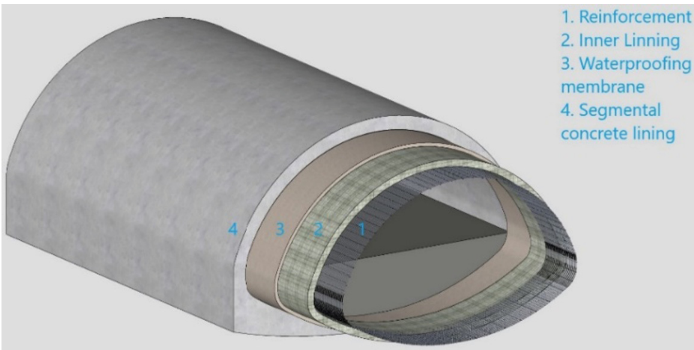

Fig. 2. Modeled cross-sectional tunnel components.

IoT Sensor Modeling

For digital twins, Internet of Things (IoT) devices must interface with BIM and IoT platforms to offer both visualization and actuation possibilities within the temporal and spatial construction site context. Dave et al. [18] proposed a framework integrating built environment data with IoT sensors by integrating open messaging standards (O-MI and O-DF) and IFC models to monitor the indoor environment. Moreover, Khan [19] developed a digital twin by modeling IoT and integrating sensor measurements in the BIM model to support building energy simulations and visualizations in DT through a virtual reality interface.

Thus, this study presents the IoT modeling adopted for the shotcrete application. Figure 3 depicts the 3D model of the IoT sensor that will be installed on the site during the shotcrete application. The sensor will be installed during the preparatory phase of shotcrete application and will measures temperature, humidity, and other relevant parameters for monitoring of construction sites. As illustrated in Fig. 4 the sensors are implanted on the tunnel curvature at adequate distances for proper measurements and accurate digital representation of the physical asset nearby the shotcreting surface. In addition, the model sensors can be defined in the established IFC data schema.

Fig. 3. IoT sensor model.

Navigation/Simulation of Robots

The notion of exploiting digital BIM models produced in the design phase to provide robotic systems with extensive semantic and geometric knowledge of the construction environment can play a crucial role. A study developed an interface for the extraction of information of data from the BIM model and making it accessible to mobile robotic systems during the construction process to support site logistics [20]. Byers and Razavialavi [21] developed a method to transfer BIM geometrical data to virtual robots in the simulation environment, to equip robots with prior knowledge and enhance navigation in terms of accuracy and efficiency. In addition, [22] developed Building Information Robotic System (BIRS) to use IFC-based information to generate optimal paths for the safe and autonomous navigation of robots during the construction phase.

The robot path modeled in the BIM model as illustrated in Fig. 5, aims to be reliable and recognizable for the navigation of mobile robots for both IRR & SFR robots. Additionally, the modeled path can be used for the simulation of robotic systems by

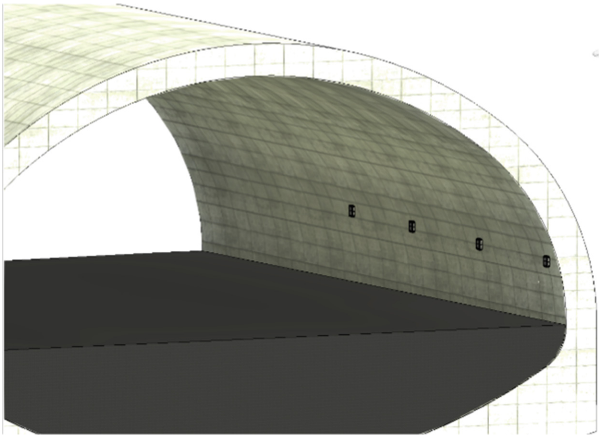

Fig. 4. IoT sensors in the BIM model.

replicating the actual construction site environment. The main path (light red color) as shown in the figure is modeled for the whole tunnel length with the purpose of facilitating the entry and exit of the robot in the structure alongside robot navigation inside the tunnel. The pit area (yellow color) is also modeled to represent the location where the robot is supposed to localize itself and navigate to this area of interest i.e., the section to be shotcreted. Subsequently, this area can also be used by the robot for surface finishing and quality assessment of the sprayed area.

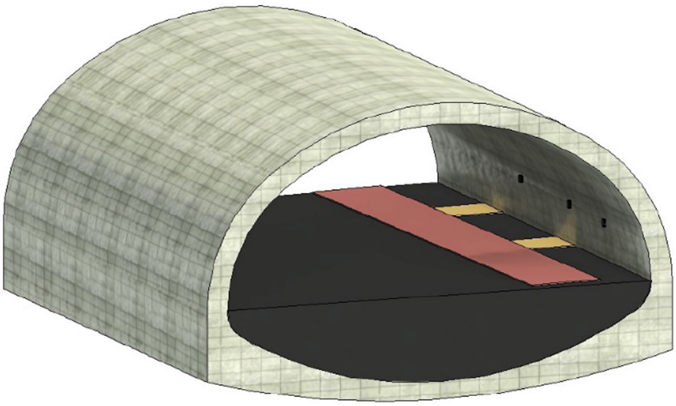

Fig. 5. Robot path in the BIM model.

5 Conclusion

This paper highlights the importance of the representation of a physical construction site subjected to shotcreting by using adaptive 3D BIM models to fuel digital twin development. By considering representing most aspects of automated shotcreting from the construction environment to IoT sensors and robot navigation, the adaptive model aims to provide holistic representation. Especially the combination of adaptive modeling of individual elements and the automation aspects would result in detailed and appropriate representation for the DT to optimize, control, and monitor the shotcreting process for greener, more cost-effective, and safer solutions. Due to limitations in the scope of the paper, only the adaptive modeling for service tunnels was presented, however, under the research study civil infrastructures in construction & repair phases such as post-tensioned bridges and ground support walls have been investigated as well.

In terms of innovation, the envisioned digital twin application aims to support the automation of shotcreting application by allowing the end-user to visualize, simulate and analyze for near real-time construction monitoring during construction and also to have the capability to examine different inspection and construction scenarios before the actual use of mobile shotcreting robot thus supporting decision making during different stages.

With regard to future work, the research aims to take into consideration additional modeling requirements that will be developed over the duration of the project. Furthermore, the developed adaptive models will be used for the digital twin deployment to realize shotcreting application on construction sites through visualization and real-time control dashboard. Additionally, the study aims to carry out a cost-benefit analysis for the developed adaptive BIM models by applying them on real-life demo construction sites of the research project in comparison to presently uses models for shotcrete application.

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