BIM TWIN

Optimal Construction Management
& Production Control

WHITE PAPER

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Abbreviations

AI	Artificial Intelligence
Aps	Alternative Plans
API	Application Programming Interface
BDT	Building Digital Twins
BIM	Building Information Modelling
BPMN	Business Process Model and Notation
CV	Computer Vision
CC	Conformance Checking
CPM	Critical Path Method
DBTP	Digital Building Twin Platform
DT	Digital Twin
DTC	Digital Twin Construction
DTCS	Digital Twin for Construction Safety
DTPP	Digital Twin for Construction Planning
DTS	Digital Twin Services
EXIF	Exchangeable Image File Format
GPS	Global Positioning System
GUI	Graphical User Interface
HSE	Health, Safety, and Environment
IDM	Information Delivery Manual
IoT	Internet of Things
IMU	Inertial Measurement Unit

JHA	Job Hazard Analysis
KPIs	Key Performance Indicators
LiDAR	Light Detection and Ranging
mAP	Mean Average Precision
MLP	Multi-Layer Perceptron
OHS	Occupational, Health and Safety
PCD	Point Cloud Data
PSM	Project Status Model
PtD/P	Prevention through Design and Planning
PII	Project Intent Information
QA	Quality Assurance
QC	Quality Control
RAM	Right-time Analysis and Mitigation
RANSAC	RANdom Sample Consensus
RGBD	Red, Green, Blue, Depth
ROI	Region Of Interest
SAP	Safe Alternative Plan
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UUIDs	Universal Unique Identifiers
YOLO	You Only Look Once

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Executive Summary

The adoption of BIM has streamlined the design process by facilitating communication between the players involved and has proven that the deployment of digital solutions may greatly improve productivity.

The construction sector is often described as a low-productivity sector, weak in terms of innovation and slow to adopt digital solutions. However, the adoption of BIM has streamlined the design process by facilitating communication between the players involved and has proven that the deployment of digital solutions may greatly improve productivity.

The act of construction brings together professionals from different companies around the same project for a limited period, and as a result the construction process is affected by numerous problems, such as design and planning issues (both human resources and materials), unsuitable working methods or equipment, as well as safety and security issues for workers on site.

The concept of the Digital Twin was first mooted in the 1970s. Initially evoked in relation to factory production processes, the notion has evolved and spread to other areas such as engineering, product design, simulation, predictive maintenance, etc. The popularity of the concept has increased considerably in recent years with technological advances such as the Internet of Things (IoT), artificial intelligence (AI) and advanced 3D modelling.

A DBT can provide a decision support environment, bringing together an automated system able to capture on-site information and the services able to process, analyse and transform this raw information into knowledge.

For the construction industry, the adoption of Digital Building Twins (DBT) in the construction site offers the promise to address the inherent complexity of construction activity. A DBT can provide a decision support environment, bringing together an automated system able to capture on-site information and the services able to process, analyse and transform this raw information into knowledge. Accurate and reliable knowledge of the current status facilitates the decision mechanisms in planning production systems that have some resilience to unforeseen events that occur randomly during on-site activities. Applied to the construction sector, a digital twin is a virtual replica of a building or physical infrastructure that already exists or is under construction.

This is the context for the BIM2TWIN project, which aimed to research, develop and test a technical solution system that includes a comprehensive set of tools for monitoring the progress of a construction site, focusing on monitoring the construction process, assessing the quality of construction, monitoring the safety and security of workers on site, and optimising the use of equipment. The solution developed in BIM2TWIN also includes a service that takes account of deviations from the planned schedule reported during construction and proposes alternative plans to respond to these deviations as effectively as possible. Thus, this project sought to highlight the potential of the DBT concept for optimising construction processes based on digital monitoring on site and in the supply chain, on artificially intelligent diagnosis of the monitored data, and on simulation and predictive analysis of proposed alternate production plans.

Thus, this project sought to highlight the potential of the DBT concept for optimising construction processes based on digital monitoring on site and in the supply chain

In the approach followed by the consortium, the first elements of reflection were to understand the current practices of the consortium's construction companies and to develop with them, based on their practices, new processes encompassing the adoption and use of the digital twin. The outcomes of this very first step were the specification of typical processes, the definition of Key Performance Indicators (KPIs) and an initial compilation of the concepts/notions/vocabularies handled by the various stakeholders. Next the exchanges themselves were analysed, enabling the initial requirements to be outlined in terms of application programming interfaces (APIs) and the necessary contents of communication between the services to be developed.

The architecture adopted was to store information on the progress of construction, interpreted from the monitoring systems, in a central database which is fed by specialised services. The central database also contains the design intent information, consisting of the design BIM models (Building Information Modelling) and the construction plans (described using a work breakdown schedule, a location breakdown schedule, and a table of resource allocations). The central database is the pivotal element of the BIM2TWIN architecture, allowing the connection of various technical services, ensuring dialogue between these services, and enabling the progress and current status of the construction site to be queried via a dedicated dashboard displaying the values of the various KPIs.

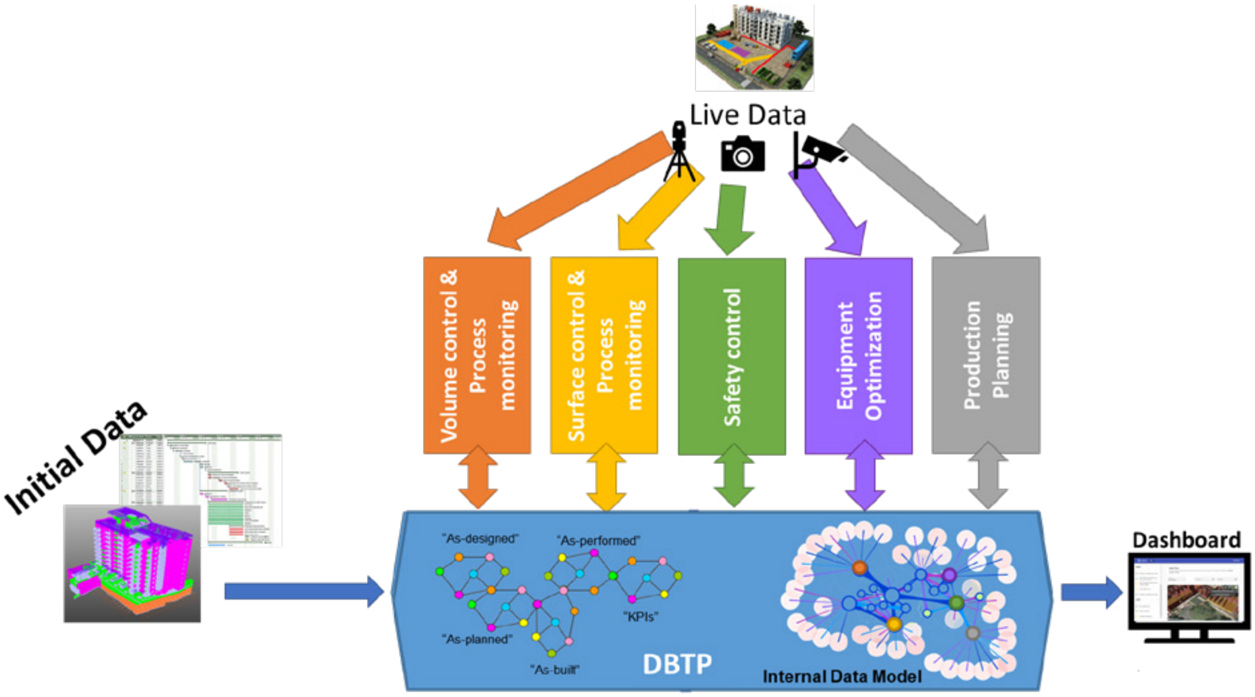


Figure 1. *BIM2TWIN global architecture.*

The BIM2TWIN project team defined the ontology for the domain of DBTs, and this enabled the team to design, build and implement a knowledge graph database. Five services have been developed and connected to this component, focusing on specific construction management aspects and specific data acquisition technologies:

- **A service for monitoring the construction process and volumetric control of built elements.** This service uses point clouds collected from time to time on site as input data and compares them with the elements in the construction plan described in the BIM and the schedules. Specific focus was placed on identifying and monitoring construction progress for walls and columns.
- **A service for monitoring the construction process and the surface control of built elements.** This service uses images collected on site using cameras as input data to analyse the progress of the construction process for certain elements (particularly columns) and compare this on-site progress with the planning; It also detects surface defects on built elements, enabling the identification of quality defects in the construction process.
- **A service focusing on worker health and safety.** This service connects to the platform to extract a BIM model reflecting the planned status of construction at any given future time. This model is analysed to identify potentially hazardous areas for the workers. A new BIM is then generated by the service, called a SafeBIM, containing the additional elements (guard rails) to make the working areas safe.

- **A service dedicated to equipment detection and optimisation.** This service recognises the equipment used on site, as well as its movements and trajectories. It provides information on the usage rate of each piece of equipment and can also be linked to the previous service to determine whether the trajectories or use of this equipment represents a danger to workers.
- **A service dedicated to optimising production plans.** This service proposes and evaluates alternative plans based on user-defined parameters. Construction planners can adjust various decision parameters, such as increasing or decreasing the work force of trade crews, increasing or decreasing the amount of equipment available on site, or changing the flow control policy. The service can simulate and thus predict the most likely outcomes of different construction plan alternatives, including that of the baseline plan, at any time, using the information stored in the DBT. Thus, in the event of deviations identified by the previous services, this service can take into account the progress made at a given moment, the faults identified, propose alternative schedules that take account of this feedback from the field, and support decision makers in deciding how to reconfigure their resources and assignments to best meet their cost, quality, schedule and safety targets.

The BIM2TWIN teams captured data from active construction sites belonging to all three of our construction company partners and deployed the newly developed tools for a variety of construction projects.

Finally, the project also sought to evaluate the performance of these innovations in the field. The BIM2TWIN teams captured data from active construction sites belonging to all three of our construction company partners and deployed the newly developed tools for a variety of construction projects. A deployment method was put in place and various demonstration sessions were held to enable our solution to be evaluated by people at the sites being monitored. This process included planning the demonstration activities, designing monitoring methods, setting up the platform's implementation in the pilot projects, implementing the platform and the services, and finally evaluating their overall performance. The evaluation phase was done on a two-cycle iterative process to improve the platform's functionalities according to the users' feedback.

Pilot sites were identified by three construction companies and project partners: Fira, Spada and Acciona, located in Finland, France, and Spain, respectively.

Pilot sites were identified by three construction companies and project partners: Fira, Spada and Acciona, located in Finland, France, and Spain, respectively. This gave the demonstration a broad range of applications since each company has its own practices, its own local context, and the individual pilot projects varied considerably from one another, with different types of uses and construction technologies. This also enriched the results.

From the users' point of view, the BIM2TWIN Digital Building Twin Platform (DBTP) is the central part of the overall system environment. It is the core, where all data should be integrated. Both design intent information (BIM and construction plans) and project status information (provided by the monitoring services) are input into the DBTP. The service functions read this data, process new information, and input it too to the platform for project plan decisionmakers to access from the dashboard through the KPIs and the 4D viewer tool.

In this white paper, we describe each of the BIM2TWIN services and components. We also pose and provide answers to basic questions about Digital Twin Construction (DTC), the Digital Building Twin Platform (DBPT), and the different services that the BIM2TWIN system concept can provide to construction planners. Finally, we describe the advantages it may provide over traditional construction production systems and conclude with potential topics we do think will be interesting to investigate in future research.

Introduction

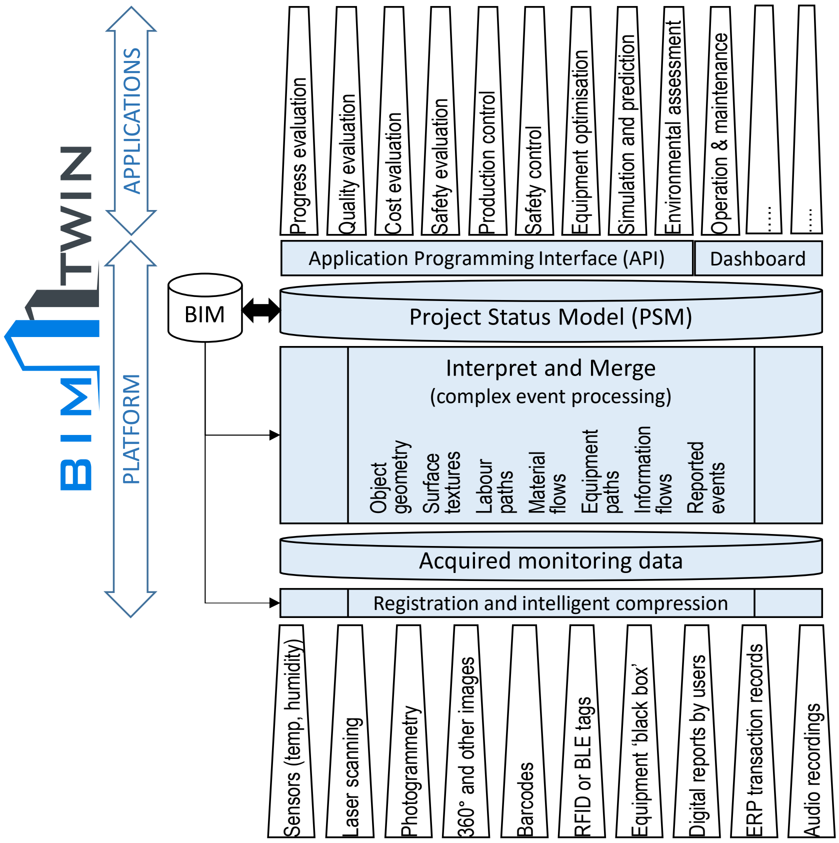
Imagine a construction project where the managers know the real-time status of everything happening on site and throughout the whole supply chain: the current progress and quality of the work, current locations of workers, equipment and materials, safety conditions, etc. Imagine managers at all levels have an overview over design information and subcontractors' commitments to pending work; that all people involved have access to reliable, accurate, real-time information of the project status, information essential to coordinate their work with others. In this scenario everyone has thorough **situational awareness**.

Enormous value could be generated and much production waste (waiting time for crews and equipment, waste of materials, rework due to quality defects and mistakes in design information, etc.) could be avoided if such real-time information were available. Removing these wastes in order to shorten construction schedules, reduce budgets, enhance quality and safety, and reduce carbon footprint, is predicated on achieving comprehensive situational awareness by comprehensive monitoring of construction projects and the desired outcomes in terms of costs, quality, schedule and safety. This is our vision of a Digital Building Twin (DBT): BIM2TWIN.

BIM2TWIN proposes a comprehensive, holistic approach to application of the digital twin concept to building construction, in an attempt to fulfil the promise of the new Digital Twin Construction (DTC) paradigm

BIM2TWIN proposes a comprehensive, holistic approach to application of the digital twin concept to building construction, in an attempt to fulfil the promise of the new Digital Twin Construction (DTC) paradigm [Sacks, Brilakis, Pikas, Xie and Girolami; 2020]. It consists of a digital building twin platform and an extensible set of construction management applications that provide full situational awareness (see Figure 2). In the current state of the art, researchers and start-up companies have taken a direct approach – identify a construction management problem, select one monitoring technology to provide data, and attempt to provide a valuable service. Yet this is severely limited, because the reliability of information inferred from a limited data stream is unreliable and inaccurate, and because the approach is not extensible nor scalable. Instead, as shown in the BIM2TWIN platform pools multiple monitoring data sources, interprets and merges the data to provide information, and exposes the information to a suite of construction management applications (through an application programming interface – API – of the Digital Building Twin Platform - DBTP) and/or directly to users through a visual information dashboard. The system as a whole is depicted in Figure 2.

Figure 2. *BIM2TWIN Platform and Applications. BIM2TWIN proposes a digital building twin platform and an extensible set of construction management applications that provide full situational awareness.*



Our starting point for this vision is to recognize that the DBT must capture the **physical status of the building** and the **status of the construction process**. This information is called the Project Status Model (PSM), which represents both the as-built product and the as-performed process. The DBT must also correspond directly with both the **building design** (the product) and the **construction plan** (the process). Therefore, its information component objects must relate to the objects in the Building Information Model (BIM), objects representing both the as-designed product and the as-planned construction process. We also recognize that the DBT is not simply data collected from monitors and sensors on site: it is a complex, whole system, with many components, which must work together to support the full production management and control cycle. This means that the **raw data** collected from multiple sources, on and off site, **must be interpreted** in combination in order **to produce meaningful information** about the product and process status. The information technology backbone of the DBT must be robust enough and standardised to support many different uses of its information.

In the BIM2TWIN proposal, we suggested that property graph representations[1] were the most appropriate technology to merge all the information, based on the BIM product and process plans but also incorporating the project status information. We further proposed that the AI algorithms needed for interpreting actual status from multiple streams of raw monitoring data must be embedded in the information backbone, providing API interfaces for the wide variety of developers that will implement the management and design applications that will help construction workers implement the functions listed above (Figure 2).

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[1] Property graphs are the common-denominator information model of most existing graph databases.

Objectives

When the BIM2TWIN project began, R&D in the construction industry had already provided some constituent parts of such a holistic system. The state-of-the-art was such that many monitoring technologies had been devised, tried and tested on construction sites. Likewise, BIM technology was mature. However, none of this work and none of the existing tools were then understood in the context of a holistic Digital Twin Construction paradigm. Construction with a system such as that developed in BIM2TWIN will be different in important ways from the current, traditional, wasteful methods we see on today's construction sites.

We planned, therefore, to achieve these objectives:

a. Conceptualize the function of a holistic digital twin information system model with respect to user requirements and operational scenarios;

b. Design and implement the holistic digital twin information system platform, adding the PSM to the BIM models and adding the artificially intelligent functions needed to run it;

c. Integrate existing monitoring and sensing technologies with the new BIM2TWIN platform, and rigorously test the performance of the new AI Interpret and Merge tools to fuse the data streams and produce useful information;

d. Specify, design and implement construction management applications on the basis of the BIM2TWIN platform; test, verify and demonstrate their function in isolation;

e. Develop the platform, applications and processes, test them on construction projects, refine them, demonstrate them and communicate the knowledge.

In the following chapters, we describe in some detail how these objectives were tackled and achieved. Yet before diving into the detail, we define the overall system architecture, into which all of the components described in this white paper fit.

System Architecture

Figure 3 below depicts the conceptual design of a construction process supported by a digital building twin. The flowchart has data and information stores and information processing activities. The main stores are:

i. The design and planning information, labelled **BIM**, is the as-designed and as-planned information.

ii. The **physical building**, the building itself, the products being fabricated off-site, and the resources engaged in the construction.

iii. The project status model, labelled **PSM**, which is the information component of the **digital building twin**. This is the current state of the project, reflecting the most up to date as-built and as-performed information available.

There are also three supporting information stores:

iv. The raw data drawn from the monitoring and sensing technologies.

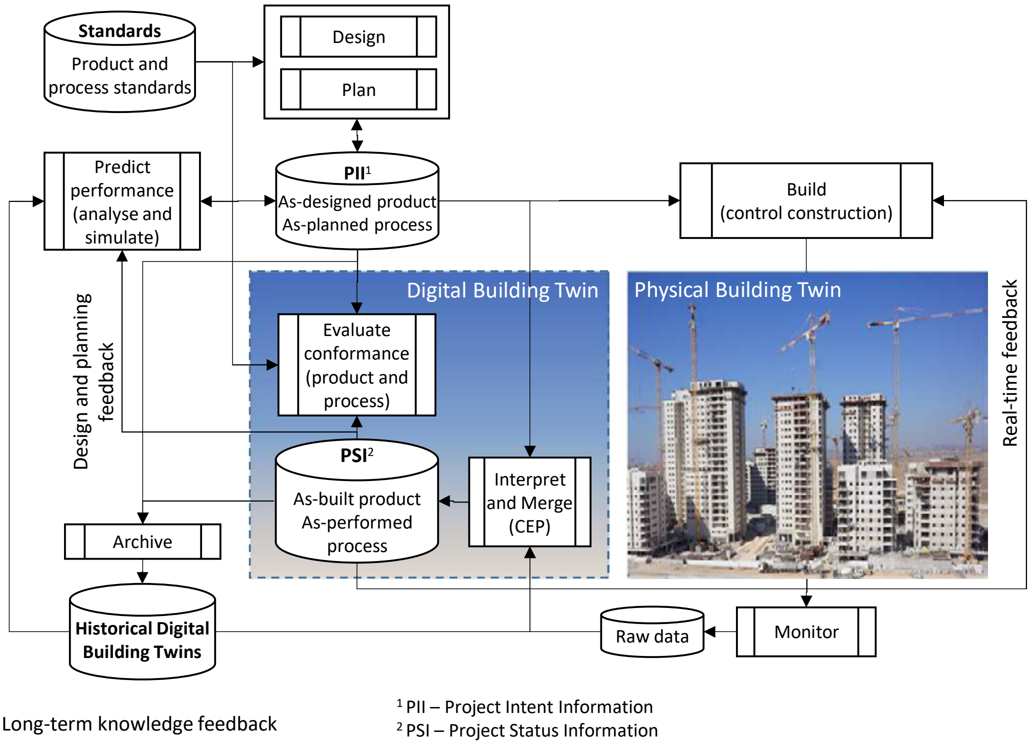
v. Industry standards, which contain construction industry codes, product catalogues, production methods and rates, etc., all of which are used for design and planning.

vi. Historical digital building twins, which accumulate over time, and are a valuable resource for case-based design or planning and for training machine-learning software modules.

The **Design and Plan** activities generate the as-designed product information and as-planned process information. At any given point in time, the design and plan information can be stored as a version – this will usually happen at 'design freeze' milestones during the design phase, and will happen more frequently during construction, as the design and the schedule are updated to reflect management decisions. The as-designed/as-planned information drives the construction process itself, through **Build (control construction)** activity. The result is the **physical building twin**, which in this construction stage, incorporates not only the finished parts of the building, but also all the material waste, temporary works, construction equipment and the construction crews employed in building the facility. In the “Monitoring” activity, a wide array of data is collected from the site and from the construction supply chain. These include data generated from spatial, visual, thermal, structural, geotechnical, environmental and other sensors, on-board construction equipment ‘black box’ monitors, drones, or mobile device construction control apps used by supervisors and workers. They also include records from supply chain digital information systems (transaction records), voice command records or other audio, satellite imagery, etc. This data is then pre-processed by the **Interpret and Merge** software modules.

Interpret and Merge, although shown as a single process box in the figure, is a set of diverse software modules, each programmed to derive the current status of some aspect of the construction product or process, i.e. convert data to information, using complex event processing [Buchmann and Koldehofe; 2009]. For example, imagine that a faucet is being installed in bathrooms on all floors of a multi-story building. After the third floor is complete, the data might include a scanned point cloud of the floor, a delivery note that includes the faucet itself, data from the workers’ construction app (on their mobile phones), and a photo taken of the faucet. From these different **data** sources, an interpretation module may derive **information** about this specific faucet: when its installation began, when it was completed, net working hours for installation, etc. This newly derived information is written to the PSM, including meta-data denoting when the data was collected and what sources were used to derive the information.

Figure 3. *BIM2TWIN digital building twin system architecture. situational awareness.*



[1] PII – Project Intent Information
[2] PSI – Project Status Information

The project status information contains both the as-built product information and the as-performed process information, which are, in principle, tightly linked and interdependent. All new project status information records are timestamped, so that the status of the project at any given point in time can be extracted as a Digital Building Twin state.

The **Evaluate Conformance** process is also implemented through a set of software modules. Their purpose is to make value judgements about the status, and they draw on information from the PSM and from the BIM, historic digital twin model information, and industry standards (general knowledge about the product or process being analysed - industry standard production rates, for example). For example, in the case of the faucet installation described above, one might conclude any one or more of the following: the faucet was installed wrongly, the required quality was not achieved, and the time taken was excessive compared to standard toilet installation durations. This can support evaluation of the reason for the problem - the wrong faucet was delivered to site and installed; the faucet was correct but the pipes or the wall behind them were not built as-designed; the plumber was not qualified or did not use the right tools; etc. These modules derive new **knowledge** about the products and the processes, and this knowledge is also stored in the digital building twin.

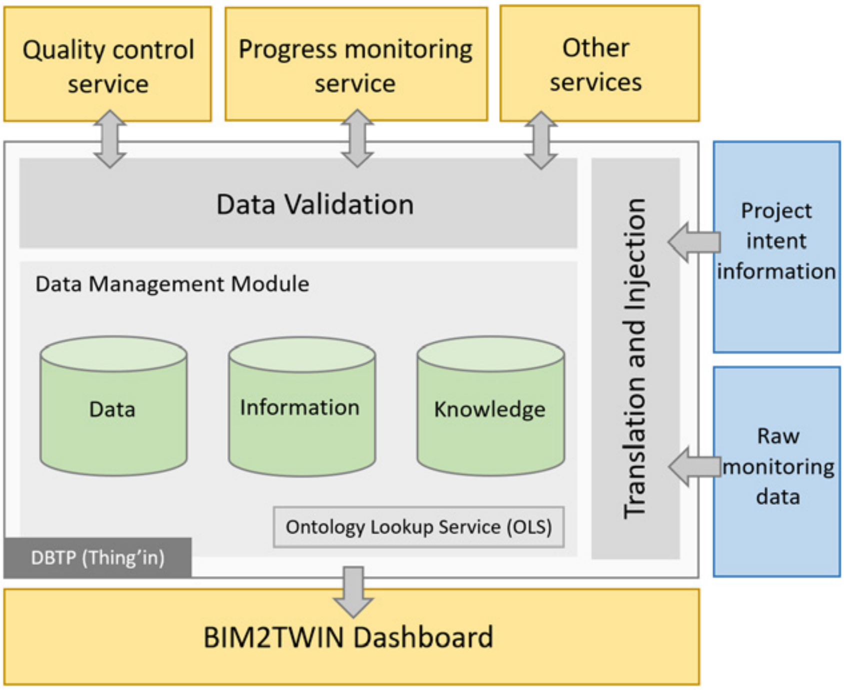
The next step, the last in the scope of the BIM2TWIN architecture, is **Predict Performance**. This action computes the probable outcomes of the project going forward from the current status date. If no change to either design or plan is contemplated, then the result of this computation will be a set of possible outcomes, each with a distinct probability of occurrence, expressed as results for budget, schedule, quality, safety, production flow quality, and other indicators. The input data is the current status PSM and the future BIM information. Similarly, any proposed change to design and/or to construction plan can be simulated to predict its outcome. In this way, alternative scenarios can be compared, to support management decision making going forward in the project. This is the decision phase of the data-information-knowledge-decision continuum.

1. Digital Building Twin: the Platform

The Digital Building Twin Platform (DBTP) is responsible for managing all information related to the Digital Twin (DT) of the construction site. This includes aspects like organizing the information in a structured way and handling the access rights of stakeholders. The basis of the DBTP is the so-called Thing'in platform developed by Orange [Coupaye, Privat, Ottogalli, Raipin-Parvedy, Camus, Bolle; 2018]. Besides other functionalities, it includes a graph database, which allows the explicit representation of the complex relationships between different construction site entities. In graph databases, knowledge is represented as a network of nodes connected through edges. By using different types of nodes and edges and attaching attributes to them, information with complex relationships can be represented. In the DBTP, the graph database serves as the single source of truth for all digital twin information. It encompasses planning information from the construction company, raw monitoring data captured on-site, and insights gained by external Digital Twin Services (DTS). It is essential to mention that the DBTP does not perform any data processing. External DTSs perform the processing. Depending on the specificities of a construction project and the use cases of interest, the required DTS should be selected accordingly. The architecture of this platform is described in Figure 4.

Due to the large number of software components and external services that interact with the DBTP, a strong focus was put on precise data structures. A new data schema was developed for the frame of digital twins of the construction phase, relying as much as possible on existing standards but also defining new terminology whenever necessary. This schema served as the internal schema of the DBTP but has the intention that other companies and projects can reuse

Figure 4. *Platform architecture of the DBTP.*



it for similar use cases. Additionally, the DBTP encompasses a data validation module that checks all data uploaded by external DTSs for compliance with the specified structure. Only fully compliant information will subsequently be added to the DBTP.

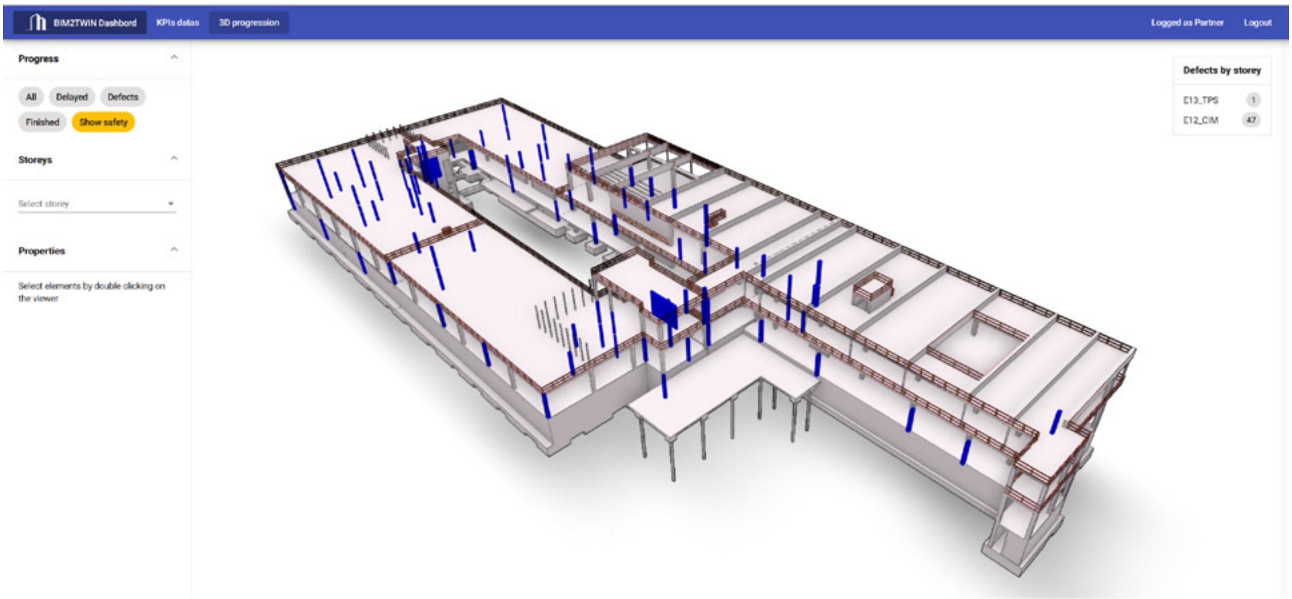
The final goal of the DBTP is to provide data structures to store information about the project intent and the project status to facilitate comparing the two and identify deviations. These insights will finally be presented to the end user, such as construction manager or other construction personnel, through the BIM2TWIN dashboard.

Dashboard

The BIM2TWIN dashboard presents the information and knowledge acquired by the DTSs to the end user. It is targeted at construction managers or other decision-makers involved in the construction project. The dashboard was designed to present a complete overview of the current status of the construction site in a condensed and easily understandable way. It should help decision-makers understand the main issues that require their attention in a short amount of time.

While the central dashboard gives a high-level overview of the construction site, DTSs developed use case-specific dashboard extensions that provide detailed insights into specific aspects. The central dashboard was implemented as a read-only application, meaning that it only displays information stored in the Thing'in database but does not allow to apply changes to the digital twin. Different from the digital twins of the construction site, cyber-physical systems use actuators to convey changes from the digital twin to the physical twin. These are, however, largely automated systems with little human interaction [Akanmu, Anumba, Ogunseiju; 2021]. On the contrary, construction sites still heavily rely on human labor, which limits the degree of automation that can be achieved considering the current state of the art.

Two main views are provided in the dashboard for every construction site supported by the DBTP. On the one hand, a 3D view gives an overview of the progress and quality aspects of the building. As an example, the visualization can be filtered for only the components that have already been built. Additionally, potential volumetric or surface defects can be closely inspected by selecting specific building elements. Moreover, a time slider allows visualizing the progress of the building at different points in time, conveying information about how the site progressed over time. A screenshot of the 3D view of the central BIM2TWIN dashboard is presented in Figure 5.

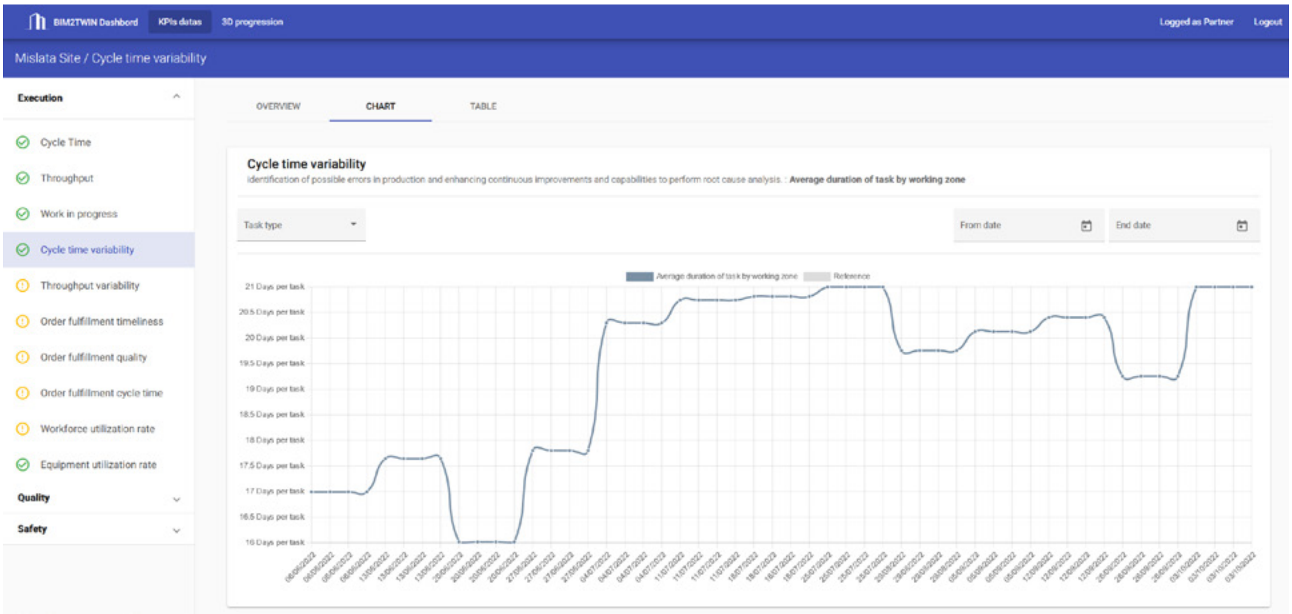


Select elements by double clicking on the viewer

Defects by storey	
E13_TPS	1
E12_CIM	47

Figure 5. *3D view of a pilot project highlighting all building elements with defects in blue.*

On the other hand, the Key Performance Indicators (KPI) visualization provides an overview of all available KPIs. They are presented in individual diagrams that allow for filtering by time interval and, depending on the KPI, several other aspects. In Figure 6, on the left-hand side, the set of available KPIs is shown sorted by the categories execution, quality, and safety. At the same time, the diagram in the middle provides insights into the currently selected cycle time variability KPI.



Cycle time variability

identification of possible errors in production and enhancing continuous improvements and capabilities to perform root cause analysis. : **Average duration of task by working zone**

Figure 6. *KPI view of the central BIM2TWIN dashboard showing the cycle time variability KPI.*

Data Management Module

The fundamental concept applied to data management of the DBTP is aggregating the different types of information according to their end-user value. For this, the pyramid approach by Ackoff [1989] (see Figure 7) forms the basis. All data is grouped into three layers: data, information, and knowledge. In the data layer, the raw data, such as sensor data, images from surveillance cameras, point clouds, and complete IFC files or construction schedules, are stored in their native format. These are all raw files that have not been tampered with. The second layer is the information layer. Here, the information is gained through statistical and arithmetical analysis of the raw data. For example, the information layer stores information about the planned start and end dates of construction processes, the status of elements detected in a point cloud, or information about surface defects detected during a quality inspection. Finally, the knowledge layer contains information with high end-user value, gathered through aggregation and evaluation of details from the information layer. In the context of BIM2TWIN, knowledge is interpreted as KPIs and similar indicators that allow a broad overview of the construction site's status, e.g., in terms of cost, security, or quality of executed processes.

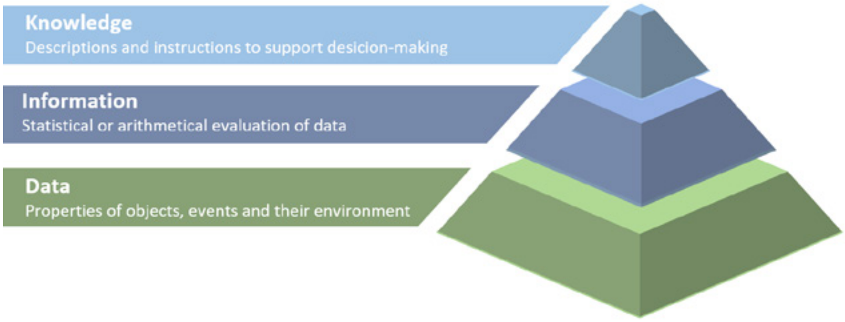


Figure 7. *Pyramid approach dividing information into three different layers based on Ackoff [1989].*

The Thing'in property graph database stores the content of all three layers [Coupaye, Privat, Ottogalli, Raipin-Parvedy, Camus, Bolle; 2018]. Whenever possible, the content is directly stored in the graph. However, data like point clouds or geometric information unsuitable for the graph structure are stored in external databases, which are referenced by the corresponding graph.

As already mentioned, the large number of parties involved in a construction project make clear data structures fundamental to ensure that all data of the digital twin can be efficiently stored and discovered. Existing data schemas are used wherever possible to describe how the graphs for the data, information, and knowledge layer need to be structured. For aspects specific to Digital Twin Construction that were not covered in existing schemas, a new schema, the so-called Digital Twin Construction Ontology [Schlenger, Borrmann, Yeung, Martinez, Sacks, Bus; 2023], was developed. It is a process-oriented schema that differentiates between project intent and project status to facilitate direct comparison.

Specific modules were developed to ensure that all involved parties correctly applied the selected schemas. First, the DBTP contains an Ontology Lookup Service that allows exploring all registered schemas. This serves as human-readable documentation but is also the basis for the data validation module. All data added to the DBTP must pass through the validation module. Based on the registered data schemas, the added data is checked for compliance. Only fully compliant data will be added to the DBTP. In this way, full interoperability between the DBTP and all external services is ensured.

Project Intent Converters

The project intent converters take project intent information from the construction company as input and translate the contained information into the graph representation used within the DBTP. This step is the starting point for every digital twin project since the project intent is the reference point for assessing the project's success. For converting the building design, a file in IFC format is required as input. This is an internationally established standard for the exchange of building models [buildingSMART; 2024]. Due to this formally defined standard, the information about the building topology and geometric details of building elements can be translated into the corresponding graph representation fully automatically. Since no established standard exists for exchanging schedules and resource assignments, the converter uses Excel files as input. However, manual adjustments must be made to the conversion process since the planning software and methodology used can vary significantly depending on the construction company and project.

Platform Interface (RestAPI)

The main access point of the DBTP for external services is the Restful Application Programming Interface (API). It is directly integrated into the Thing'in platform and provides a wide range of functionalities. It mainly allows querying, updating, and deleting information of the digital twin. Moreover, it can be used to configure the initial setup of the platform, like the validation rules, user access rights, and other configuration aspects.

Model Checking

During the execution of the BIM2TWIN demonstration pilot sites, it was identified that the quality of Project Intent Information (PII) provided by the construction companies could differ significantly. Depending on the use cases to be implemented, certain errors and inaccuracies need to be corrected, while others might not influence the final results. Specifically tailored to the use cases implemented in BIM2TWIN, model-checking and healing were implemented. The following model-checking operations were conducted to inspect IFC files before their injection into the DBTP:

- Semantic consistency: all elements must belong to their designated IFC class, e.g. foundation elements could be classified as IfcSlab, but they should be managed as IfcFooting.

- Clash detection: geometries of elements must not overlap (see Figure 8).
- Element modelling checking: verification of correctly modelled elements in the model, following typical BIM practices for architectural and structural modelling.
- Building storey modelling checking: elements must be modelled on the corresponding storey; for example, a wall starting from the ground should only be associated with the ground floor level.
- Property checking: some elements must have specific properties describing their functional characteristics, e.g., structural elements must have the "Load-Bearing" property.

This checking phase includes the removal of unnecessary components from IFC files, such as electrical elements, piping, and architectural details, to reduce file size, and consequently, the size of the Thing'in graph, thereby enhancing manageability. Additionally, construction companies provide federated BIM models that contain a set of domain-specific IFC files. For injection into the Thing'In database, these need to be merged into a single IFC file.

Executing these operations involved automatic and extensive manual effort and communication with the companies. Initial issue identification utilized typical Quality Assurance/Quality Control (QA/QC) BIM software, e.g., BIMCollab and Solibri, producing BIM Collaboration Format (BCF) issues, shared with all the stakeholders. Indeed, changes to the shape and position of elements must be managed using native authoring software, as these corrections were not directly applicable to IFC files. For semantics and file merging, IFC-based authoring software applications like SimpleBIM and usBIM were used.

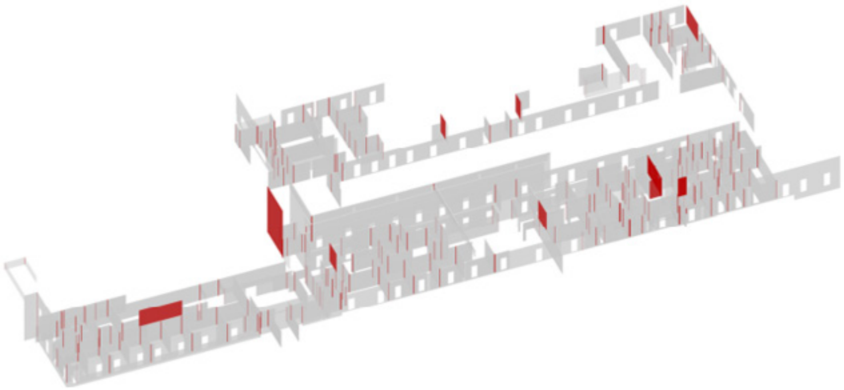


Figure 8. *Overlapping building elements identified in the IFC file of a pilot site (areas of overlap colored in red).*

2. Progress Monitoring Service

Monitoring work in progress on construction sites is critical for project management, impacting various aspects such as time, cost, quality, and safety. This task is particularly challenging due to the complexity and interdependency of activities [Arif, Khan; 2021]. Conventional progress monitoring methods rely on visual inspections and periodic reports, often resulting in slow and subjective assessments [Golparvar-Fard, Peña-Mora, Savarese; 2009]. While effective monitoring is essential for project success, traditional approaches may only be adequate if the project design or assumptions are flawed. Building Information Modelling (BIM), which digitally represents buildings and captures 3D geometry and semantic component descriptions, is a foundational tool for monitoring automated construction progress [Kim, Kim, Lee; 2020 and Machado, Vilela; 2020]. Recognized as a rich data source, BIM facilitates access to geometric data, visualizes schedules, and manages progress-related information, thus playing a pivotal role in automated project progress monitoring [Kim, Kim, Lee; 2020]. A well-designed BIM model facilitates operations analysis, aids site management, enhances communication, coordinates contractors, and optimizes logistics [Kopsida, Brilakis; 2020]. However, due to their static nature, conventional BIM and construction schedules may not adequately capture real-time as-built and as-performed states during construction [Kopsida, Brilakis; 2020].

Here, we focus on the above issues from the point of view of an automated approach for monitoring medium to large-scale construction sites using Digital Twin (DT) technology. The progress monitoring application interfaces with the DT database in the presented framework, enabling authorized users like project managers to access Gantt chart-style progress statuses at the activity level. Each activity corresponds to a group of tasks tied to specific elements on the construction site, providing a detailed overview of progress at the granular level. The Digital Building Twin Platform (DBTP) graph database stores details related to the construction site in three abstractions: data, information, and knowledge; please refer to Chapter 1 for more details on the DBTP.

Method and Components

Data to Information

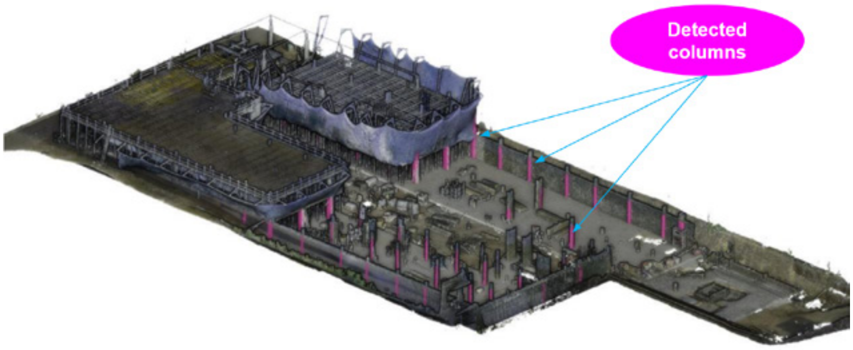
The platform receives both as-designed and as-planned data. Regular site inspections are then undertaken to document the current as-built status of elements. These inspections encompass two main types: laser-based 3D scans and image-based captures. Laser scans, although less frequent due to cost and potential hazards to workers, offer sub-centimetre accuracy and provide spatial information. Conversely, image captures excel in surface detail and texture representation. Each data source provides distinct advantages over the other, contributing valuable insights to the overall assessment process.

The data collected are used by specific software according to their type to detect as-built information.

Turning raw 3D point clouds into as-built elements

Scan-to-BIM technology offers a holistic assessment of as-built conditions, facilitating performance enhancement within construction projects [Bosché, Ahmed, Turkan, Haas, Haas; 2015]. Integrating laser scanning with advanced wireless sensors presents opportunities for comprehensive project exploration, bolstering progress monitoring by fusing as-planned models with reality-captured data. Managing vast and intricate datasets for real-time progress monitoring necessitates an intelligent system capable of continuous learning from diverse sources. Two potential object detection solutions have been proposed to calculate the as-built element. The first method is based on detecting and segmenting the as-built point cluster from the as-built Point Cloud Data (PCD) with the help of an as-designed model [Hu, Brilakis; 2024]. The second method exploits planar polygons – a versatile data abstraction often used to design building elements such as walls, columns, and slabs. A pivotal step in accelerating the detection task involves achieving global registration between the BIM model and PCD. Once registered, the Region-Of-Interest (ROI) can be confined to the upscaled bounding box of the query as-designed element, provided that the BIM model and PCD share the same coordinate system. Then, we use our object detection method to detect and cluster planar polygons in each dataset. We create a matching step to compare planar polygons within associated clusters. This comparison not only filters out noisy data but also identifies local discrepancies in position, ultimately eliminating false detections.

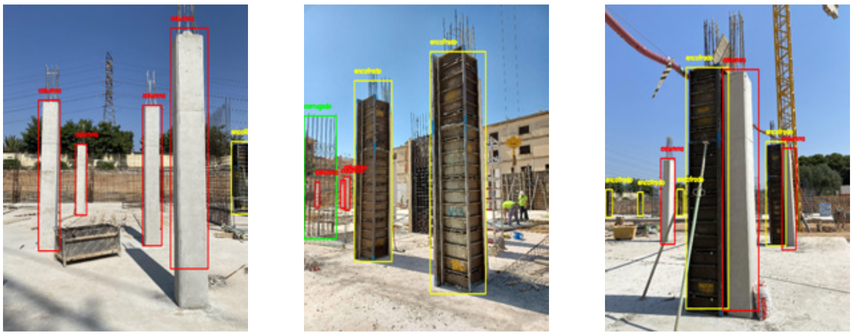
Figure 9. *Detected columns in the Spanish pilot site point cloud.*



Turning raw images into as-built elements

Typically, in the context of image-based, construction site monitoring is carried out with fixed cameras installed, for example, on cranes [Yang, Vela, Teizer, Shi; 2014 and Jiyao, Qilin, Bin, Binghan; 2023]. However, here we focus on information from images captured by construction workers, with mobile phones at the end of their workday, with the aim of creating a simple and low-cost tool. Given the widespread use of smartphones, interacting with the system to enter information is simple and thus seeks to integrate construction workers into the progress monitoring process.

Figure 10. *Example of columns construction state detection made on the project.*



The image analysis process uses an Artificial Intelligence (AI) model developed based on the YOLO v8 (You Only Look Once) neural network architecture. Additionally, most methods focus on detecting the presence of objects in images (i.e., 0% or 100% progress), while the discussed approach, herein, can detect between statuses of an element within an activity (columns with rebars, with formwork, already finished: concrete detected). This enables a more granular progress control and, therefore, more efficient planning of quality check activities. After analysing the photograph, to identify the captured columns, a virtual camera is configured in the environment of the 3D BIM model to recreate the original image taken at the construction site. Positioned in the virtual environment with the EXIF data of the captured image, a pairing of 2D projections is executed to adjust the precision of the camera location and determine the progress of the columns detected in the image.

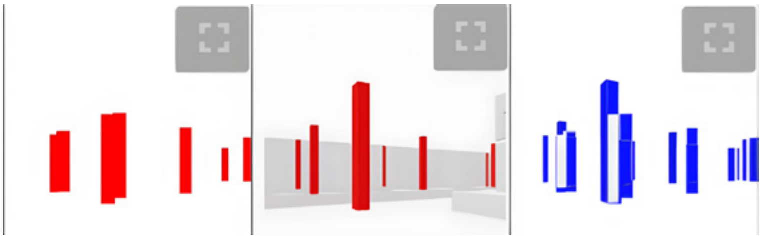


Figure 11. *Computer vision result projection (left), virtual camera projection (center), and the result of the 2D matching (right): in blue colour, columns that are in one projection but not in another and in light-grey colour, columns that are matching in both reprojections.*

Big Picture

To enhance communication between the DBTP and its services, such as progress monitoring, the DBTP offers Rest Application Programming Interfaces (APIs). By harnessing these APIs, our Python and JavaScript libraries enable users to retrieve, create, and update nodes within the DBTP. The as-built status of each element undergoes continuous updates within the DBTP through specific object detection processes, utilizing captured laser scans and images. Upon detection, as-built nodes are generated in the graph, annotated with construction stages, and linked with corresponding as-designed nodes. While laser-based object detection algorithms may struggle to differentiate construction stages, image detectors excel in this aspect. With as-designed, as-planned, and as-built nodes in the graph, the subsequent step involves creating as-performed nodes using this information.

Progress Monitoring

This software module extracts crucial data from the DBTP, including as-planned and as-built dates, facilitating a thorough comparative analysis at the activity level to provide a holistic view of the site's progress. Visual representation is achieved through a Gantt chart, enhancing comprehension. Activity-level progress is classified into three statuses: on schedule, ahead of schedule, and behind schedule, with the extent of delay determined by the maximum delayed task in cases of falling behind. To deepen insight, the module computes the percentage of completed tasks and identifies delay duration, leveraging this information to estimate a revised end date using a projection function. Drawing on an S-shaped function, this projection method closely mirrors construction activity progression [San Cristóbal; 2017], bolstering accuracy and predictive capabilities.

Limitation

Progress monitoring can exhibit bias depending on the data quality, as it relies heavily on the accuracy of algorithms that transform raw data into as-built nodes. While terrestrial laser scanners offer high precision, they are expensive and slow in data capture. Therefore, their use limits the frequency of scanning, which in turn impacts progress monitoring. Mobile scanners, such as PointPix [Trzeciak, Pluta, Fathy, Alcalde, Chee, Bromley, Brilakis, Alliez; 2023], provide flexibility and speed, allowing rapid data collection over extensive areas, yet they often sacrifice detail, especially in complex environments. This disparity between mobile and terrestrial scanners underscores a critical gap in construction inspection. While terrestrial scanners can capture intricate details, they lack mobility and efficiency. Bridging this gap necessitates advancements in technology and methodology, aiming to merge the agility of mobile scanners with the precision of terrestrial ones for comprehensive inspection processes.

Regarding images acquired from smartphones, it was known that the georeferencing obtained would not be precise. Moreover, the algorithms developed to correct the position have not given reliable results either. Other challenges persist in localizing images within construction sites, particularly in GPS-denied areas, hindering the accurate alignment of as-built data with its as-designed counterpart. Efforts are ongoing to enhance this accuracy in pinning as-built data to its corresponding as-designed elements.

Information to Knowledge

Key Performance Indicators

The information nodes play a crucial role in elevating the analysis to a higher level of abstraction, allowing for a comprehensive assessment of overall site performance through Key Performance Indicators (KPIs). Two predetermined KPIs are systematically computed: KPI1PM, which measures the percentage of delayed tasks per activity, and KPI2PM, which assesses the percentage of delay in days per activity. KPI1PM quantifies the prevalence of task delays within individual activities by dividing the number of delayed tasks by the total scheduled tasks for each activity. This ratio provides nuanced insights into task-level performance, aiding in understanding project progression. Concurrently, KPI2PM calculates the ratio between the number of delayed days and the planned duration (as-planned days) for each activity, offering a comprehensive view of temporal performance. This metric elucidates the extent of delays compared to the initial project timeline, facilitating informed decision-making regarding project management strategies.

In addition, if progress is detected during the images or point cloud processing, an email is sent to the Quality Managers. The objective is to quickly inform the manager about the newly detected elements and allow them to see the results online. This information helps schedule an earlier site visit to validate identified progress and initiate the next task more quickly.

User interface

For laser scans, the progress monitoring application is tightly integrated with quality control presented in distinct tabs as depicted in Figure 12. The progress monitoring interface boasts simplicity and user-friendliness, featuring just one button alongside a Gantt chart below to facilitate interpretation for construction managers. Gantt charts were selected for their widespread use in construction scheduling, ensuring familiarity and effectiveness as visualization tools for managers. Each activity is represented graphically by two horizontal bars: one representing the as-planned schedule and the other the as-performed schedule. The as-planned schedule is depicted by a grey bar, while the as-performed schedule is shown with a coloured bar. In the chart, a dark red bar indicates that the activity is complete but delayed, while a dark green bar denotes that the activity is not complete but on schedule. Light red signifies that the activity is behind schedule and not yet initiated, whereas light green indicates that the activity is on schedule and pending commencement. Text overlaid on the grey bar corresponds to the activity name assigned by the construction company, while text overlaid on the coloured bar provides progress status, days ahead or behind schedule, and projected completion time.

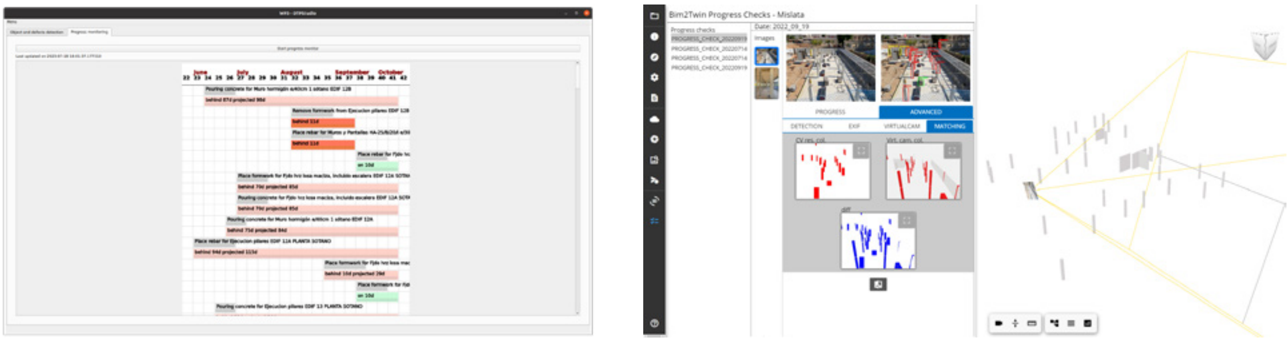


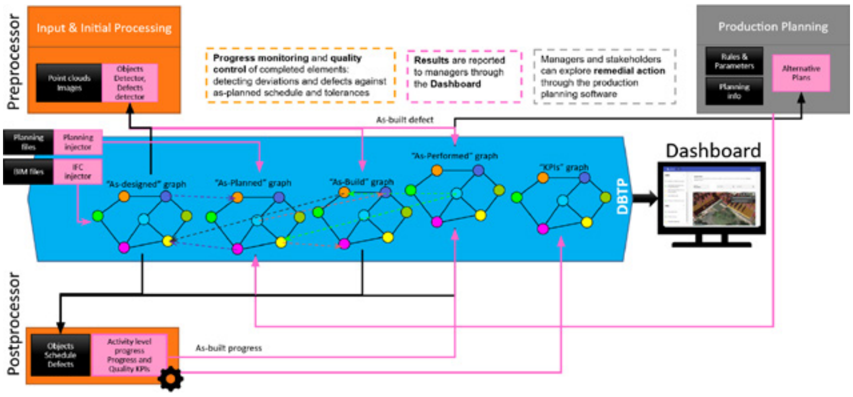
Figure 12. *Gantt chart interface for tasks progress results (left) and web platform interface of image-based progress monitoring (right).*

In the case of the image-based progress monitoring web platform, an intuitive interface allows Quality Managers to review the column progress detection results, which have been carried out automatically after the images are uploaded by on-site workers. Through this user interface, managers can view detection results graphically, in both 2D images and 3D geometry within the virtual BIM model. The primary goal of the platform is to empower Quality Managers to interpret progress results accurately and validate work progress against real-world conditions.

Communication with the DBTP

The digital twin platform assumes a pivotal role within our framework, as depicted in Figure 13. It swiftly transforms data into valuable information, consolidating it on the platform from the earliest stages of planning and design. We maintain access to timely information through seamless integration with the platform across all processing stages, ensuring responsiveness to changes such as site schedule updates. This dynamic, two-way exchange extends beyond progress monitoring components; other services leverage data, including as-built elements, for tasks outside our primary focus. These may involve generating alternative plans or providing visualization in the Dashboard. In contrast to our approach, where data updates are promptly synchronized with the cloud server after each survey, the conventional method integrates components as needed. This means that data updates occur immediately on local software and intermittently on the central server. While this traditional approach reduces queries to the central server, which is advantageous in on-site environments with unreliable internet connections, it can lead to data discrepancies and require excessive queries for creating and managing a local database copy. Additionally, such practices can introduce security vulnerabilities. Our approach, tailored for off-site use, ensures that raw data is swiftly uploaded to the cloud server after each survey. Authorized office users can access these site updates within minutes, significantly enhancing the security of the entire system.

Figure 13. *Processing Pipeline with the DBTP in the middle.*



3. Quality Control Service

Quality control on construction sites currently involves many time-consuming tasks, like repetitive tasks, including onsite inspection, data collection, analysis for defects, communication for issue resolution, and execution [Akinci, Boukamp, Gordon, Huber, Lyons, Park; 2006 and Dong, Maher, Kim, Gu, Wang; 2009]. Finding and fixing mistakes early is significant because fixing them later can waste around 6 to 12% of the construction costs [Patterson, Ledbetter; 1989 and Josephson, P.-E., Hammarlund; 1999]. Even though there's been a lot of research on automatic ways to find construction defects, the current methods still have limitations to standalone software, prohibiting collaboration and broad adoption. It's crucial to have a consistent and accurate quality inspection process in place to ensure buildings meet quality standards from start to finish. Construction managers or experts currently handle quality control during building construction, but it's a slow process that demands specialized skills. That's why there's a push to develop automated systems that can quickly spot and measure defects, saving time and making decisions easier when issues arise. Here, we focus on developing a tightly integrated system with a Digital Building Twin Platform (DBTP) for quality control. The DBTP graph database stores details related to the construction site in three abstractions: data, information, and knowledge.

Data to Information

Over the past decade, significant interest has been devoted to utilizing non-contact sensing devices to evaluate construction project quality. Notably, 2D cameras, 3D cameras, and laser scanners have emerged as critical tools in this domain. RGB cameras offer a cost-effective option for capturing high-quality surface defect data but are sensitive to environmental factors like noise and lighting variations [Paneru, Jeelani; 2021]. Moreover, they lack inherent 3D capture capabilities crucial for dimensional quality inspection. 3D cameras provide a more affordable solution capable of capturing 2D and 3D surface information, although they are less precise than laser scanners [Wang, Law, Garcia, Yang, Kong; 2021]. On the other hand, laser scanners produce detailed 3D point cloud representations of an object's external surfaces or overall 3D geometry, facilitating accurate dimensional assessments using a 3D coordinate system with geometric or geodetic coordinates [Tang, Wang, Wang, Guo, Zhang; 2022].

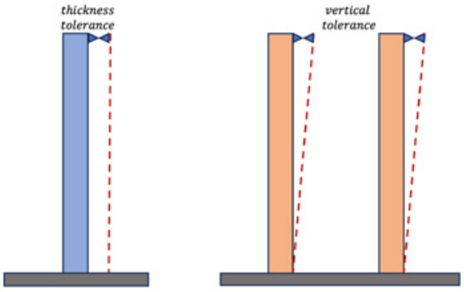
The 3D point clouds and 2D images collected are used by specific software according to their type to detect quality control information.

Turning raw 3D point clouds into quality control information

We aim to assess the dimensional quality of structural members using 3D point cloud data obtained from laser scanners, which capture various spatial attributes of buildings such as length, width, height, diameter, circumference, and flatness. Recent research has produced diverse methods for evaluating the geometric quality of construction elements. For instance, [Mirzaei, Arashpour; 2020] proposed an end-to-end segmentation method based on point cloud data for quality assessment, and [Nuikka, P. R. ; 2008 and Bosché, E. G.; 2014] examined surface flatness. Similarly, [YiTan; 2020] presented a system for automatic geometric quality inspection using BIM and LiDAR.

Our study presents quality assessment systems that are tightly integrated with DBTP. It compares as-built elements with their designed counterparts to ensure compliance with construction standards stored in the DBTP ontology. We primarily focus on norm deviations in constructed columns, slabs, and walls. Deviations beyond predefined tolerances are classified as defects. We analyse length and vertical discrepancies for columns while we evaluate the thickness and vertical deviations for walls and slabs. Figure 14 depicts these variations.

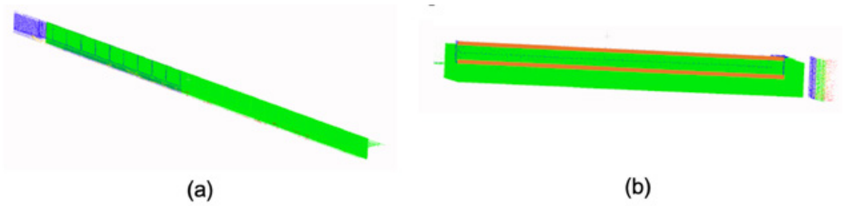
Figure 14. *Illustration of the vertical deviation and the thickness deviation.*



The quality control assessment software retrieves laser scans and corresponding as-designed data from the DBTP. We use a specific object detection algorithm brief to detect elements in the laser scans. As the walls and slabs have similar geometry, we use identical methods to compute their deviations. Initially, the surface of the as-built element should be extracted using the RANSAC (RANdom Sample Consensus) algorithm by randomly selecting a group of points and fitting a surface model to these points while tallying the number of points (inliers) that conform to the surface within a given error threshold. The thickness of the wall or slab is the distance between two large surfaces of target elements, i.e., the average sum of all the points on one surface to another. The thickness deviations are then calculated by comparing the thickness of the as-designed and as-built elements. The angle between the surface normal of the as-built element surfaces is used to calculate the tilt deviation of the wall or slab.

The column length is calculated as the distance between the most minor surfaces of the element. Figure 15 shows the detected thickness deviation of a wall. The green area is the as-designed data. In (b), two orange lines denote the detected surfaces of the Point Cloud Data (PCD). As can be seen, there is a significant thickness deviation between the as-built and as-designed data, therefore, there is a defect.

Figure 15. *Deviation of the wall's thickness.*



Turning images into quality control information

Attention has predominantly been paid to concrete surface defects in surface quality control, and in automating the defects identification process. A notable advancement beyond existing commercial tools is the capability of the tool developed in this project to measure defect characteristic dimensions crucial for precise qualification. Authors of [Chow, Su, Wu, Li, Tan, Liu, Mao, Wang; 2020] introduced a method employing deep learning classifiers to classify defects. Meanwhile, [Zoubir, Rguig, El Aroussi, Chehri, Jeon; 2022] utilised deep learning and transfer learning techniques to identify discrepancies in bridges. Early defect detection is emphasized for ensuring infrastructure health, as discussed by [Wang, Su; 2022], who achieved promising results using a hybrid network combining a convolutional neural network, transformer, and MLP (Multi-Layer Perceptron). In [Chow, Liu, Tan, Su, Wu., Li, Wang; 2021], an automatic defect inspection method employing a 360° camera and LiDAR was introduced, where defect evaluation was integrated into BIM by aligning pictures and depth data. In [Wang, Su, Fu; 2022], authors proposed a methodology utilizing a deep learning one-stage object detection neural network to detect irregularities in concrete surfaces. In the work presented here, we developed software that includes artificial intelligence (AI) models and computer vision techniques to classify and measure concrete defects from images. We aimed to identify four types of surface concrete defects: fissures, honeycombing, exposed bars, and pitting (Figure 16). The input images were captured with RGB or monochromatic cameras.

An AI-based model has been adopted to identify and classify surface defects, and vision-based algorithms measure defects characteristic dimensions. The defect measurements are converted from pixels to a real-world unit (millimetres) using the depth value (distance from the surface to the device) obtained from a depth camera.

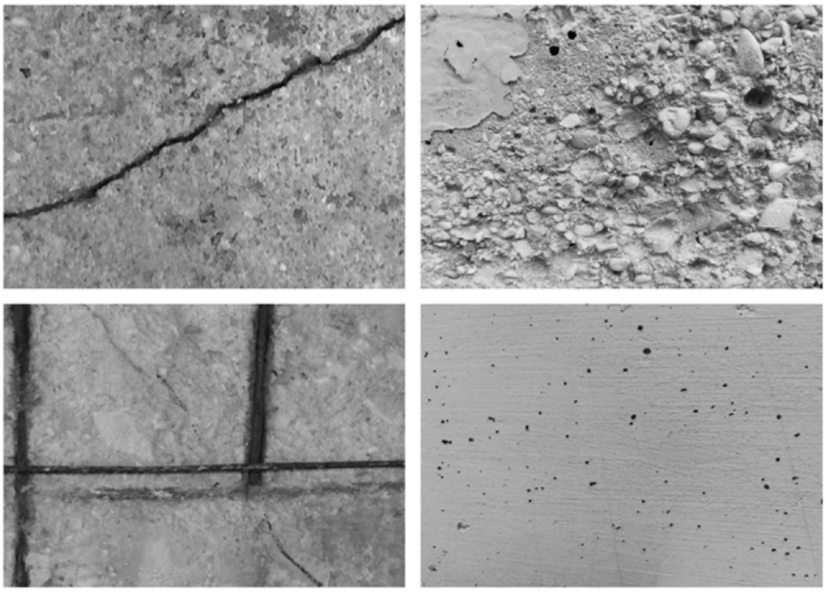


Figure 16. *Concrete defects considered for the developments of the surface quality control tool: crack (top left), honeycombing (top right), exposed bars (bottom left), and pitting (bottom right).*

The developed surface quality control method identifies and classifies the above-mentioned surface defects. The software can capture and analyse data in real time and integrates analysis results with essential information in the BIM2TWIN platform. The images were analysed by the software when a defect was identified to define the criticality level by measuring the specific features of the defect, depending on its type.

Infrared (IR) and Hyperspectral (HS) cameras represent the potential add-on of the monitoring toolkit. The IR camera is a valuable sensor for detecting non-visible sub-superficial defects. The HS camera can be exploited to filter noise and increase the contrast in images to improve the visibility of defects. Hyperspectral Imaging (HSI) can be an essential resource in discriminating different types of concrete contaminants and in evidence efflorescence. The analysed data were then uploaded into the DBTP, allowing site managers to visualize the images and the related data, accelerating the decision-making process, the data-flow is depicted in Figure 17. Our approach not only accelerates the quality control phase but also improves the overall efficiency of the construction process. The aim is to ensure that every construction phase is monitored, analysed, and optimized to achieve the best possible results.

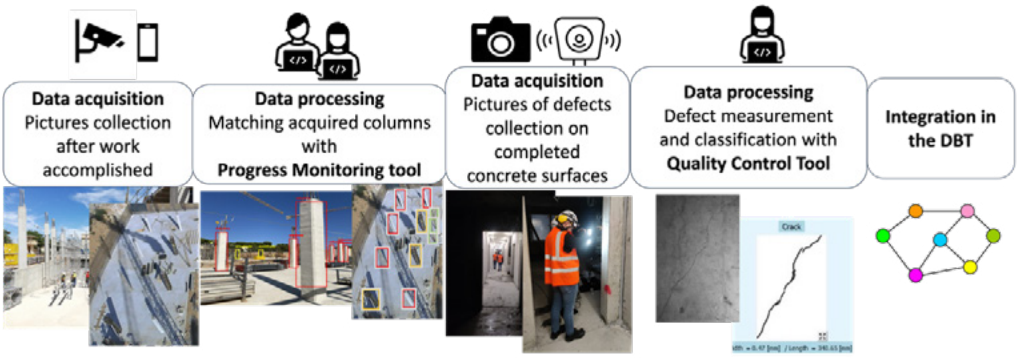


Figure 17. *Data flow: from information collection to integration.*

Limitations

Quality control utilizing 3D point cloud data can be influenced by bias, heavily relying on the accuracy of algorithms that convert raw data into as-built nodes. Point cloud data frequently comprises noise, errors, and inaccuracies stemming from various factors such as sensor limitations, environmental conditions, and occlusions. Filtering out this noise and ensuring data accuracy is imperative to facilitate reliable quality control assessments. The data acquisition process for quality control adheres to strict protocols that must be followed meticulously to obtain high-quality data suitable for the intended task. Implementing advanced filtering techniques and calibration procedures is essential to mitigate noise and enhance the accuracy of point cloud-based inspections.

Moreover, our quality control software is limited to supporting only common shapes like cuboids, making it ineffective for assessing complex structures such as stairs. By integrating technologies like machine learning, algorithms can evolve to encompass a broader range of structural categories, improving their applicability in real-world construction projects for comprehensive quality control. Additionally, point cloud data generated by laser scanners can be highly dense and intricate, presenting challenges in processing, storage, and analysis. Effectively managing large volumes of point cloud data requires robust computational resources and efficient algorithms to accurately and promptly extract relevant information.

Challenges encountered in the development phase of quality control with images primarily revolved around the scarcity of data for training neural networks and pattern classification for automatic defect recognition. While public datasets were available in the literature, they often comprised low-resolution images and lacked labelling for all previously defined defects. To address this, internal data was collected to create models for concrete defect classification and measurement, resulting in a notable improvement over the existing method. Another challenge involved analysing hyperspectral images, which successfully identified efflorescence and enhanced defect image contrast by filtering it out. However, attempts to characterize samples degraded by contaminants according to European Union standards using hyperspectral images yielded unsatisfactory results. The primary issue with hyperspectral cameras lies in the noise generated by sensor temperature instability and ambient light influence, posing significant challenges for outdoor applications of this technology.

Information to Knowledge

Key Performance Indicators

Translating information regarding built quality into a higher-level abstraction constitutes a pivotal aspect of the management loop. For top-level site managers, specific defect details may hold little interest; instead, they prioritize quantified defect information, such as at the workplace or workers' team level. We focus on two key performance indicators (KPIs) to provide such insights. Two predefined KPIs are systematically calculated: KPI1QC, which assesses the percentage of tasks affected by defects per activity within a specified time frame, and KPI2QC, which evaluates the percentage of defect-free activities within a given time frame. KPI1QC aids in identifying the types of activities contributing to defects, facilitating decisions on potential construction method adjustments. Conversely, KPI2QC gives managers insights into the percentage of defect-free activities, enabling them to monitor overall construction performance and quality.

User Interface

The quality control systems for laser scans and images feature distinct user interfaces. For laser scans, the quality control application is closely linked to progress monitoring which is segregated into tabs, as illustrated in Figure 18. This application seamlessly integrates with the DBTP for data retrieval and transmission. Its interface comprises three main sections: the top-left displays all elements with their names; the top-right offers a 3D visualization of both as-built and as-designed elements, and the bottom section presents the calculated quality control values for the selected element.

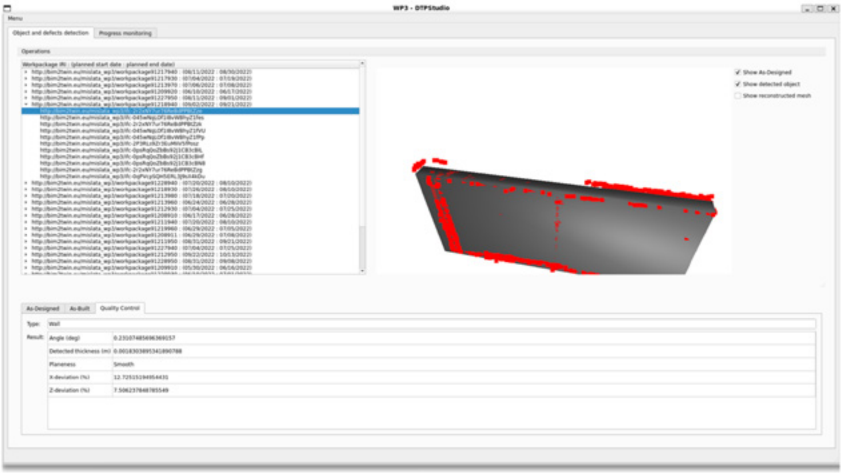
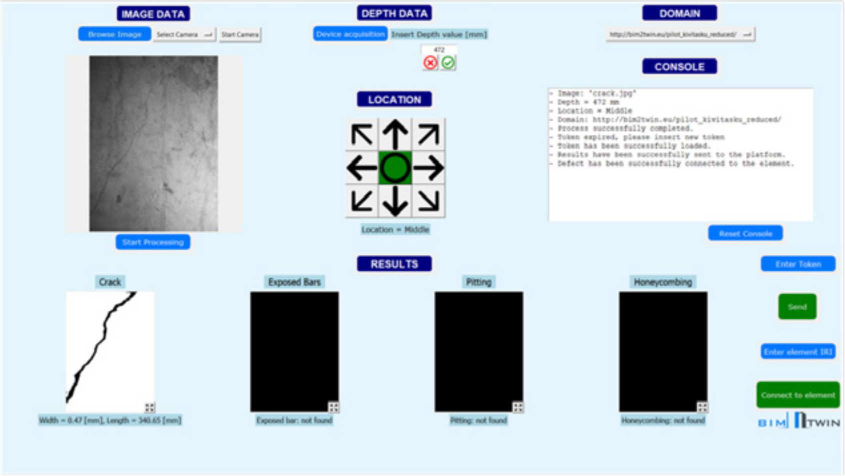


Figure 18. *The main window of our DTPStudio showing a detected wall (red points) overlapped with the as-designed representation and its quality results (bottom part of the interface).*

For surface quality control, a graphical user interface (GUI) has been created that enables the control of vision systems, post-processing of images and real-time display of any identified defect along with the measurement of its characteristic features.



```
- Image: "crack.jpg"
- Depth = 472 mm
- Location = Middle
- Domain: http://bim2twin.eu/pilot_kivitasku_reduced/
- Process successfully completed.
- Token expired, please insert new token
- Token has been successfully loaded.
- Results have been successfully sent to the platform.
- Defect has been successfully connected to the element.
```

Figure 19. *Visualization of detected defects.*

The GUI is compatible with Windows based tablets equipped with connected camera, guaranteeing the portability of the system. Users can either capture live images or upload existing ones. The images are analysed by the AI-based algorithms, and the result of the analysis is displayed. Finally, users have the option to transmit this information to the DBTP and visualize the images and the information of the detected defects on the BIM2TWIN dashboard (Figure 20).

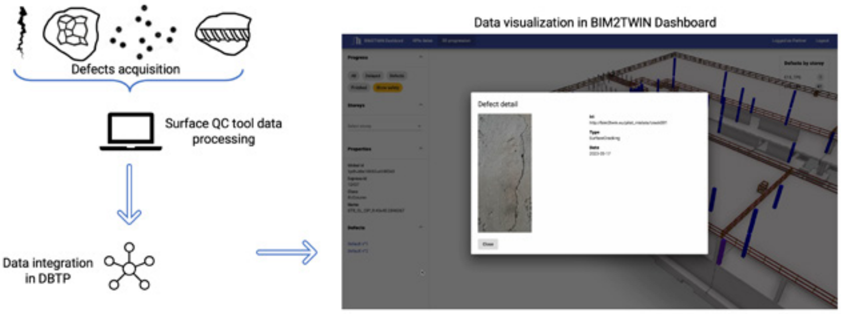


Figure 20. *Global overview of the integration of surface defects into the BIM2TWIN platform and consequently Dashboard.*

Big Picture

As discussed at the beginning of this chapter, the DBTP plays a central role by facilitating access and storage of information and knowledge. It is also critical in transforming raw data, including 3D point clouds and images, into valuable information and knowledge. The DBTP-based processing pipeline for quality control inspections enables algorithms to access information regarding quality standards and as-built elements. Through tight integration, as previously discussed, we ensure the utilization of up-to-date quality standards to determine the severity level of detected defects. This integration also facilitates rapidly disseminating knowledge and information concerning quality issues to other services, such as production planning, connected to the DBTP. The timely provision of defect information is vital in the construction pipeline as it can mitigate construction costs by enabling early detection of issues.

4. Occupational Health and Safety Service

In construction, job hazard analysis (JHA) is still a labour-intensive, error-prone, and thus time-consuming process [Teizer, Melzner; 2018]. A safety engineer analyses the hazardous components of tasks involved in an activity to determine the priority order of mitigation that needs to be implemented to make workplaces safe. 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, F. Boukamp, J. Teizer; 2015].

Those two measures rank the potential risk from the 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 with the 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 follow manual, time-consuming, and error-prone processes [Li, Schultz, Melzner, Golovina, Teizer; 2020].

We focused on the occupational health and safety of construction workers through a system of prevention through design in construction operation planning, proactive real-time risk detection and warning on construction sites, and rapid, personalized feedback in learning and decision-making. There are, as described, many potential safety risks on site, and we, therefore, focused on solutions for more than 50% of the fatalities in construction: a) workers falling from heights and b) struck by and/or caught in between equipment or loads. To mitigate these two risks, we enhanced the BIM2TWIN platform with (1) intelligent computational rule-checking algorithms for safe workspace planning, (2) automated remote sensing and analysis for proactive risk detection and prevention, and (3) Reporting and visualization for enhanced hazard awareness for improved safety behaviour.

Methods

Two main approaches exist to capture domain intelligence and knowledge in computers, also referred to as artificial intelligence (AI). The first can is often referred to as a data-driven approach, which, based on the input data, finds undying patterns automatically (i.e., unsupervised learning) or based on the data and human knowledge captured as labels find the underlying patterns (i.e., supervised learning). Both supervised and unsupervised learning require large amounts of data representing the individual scenarios. For hazard identification, this kind of data is not easy to acquire as this would need the hazardous situations to exist until data has been collected, which is not feasible.

The alternative to data-driven approaches is knowledge-driven ones, requiring less data but additional knowledge engineering. Knowledge-driven approaches do not automatically identify the underlying patterns but only represent the intelligence provided in the knowledge base. However, this knowledge base can be created by interacting with domain experts, investigating construction safety regulations, and applying common sense logic. This way, it is possible to describe the nature of hazardous scenarios with rule-based logic and use that for identification in the data. The presented results are based on knowledge-driven approaches due to the described complexity of collecting data that represent hazards in construction. The knowledge representation and analysis are based on spatial artifacts. Spatial artifacts [Bhatt, Dylla, Hois; 2009 and Bhatt, Schultz, Huang; 2012] can be used for this purpose as they represent empty-space regions that emerge and change based on the existence of BIM elements or situations in the 3D space.

The diagram shown in Figure 21 illustrates how safety can be considered in a digital twin setting. The safety service component is an independent digital component, which interacts with the surroundings. The system consists of the Digital twin service for production planning, the Digital twin service for Construction, and the direct interfaces to the building itself. The construction safety component comprises three sub-components, which are called Prevention through Design and Planning (PtD/P), conformance checking (CC), and Right-time Analysis and Mitigation (RAM). Those components and their concern are described in the following.

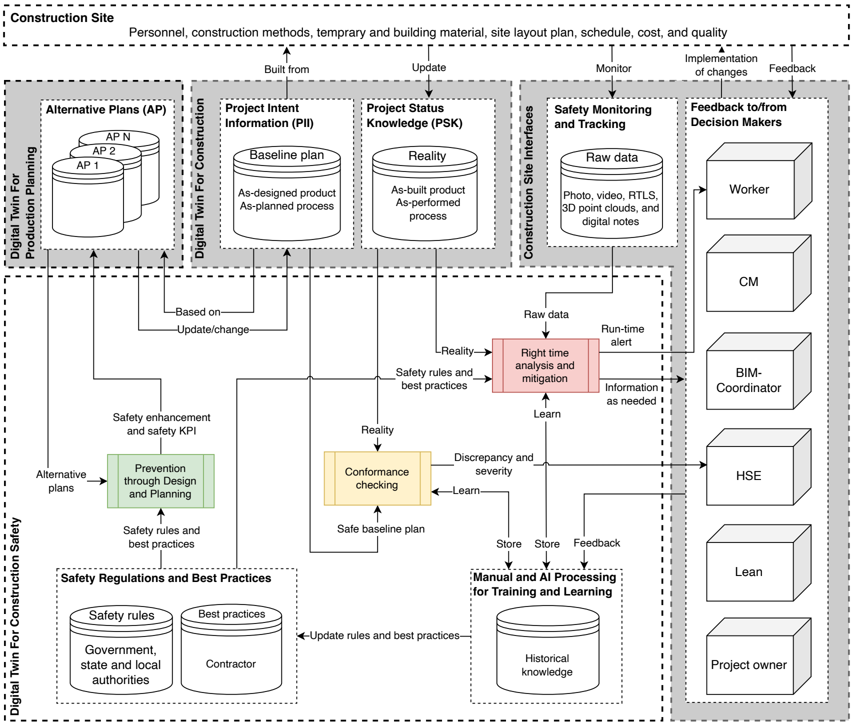
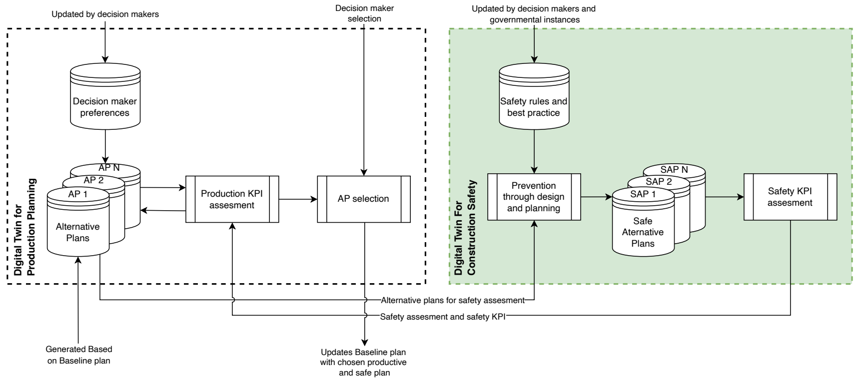


Figure 21. *Overview of the Digital Twin enabled construction safety [Teizer, Johansen, C. Schultz; 2022].*

Prevention through design and planning (PtD/P)

The left side of Figure 22 illustrates how the Alternative Plans (APs) are generated based on the decision-makers' preferences and the current baseline model. The APs are handed to the PtD/P module of the Digital Twin for Construction Safety (DTCS) - right side of Figure 22, in green colour - and enhanced with safety measures (e.g., guardrails to separate pedestrian workers' pathways from heavy construction equipment traffic and schedule changes) based on the safety regulations that apply to the specific construction site (note: this may vary locally). This can, as mentioned, result in more than one Safe Alternative Plan (SAP) for each AP. The system analyses the hazard spaces identified in the design and hazard spaces identified in the process (e.g., work crews working simultaneously on different stories, creating hazard zones in terms of being struck by an object from above). The SAPs are returned to the Digital Twin for Construction Planning (DTPP) for decision-maker selection, consequently updating the baseline plan from which the construction site is built [Johansen, Schultz, Teizer; 2022 and Johansen, Schultz, Teizer; 2023]

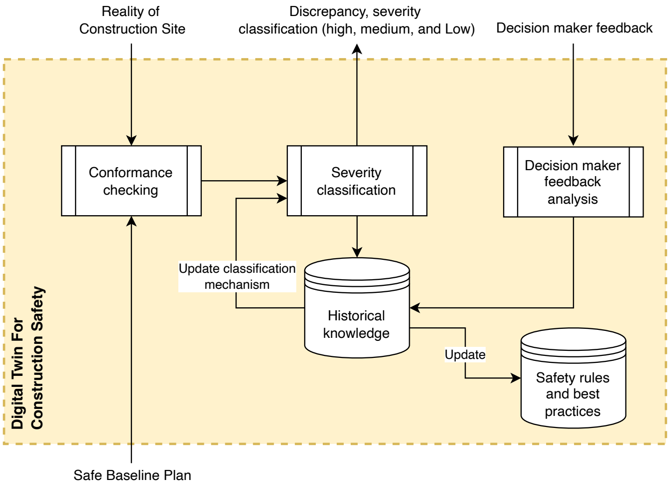
Figure 22. *Prevention through Design and Planning module [Teizer, Johansen, C. Schultz; 2022].*



Conformance checking (CC)

The conformance checking should find and classify discrepancies between the plan (created in PtD/P-module) and reality (captured by sensors) – Figure 23. For example, an incorrectly installed or removed guardrail would result in a relatively high severity. This information is stored, and when the HSE expert has visited the problem, they can provide new information on the correctness of the output (in terms of both incident classification and its severity). This information provided by the HSE expert should be used to improve the classification of future occurrences and to update the best practices. An example of an updated best practice could be using a safety net in some situations to avoid the repeated removal of, e.g., a guardrail [Johansen, Figueiredo, Golovina, Teizer; 2021].

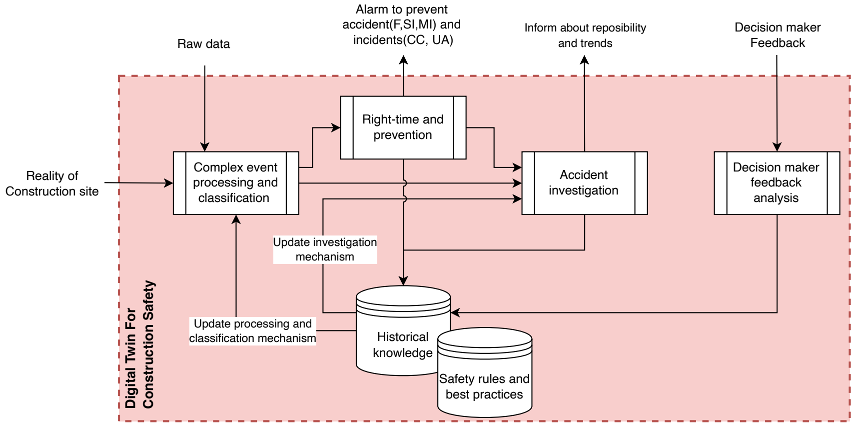
Figure 23. *Conformance checking module [Teizer, Johansen, C. Schultz; 2022].*



Right-Time Analysis and Mitigation

Based on the reality of the construction site, the raw safety monitoring data, historical knowledge, and safety regulation module perform complex event processing and classification, from which the workers are alerted to prevent both accidents (i.e., fatalities, serious injury, and minor injury) and incidents (i.e., close calls and unsafe acts) – Figure 24. The module subsequently performs an accident investigation, where the root cause of the incident or accident can be determined and prevented in the future. Also, in this module, the feedback to and from the decision-makers is stored and used in classification- and investigation mechanisms. The safety rules are also included in this diagram. These are updated and used in the PtDP module (i.e., the first module of the DTCS), conceptually closing one of the loops of the DTCS [Johansen, C. Schultz, J. Teizer; 2023].

Figure 24. *Right-time analysis and mitigation module.*



Results

Figure 25 visualizes the spatial artifacts that were identified in the PtDP analysis. The artifacts comprise three different kinds of regions: Movement space, i.e., regions where workers can move around, such as slabs. Those are coloured green, visible at the bottom. The second kind is Fall spaces, which represent regions where items or humans will drop more than the regulation allows. Those are visualized in yellow. The third kind is Fall hazard spaces, which represent the regions where workers are exposed to fall from height hazards, which are identified as the intersection between the Fall space and the Movement space, i.e., where workers that move around on the construction site can access a region where they would fall more than the regulation allows.

The fall spaces are not immediately visible from the view in Figure 25, as they are inside the fall space. However, they become very apparent when they are exchanged for fall protection equipment, and the analysis spaces are hidden, as shown in Figure 26. This way, the fall protection equipment needed to comply with the fall from height regulation is identified and injected directly into the BIM model. The digitalization of fall protection equipment facilitates site-wide planning and knowledge about where protection equipment is needed, which promotes a collaborative effort to make sure they are installed as planned. Besides allowing everybody on the construction site to obtain this information, it can also be used in automated conformance-checking approaches to instruct where the Unmanned Aerial Vehicle (UAV) or Unmanned Ground Vehicle (UGV) must go to collect meaningful data and, in the following analysis. The information can, for example, be used to set the boundaries of the search space, which drastically decreases the complexity.

Figure 25. *Spatial artifacts from the PtDP module.*

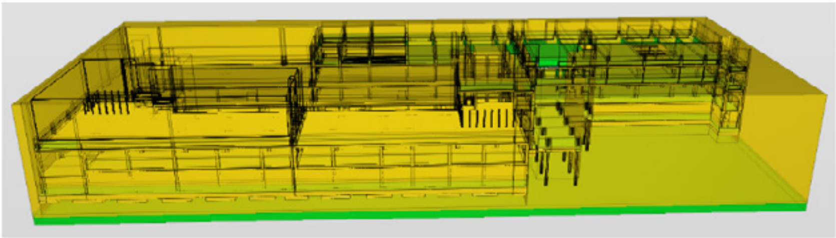
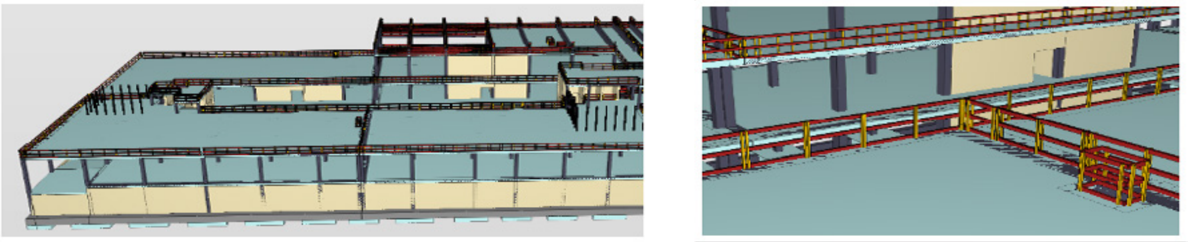


Figure 26. *Fall protection equipment injected into the BIM model from the PtDP module.*



While the safety analysis primarily relies on knowledge-driven approaches, it also benefits from information that is extracted in data-driven approaches. Figure 27 visualizes the data fusion of RTK-GNSS location data and location data provided by one of the project partners, which is extracted from RGBD (red, green, blue, depth) in a data-driven approach. Both inputs are considered in the Right-time Analysis and Mitigation (RAM) module called "ProActiveSafety", which extracts safety incidents that represent scenarios where workers were present under a crane load, a competing work crew, or in close vicinity of a moving vehicle, also referred to as struck-by hazards.

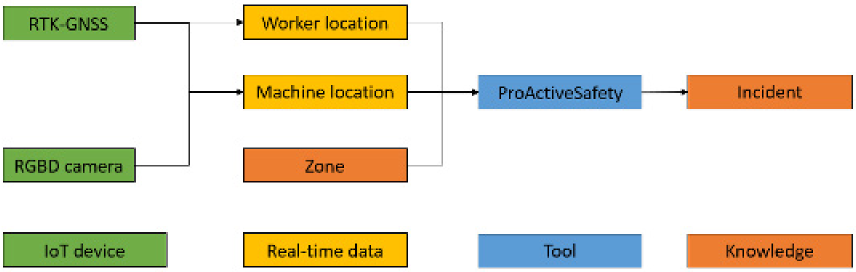
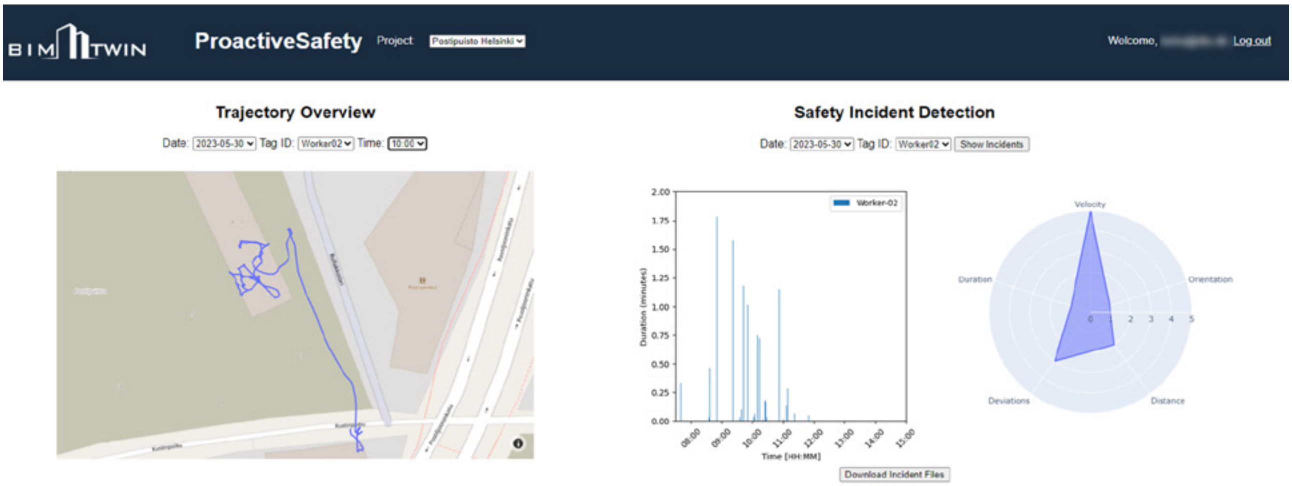


Figure 27. *Data fusion of RGBD and RTK GNNS location for the RAM module.*

Figure 28 shows the worker interface, which can be accessed by the workers to get an overview of the trajectories for a day, but also how well they did in terms of staying out of hazardous situations. It graphically represents how many times they went into safety incidents that could have been prevented if they had selected a different route or looked up to avoid the crane load. Besides giving feedback to the workers and improving their safety behaviour, the interface could also provide an overview of the site's performance. Privacy is essential, so a site-level incident count and heat map should be presented anonymously. However, such presentation of the site performance could identify overall issues and tendencies that could potentially be resolved through changes to the site layout (e.g., adding moving pedestrian crossings, redirecting heavy machinery, moving material storage, relocating material delivery, or creating zones that the crane is not allowed without approval.

Figure 28. *Worker feedback interface for insight and improved behavior.*


Project: Postipuisto Helsinki

Welcome, [redacted]

Trajectory Overview

Date: 2023-05-30 Tag ID: Worker02 Time: 10:00

Safety Incident Detection

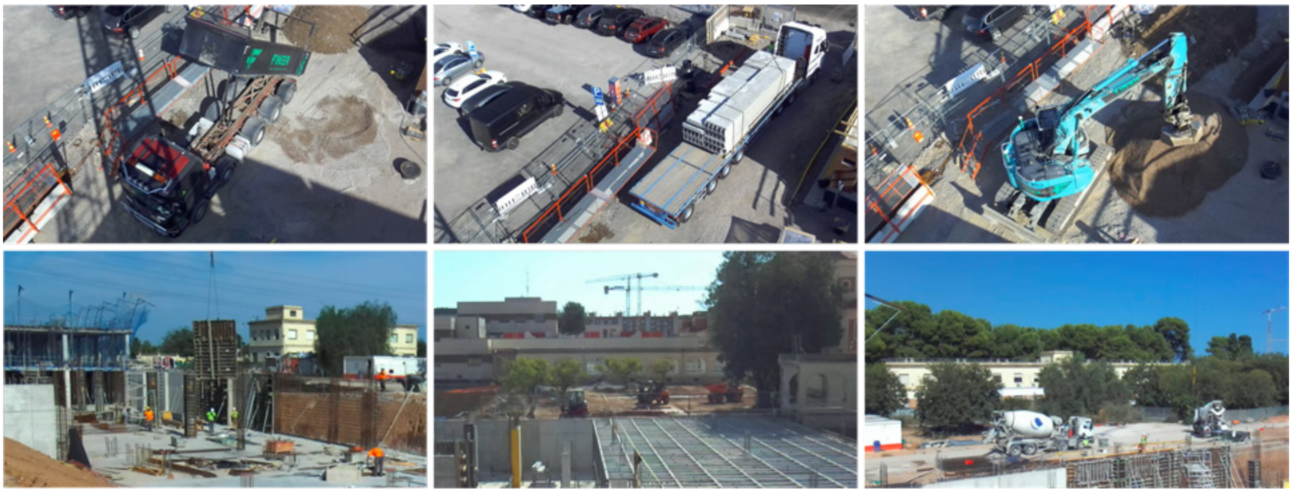
Date: 2023-05-30 Tag ID: Worker02

5. Equipment Optimization Service

The efficient control and management of construction equipment on construction sites is essential [Navon; 2005], as requirements differ from project to project and require flexible adaptation of equipment utilisation. The combination of machine utilisation and manual work leads to diverse and complex challenges on construction sites [Sundquist, Gadde, Hulthén; 2018]. Furthermore, there is the need to be able to react to unforeseen situations, such as delivery delays or technical failures, which have an impact on the construction process. These factors make the continuous monitoring of the position and status of equipment essential and form the basis for optimising the use of equipment, such as construction machines, increasing safety and reducing costs by reducing idle times.

A wide range of specialised equipment is used in construction work, each of which is tailored to specific applications. For example, construction machines such as excavators and dump trucks are used for earthworks, while concrete pumps, concrete mixers and formwork are primarily used for concreting work (Figure 29). Cranes and lorries are used to transport materials. Some of this equipment can be equipped with technological solutions, such as Internet of Things (IoT) sensors [Jiang, He; 2020], to transmit real-time location and status information to the DBT platform. However, this requires a technological upgrade to the machines, which is associated with additional costs and increased maintenance. In addition, it would be necessary for subcontractors to also equip the construction machines they use with IoT sensors to collect data from these machines.

Figure 29. *Equipment such as machines are used for various processes.*



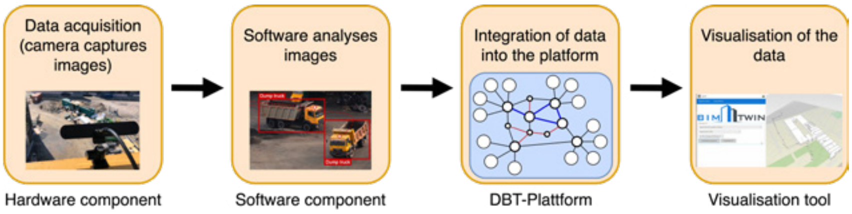
Camera-based monitoring systems represent a promising option for the collection of position and status information [Xu, Wang, Shou, Ngo, Sadick, A.M., Wang; 2021]. These systems utilise an artificial intelligence-based detection model to identify various pieces of equipment on images and track their movements. Such an approach makes it possible to capture data on the position and status of equipment on construction sites, provided that the equipment is known for the detection model and is within the detection range of the camera. The advantage for construction companies is that they can utilise a flexible and efficient method of data collection without the need to upgrade construction equipment with sensors in advance. However, it is crucial that camera-based systems have a clear line of sight to the monitored areas to ensure effective data collection.

Components & Methods

The data acquisition system, which is based on camera technology, consists of two central elements. Firstly, it includes a software component that is responsible for analysing camera images and providing data on detected construction machines. Secondly, it consists of a hardware component that includes both the camera for data acquisition and the computer for analysing and processing this data (Figure 30)

The data acquisition system sends the collected data to the DBT platform. In this platform, data provided by Control & Management of Construction Equipment activities representing the actual process (as-Performed) is linked to the planned data (as-Planned). This link is made specifically between the planned (as-PlannedEquipment) and the actual deployment (as-PerformedEquipment) of the construction machines, including the recorded geographical positions. In the final phase, it is offered a visualisation tool that allows the movement paths of the construction equipment to be displayed on a map in conjunction with the IFC model by downloading it from the platform. In addition, logistical information such as planned and actual deliveries are visualised in a table.

Figure 30. *Concept: From generating the data to processing and presenting the information.*

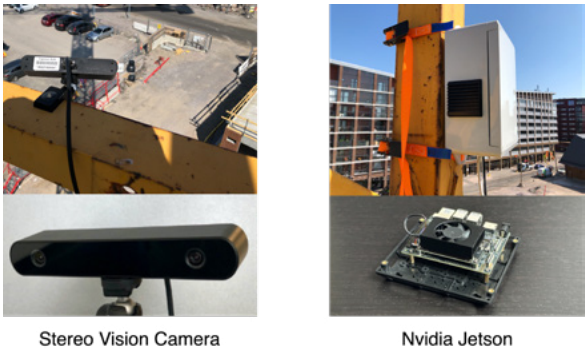


Hardware components

A stereo vision camera is used to capture three-dimensional data of the environment (Figure 31). This technology uses two horizontally offset images, analogous to human stereoscopic vision, to measure the distances from the camera to the object, which is made possible by generating a depth map. The camera is also equipped with an Inertial Measurement Unit (IMU), which makes it possible to measure the orientation of the camera. It also complies with protection class IP66, making it completely dustproof and resistant to strong water jets, which is recommended for use on construction sites.

For efficient processing of the data obtained, the use of a single-board computer, such as an Nvidia Jetson model, is recommended to process the image data directly on site [Kosse, S., Pawlowski, D., & König, M.; 2022]. This computer was used for data collection on the Postiaukio pilot site in Finland, which was housed in a specially constructed case with data storage. The advantage of this system is that it is specially designed for AI applications and has a maximum power consumption of 25 watts, which is energy-saving.

Figure 31. *Hardware for data acquisition and processing used on the Postiaukio pilot site.*



Software Component

The software component uses a computer vision algorithm to detect construction machines in images. It determines their locations, tracks them over several images and records their movements in the form of trajectories. The trajectories are three-dimensional and labelled with geographical coordinates, whereby each point on a trajectory is assigned a specific GPS position. Each trajectory is given a unique ID and a class label that specifies the object type. In addition, time stamps, a confidence value for identification certainty, the speed, and the movement status (IDLE for standstill and MOVING for movement) are recorded at each point on the trajectory. This data collection provides a basis for analysing the movement patterns.

The computer vision algorithm integrates three main components that were implemented sequentially. The initial component consists of a real-time YOLOv5 detection model (AI) [Jocher et al; 2022], which indicates the position and size of the machines by a bounding box when it detects them (Figure 32). For the training of the detection model, 15,900 images were used. The underlying training dataset includes nine different classes of objects, allowing the detector to identify the following types of machines in images:

- Excavator
- Pump truck
- Dozer
- Concrete mixer
- Roller
- Loader
- Dump truck
- Mobile crane
- Tower crane

The performance of the detector was verified by evaluating 2870 images, achieving a mean average precision (mAP) of 0.85 mAP@0.5 and 0.6 mAP@0.5:0.95. These results indicate that the model can identify the machines with good accuracy.

Figure 32. *Use of the detector that recognises both the excavator and the dump truck.*

The second component comprises tracking, which continuously follows a detected machine over a series of images if it remains within the camera's field of view (Figure 33). This involves setting up a tracker with a random identification number that predicts the position of the machine for the next image by relying on the movement dynamics (speed, direction, and size of the object). The tracker is updated with data on the position and size of the bounding box from the detector to refine its predictions. Even if the detection fails, for example because the machine is obscured by another object, the tracker can predict the position for the next 60 images. If the detector can no longer identify the machine and the tracker is therefore considered invalid, it is deleted from the system. However, the trajectory recorded up to that point remains in the system.

Figure 33. *Dump trucks and excavators are recognised and tracked. The trajectories on the right are three-dimensional, shown from a bird's eye view.*

The final component involves the conversion of local three-dimensional coordinates into GPS coordinates. As part of the tracking process, the distance between the stereo camera and the detected machine is measured, resulting in the generation of a three-dimensional coordinate, whereby the origin of the coordinate is the camera itself. Using the known GPS coordinates of the camera and its orientation (the camera direction in degrees relative to the magnetic north pole), the spatial offset between the camera and the identified machine can be determined. This results in the specific GPS position of the machine, whereby the entire trajectory is georeferenced (Figure 34).

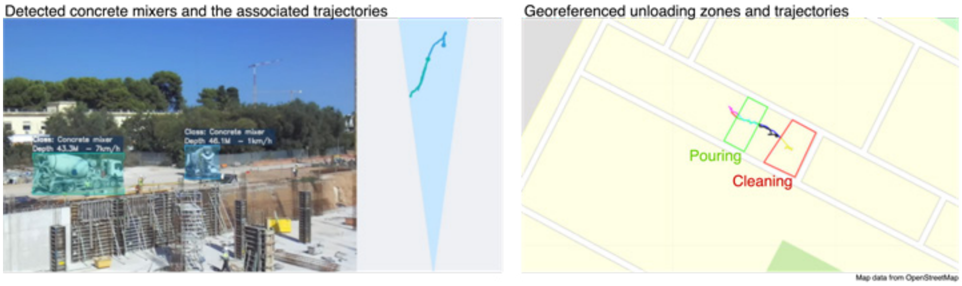
Figure 34. *The trajectories shown on a map in Figure 34.*

Dashed line:	Camera field of view
Pin:	Location of the camera
Blue trajectorie:	Construction site fence
Red trajectorie:	Excavator
Yellow trajectorie:	Building boundary
Green trajectorie:	Dump truck

Capture of Logistical Processes

Within the scope of Control & Management of Construction Equipment, the focus was on two main areas: firstly, the localisation and status detection of machines and, secondly, the monitoring of logistical processes involving the delivery of construction materials. These objectives were achieved by determining the coordinates and dimensions of loading and unloading zones using GPS technology (Figure 35). By analysing whether a particular construction machine or truck is allowed to enter such a zone, an event log can be generated. This log, which contains an identification number, time stamps for arrival and departure and the duration of the stay in the zone, makes it possible to assign the actual arrival time of a delivery to a planned delivery. In this way, it is possible to efficiently check whether there are delays or failures in the delivery process.

Figure 35. *Detected concrete mixers on the Spanish pilot site and the associated geo-referenced trajectories and working zones (name of the working areas shown).*


Detected concrete mixers and the associated trajectories

Georeferenced unloading zones and trajectories

Data Integration and Visualization

The data from the acquisition system is integrated into the DBT platform in accordance with the ontology defined within BIM2TWIN. This means that when a construction machine is identified by the computer vision algorithm, the equipment type including ID and the trajectory, consisting of GPS positions, are stored in the DBT platform. Planning data for the equipment is already stored in the DBT platform, which links the detected and tracked equipment (as-Performed) with the planning part (as-Planned). In particular, when a delivery process is identified (see section Capture of logistical processes), the delivery process is also linked to the equipment based on the event log. As the delivery process was also planned, this realised delivery process is also linked to the planned delivery process (Figure 36).

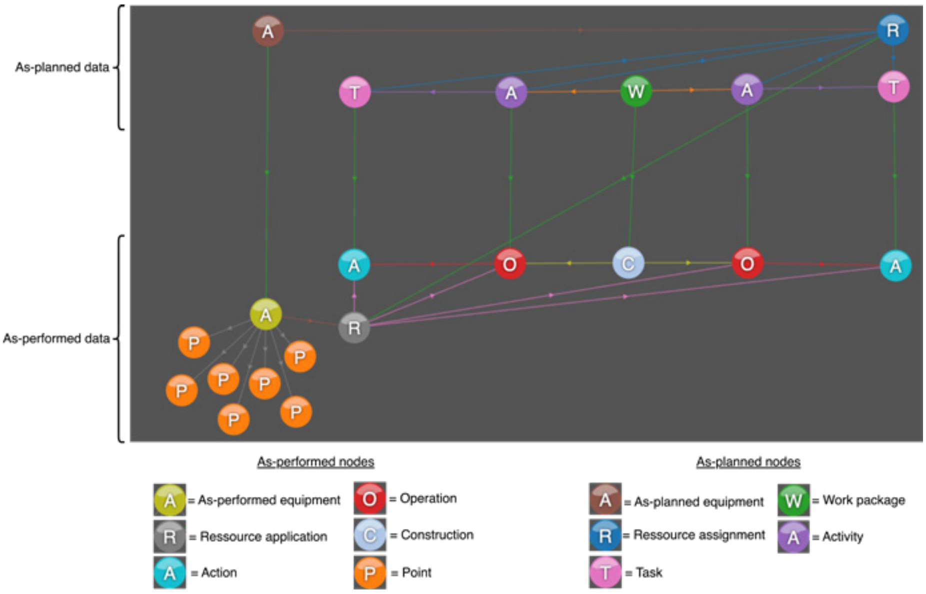


Figure 36. *The integration of as-Perfomed data for a piece of equipment that is linked to a delivery process is illustrated.*

To make this data accessible to a user, a visualisation tool was developed as part of WP6, which presents the data in a processed form. The IFC model, a map section and the equipment data are downloaded together with the corresponding GPS positions. This allows the user to track the movements of the equipment (Figure 37), but also to compare the planned processes with the processes that took place and to see whether, for example, the fulfilment rate for deliveries was achieved on a particular day (Figure 38).

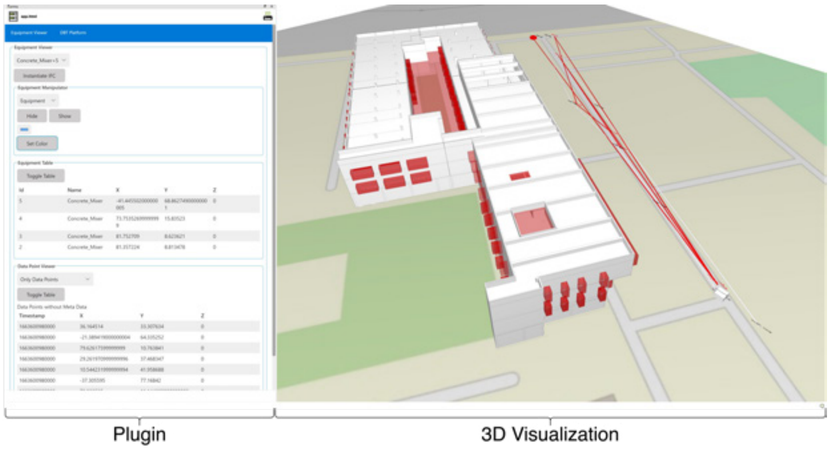
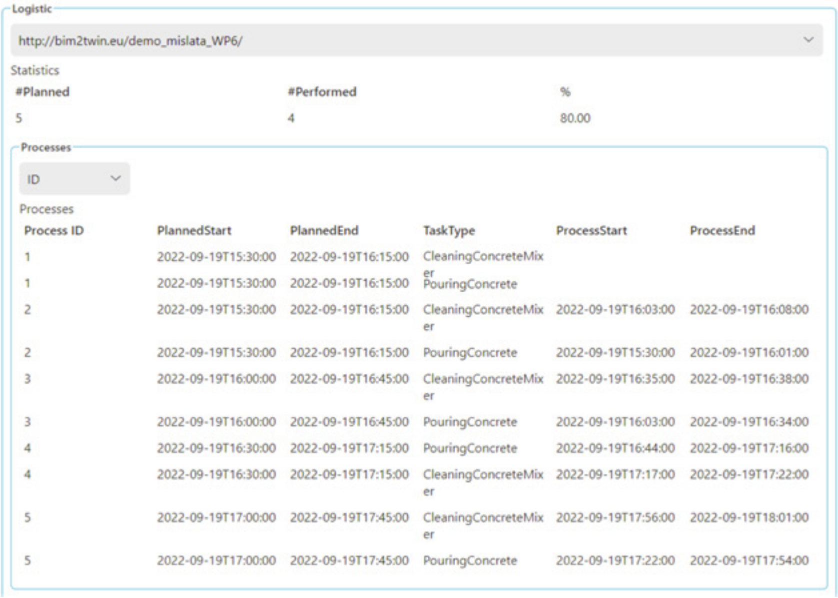


Figure 37. *This tool imports the IFC model and the equipment data, including the trajectories, from the platform and displays them together on a map. Within the 3D visualisation, a trajectory, marked in red, is visualised together with its metadata in the plugin window.*



#Planned	#Performed	%
5	4	80.00

Process ID	PlannedStart	PlannedEnd	TaskType	ProcessStart	ProcessEnd
1	2022-09-19T15:30:00	2022-09-19T16:15:00	CleaningConcreteMixer		
1	2022-09-19T15:30:00	2022-09-19T16:15:00	PouringConcrete		
2	2022-09-19T15:30:00	2022-09-19T16:15:00	CleaningConcreteMixer	2022-09-19T16:03:00	2022-09-19T16:08:00
2	2022-09-19T15:30:00	2022-09-19T16:15:00	PouringConcrete	2022-09-19T15:30:00	2022-09-19T16:01:00
3	2022-09-19T16:00:00	2022-09-19T16:45:00	CleaningConcreteMixer	2022-09-19T16:35:00	2022-09-19T16:38:00
3	2022-09-19T16:00:00	2022-09-19T16:45:00	PouringConcrete	2022-09-19T16:03:00	2022-09-19T16:34:00
4	2022-09-19T16:30:00	2022-09-19T17:15:00	PouringConcrete	2022-09-19T16:44:00	2022-09-19T17:16:00
4	2022-09-19T16:30:00	2022-09-19T17:15:00	CleaningConcreteMixer	2022-09-19T17:17:00	2022-09-19T17:22:00
5	2022-09-19T17:00:00	2022-09-19T17:45:00	CleaningConcreteMixer	2022-09-19T17:56:00	2022-09-19T18:01:00
5	2022-09-19T17:00:00	2022-09-19T17:45:00	PouringConcrete	2022-09-19T17:22:00	2022-09-19T17:54:00

Figure 38. *A section is integrated into the plugin window that displays all processes associated with the equipment in tabular form. This visualisation enables a direct comparison between the planned and performed processes.*

Results

The development of the system for data collection using camera technology represents an opportunity in the management and monitoring of construction site equipment. By combining stereovision cameras and computer vision algorithms, it enables the efficient collection of position and status information of construction equipment in real time. This provides a robust solution to the challenges associated with monitoring and controlling equipment usage on construction sites, particularly in terms of flexibility, safety, and cost optimisation.

The camera-based monitoring system was used at two pilot sites, Valencia (Spain) and Postiaukio (Finland), to collect data for the development of the algorithms and to test the system on a small and large construction site. **A total of 30 construction processes were documented at these sites.** Overall, the system made it possible to record and analyse GPS positions and monitor the status of construction machines on both the larger construction site in Valencia and the smaller one in Postiaukio. One limiting factor, however, is the restriction of tracking to the camera's field of view, which requires strategic planning of the installation locations. Positions near tower cranes are ideal, as these usually have access to power supplies and are close to important working zones such as loading, unloading, or concreting areas. In the future, it should be considered to implement a re-identification process that enables continuous tracking of machines across different camera areas and assigns a unique ID to each machine. However, this poses a significant challenge as construction machines rarely have unique, easily recognisable markings and often have similar visual characteristics, making it difficult to uniquely identify a particular machine.

Another problem is the detection of idle times using only this system, as differences in the operating status of the machines (engine on or off) cannot be detected using computer vision techniques. But it is possible to detect whether a machine is moving or not. In such cases, the use of IoT sensors could offer a solution, but the challenges mentioned at the beginning of the chapter should be considered. It should also be considered that cameras are equipped with an integrated IMU (Inertial Measurement Unit) and magnetometer to automatically determine the orientation of the camera and make any corrections in the event of positional deviations. It is also important that the GPS position of the camera is precisely determined during installation, as was made possible at the Postiaukio site by the RTK-GNSS system, as this has an influence on the calculation of the GPS positions to the equipment.

In summary, the system offers a viable and flexible solution that can transform the way construction companies monitor their equipment. It promises not only to optimise operations, but also to improve safety standards and reduce environmental impact through more efficient machine use in combination with data mining and process mining algorithms.

6. Proactive Production Planning and Control Service

Predictive simulation can provide planners with forward-looking situational awareness, allowing them to test various production plans and what-if scenarios without real-world consequences [Lappalainen et al., 2021]. This enables the anticipation of risks and preparation of mitigation strategies, leading to more resilient production systems. In essence, predictive simulation facilitates virtual prototyping not just of products, but of processes as well. It accelerates learning and experience generation, moving beyond the traditional model of learning once per project to a continuous learning process at any project stage. In the long term, predictive simulation can even evolve into a closed-loop optimization system for autonomous planning and control of construction sites [Sacks et al., 2020].

Currently, however, most construction firms use software tools that implement the Critical Path Method (CPM) for scheduling, relying heavily on experienced planners to set task durations and dependencies between tasks. However, the CPM model abstracts away much of the detail needed for production planning and control – it ignores the flows of materials, crews, locations and information on site that determine whether work can proceed or not, and it does not model the waiting times and the non-value adding activities. As a result, teams are left to react to plan failures, because they do not have the right tools to model production planning and control that are needed for proactive schedule updates [Koskela and Howell, 2002]. Furthermore, the assessment of schedule and production risks is often qualitative, or at best, relies on stochastic Monte Carlo methods applied to CPM project networks. This approach has significant limitations, particularly in ignoring the covariance between tasks due to resource co-dependency, the uncertainty in the values of production rates, crew return times, and other factors, and the influence of external factors like other projects running in parallel and competing for resources.

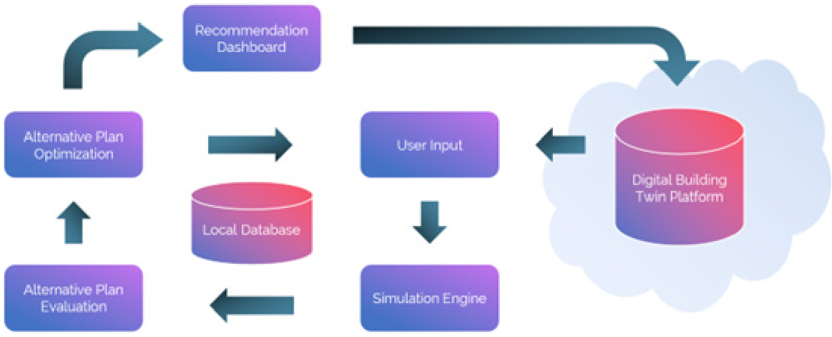
Methods

To overcome these challenges, innovation is needed in construction planning and management. Agent-based simulations offer a probabilistic alternative to the deterministic CPM model, and they correctly model the various flow of production on the construction site. In this framework, agents represent various elements of a construction project – from designers and workers to equipment and spaces. Programmed with behavioural patterns, the agents execute work as per the designed and planned models, resulting in emergent outcomes that can be measured in terms of cost, duration, quality, and safety. The product design and the construction process – the Project Intent Information (PII) – are represented in a Building Information Model (BIM) and the construction plan (work breakdown structure, location breakdown structure, site organisation plan and schedule). This way the tasks can be derived directly from the designs. Consequently, this ensures that the right building parts will be constructed at the right time.

Unlike traditional CPM planning and management, this approach of planning tasks by the BIM ensures that task dependencies are automatically built-in to plans, instead of needing to rely on planners' expertise of identifying dependencies. The current status of the project is provided in a Project Status Model (PSM), compiled using the various monitoring tools described in the earlier chapters of this white paper. The agent-based simulation can start from any given point in time, usually the latest known status date. Once initialized to the start date, the agents interact within the digital twin environment in accordance with goals set by the intent information model. This simulation can be run multiple times to explore the range of probable emergent outcomes. This is a powerful tool for predicting the outcomes of different design and plan alternatives. To date, however, the application of agent-based simulation in construction has been limited by a lack of data on behaviour and site environments and by the difficulty of compiling and maintaining accurate project status information [Abdelmegid et al., 2020].

Figure 39 illustrates the system architecture developed in the BIM2TWIN project for embedding predictive simulation within the Digital Twin Construction framework. Our system is composed of five main modules that synergistically provide decision support for construction production planning and control. The system is connected to two databases: the Local Database, which stores baseline production plans, the completed alternative plans with their evaluations, and visualization data; and the Digital Building Twin Platform, a graph-based online repository that stores the current project status and intent information.

Figure 39. *System overview for a predictive simulation system with a DBTP.*



Synergy with DBTP

The effectiveness of predictive simulation is inherently tied to its accuracy, which, in turn, depends significantly on the quality of the input data it utilizes. To avoid the pitfalls of a ‘garbage in, garbage out’ situation, it is imperative to provide the simulation with the most accurate and up-to-date information available. This encompasses two critical components: the current state of the project (Project Status) and the envisioned development (Project Intent). The role of the Digital Building Twin Platform (DBTP) becomes crucial in this context.

The DBTP functions as a centralized repository of verified information, ensuring that all stakeholders have access to a consistent and shared “source of truth” throughout the project’s lifecycle. It documents both the latest design and the production plan – what we refer to as Project Intent Information (PII). This ensures that any planning or decision-making is grounded in the latest project specifics. Furthermore, the DBTP integrates data streams from automated progress monitoring systems into a comprehensive PSM. This model offers a real-time snapshot of the project’s current state, detailing completed works and ongoing activities. Accurate reflection of the project’s status in the PSM is vital for establishing the correct starting conditions for the predictive simulation.

The predictive simulation leverages the PII not only to assess current plans but also to generate and evaluate alternative production strategies and ”what-if” scenarios. This ability to simulate different approaches in a risk-free environment is invaluable for strategic planning and decision-making.

Lastly, the continuous accumulation of data from various projects into the DBTP paves the way for the creation of a historical digital twin database. Such a database can be instrumental in calibrating the simulation’s parameters, like production rates, on the basis of real-world data and trends observed across multiple projects.

Defining Alternative Plans

In construction planning, a broad range of parameters must be considered to devise alternative plans. These parameters include labour, equipment, materials, logistics, work breakdown structure, and location systems, each critical for project efficiency and effectiveness.

Labor considerations focus on production rates influenced by worker skill levels and production methods. Enhancing production rates can accelerate project completion and efficiency. Additionally, the configuration and size of crews, as well as the distribution of crews across different trades or contractors, are vital. Adjusting these factors enables simultaneous workflows in various areas, speeding up the project. Furthermore, training crews in multiple trades (multi-skilling) enhances workforce flexibility, increases utilization, and reduces unnecessary movement. Equipment use, specifically the type and quantity of machinery and tools like cranes and elevators, plays a significant role in project progression.

Optimizing equipment utilization can enhance process efficiency and shorten project durations. Material and logistics management involves decisions about material delivery sizes and frequencies, and inventory buffer sizes. Planners also choose between push or pull material delivery strategies, impacting on-site material flow and construction costs and efficiency. Modifications in construction methods and product designs can lead to adjustments in the work breakdown structure, such as task dependencies, significantly affecting project timelines and resource distribution. Finally, the choice of location system, including various zoning strategies and resolutions (e.g., floors, zones, apartments, rooms), profoundly affects on-site work organization and execution.

Figure 40 shows the User Input Module that captures the user's input data to select the most appropriate alternative production plans for the simulation.

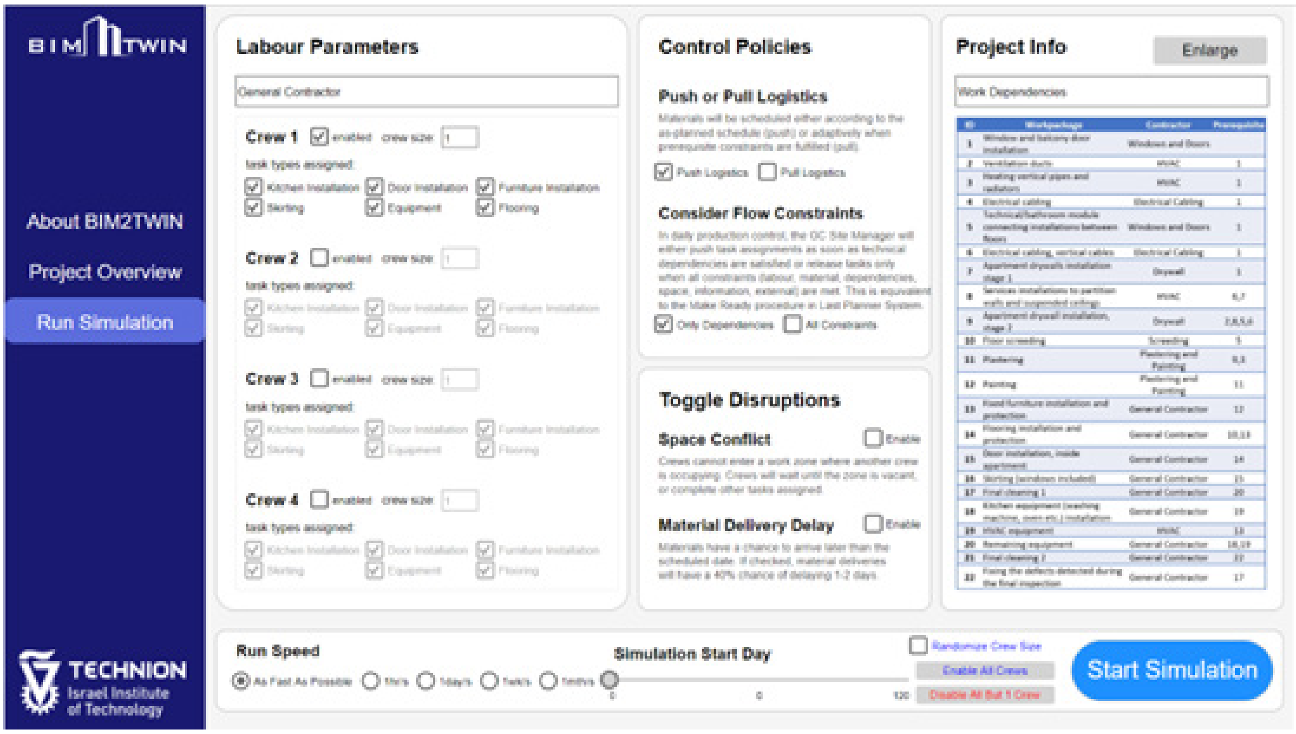


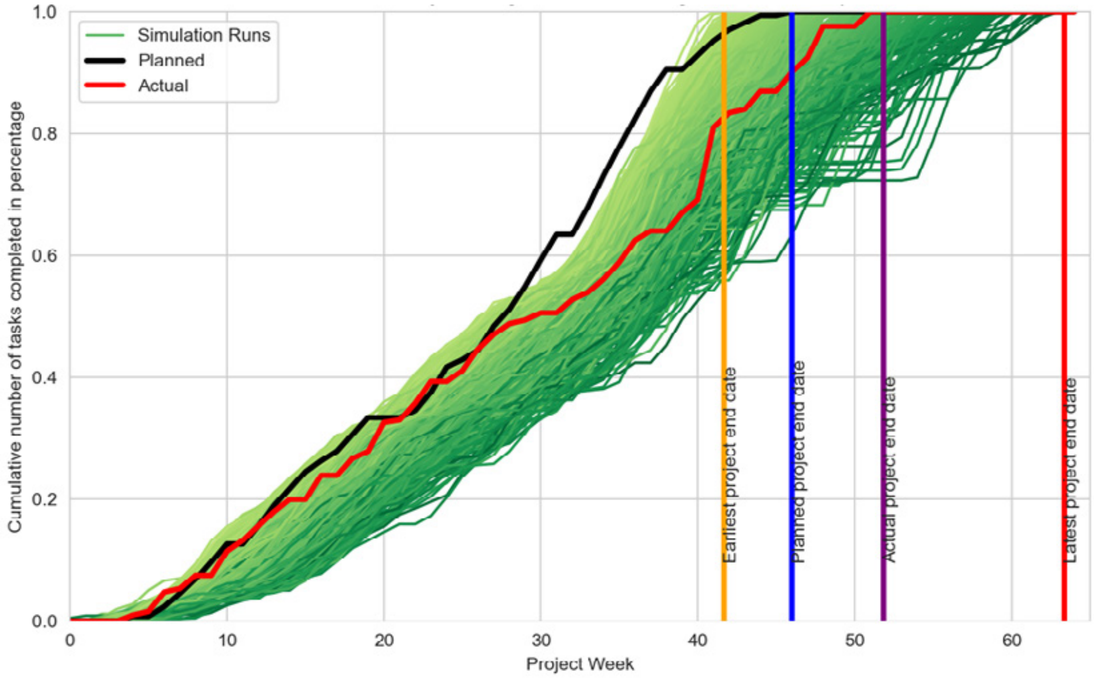
Figure 40. *Interface to define alternative production plans.*

Agent-based Stochastic Simulation Engine

While planners have a wide scope of actions to explore in their production planning, the complexity and sheer number of variables involved often make it challenging to consider them all effectively in day-to-day planning. For an average-sized residential project in Europe, with about 20 work packages, there could be several million possible plans derived from these variables. Identifying the optimal plan out of this multitude solely based on intuition is virtually impossible. Therefore, planners often resort to best practices and rules of thumb, altering only those elements that are tangible, obvious, and intuitive. This is where simulations can play a transformative role, helping planners navigate this vast solution space to identify a few optimal plans worthy of consideration.

The Simulation Module is configured with agent behaviour specifications and implemented using AnyLogic® software. It simulates alternative plans stochastically multiple times to get a fan of possible results (Figure 41 shows an example). Subsequent to the simulation, the Alternative Plan Evaluation Module processes the raw outputs, evaluates the performance of each plan, and assembles decision aids and KPIs. The Alternative Plan Optimization Module uses optimization algorithms to create and refine additional alternative plans based on the evaluation results.

Figure 41. *Progress trajectory of 500 simulation runs (green) plotted against the planned (black) and actual (red) progress.*



Proactive Recommendation Dashboard

The Recommendation Dashboard Module (Figure 42) displays the simulated production plans alongside their evaluations, enabling users to make informed decisions for the upcoming production cycle. The simulation results can also be visualized in 4D (Figure 43) so planners can visually compare the outcome of different production plans.

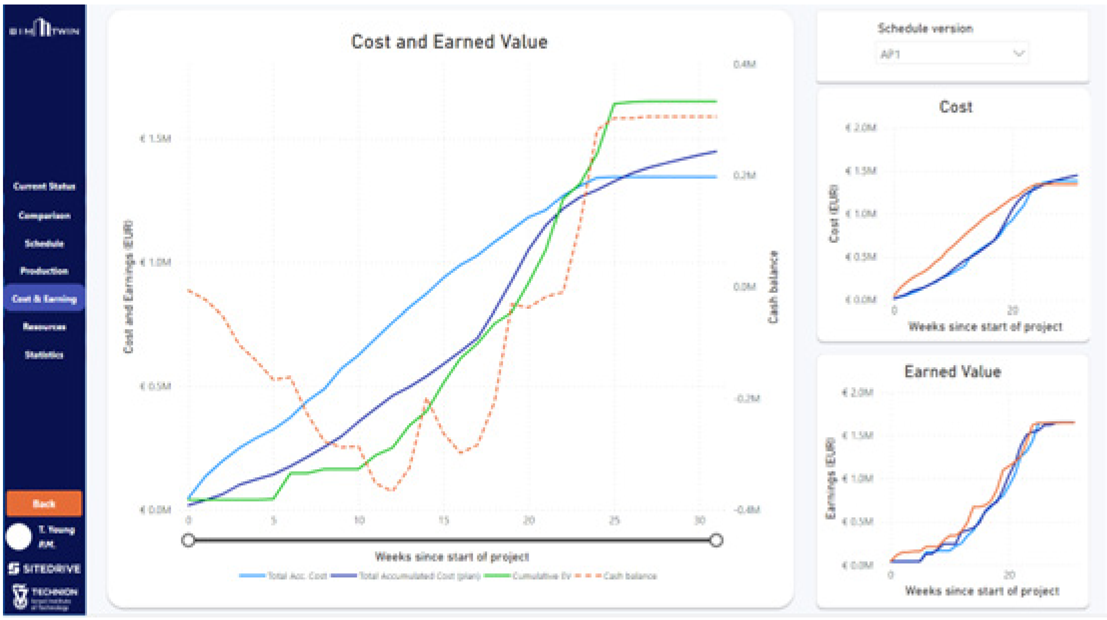


Figure 42. *Recommendation Dashboard in PowerBI.*

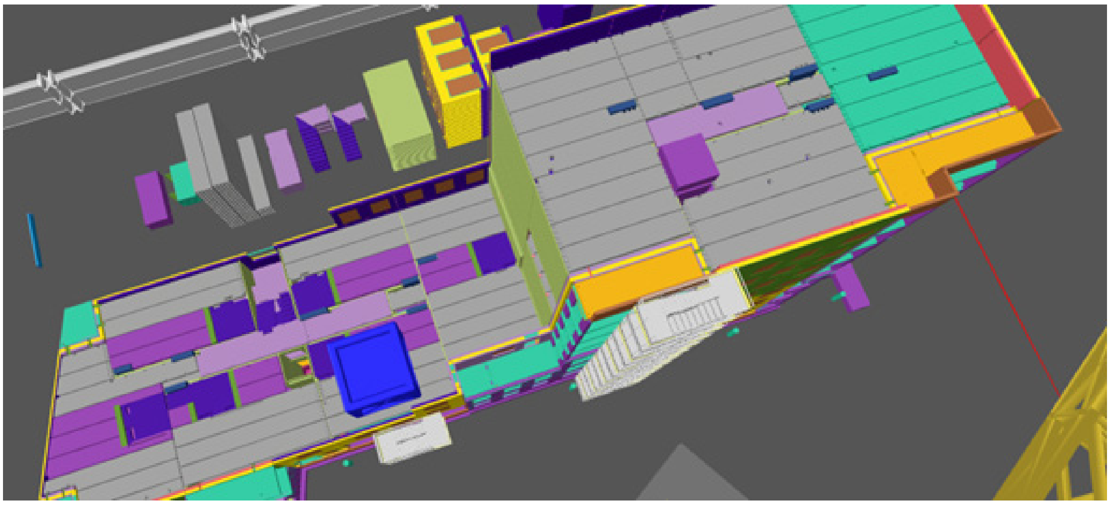


Figure 43. *4D visualization of the simulation during the frame erection phase of the Postiaukio pilot project.*

Results, Learnings, and Conclusion

The effectiveness of the predictive simulation system is highly dependent on the availability and quality of project status and intent information housed in the Digital Building Twin Platform (DBTP). Our experience shows that the system's integration with the DBTP is not only feasible but also creates a synergistic relationship, particularly when combined with automated progress monitoring, culminating in a closed-loop system.

To date, the application of our system to a real-world project has yielded a 70% accuracy rate in simulation predictions. This level of precision has provided practitioners with greater confidence in their decision-making processes and fostered an optimization-centric approach to project management.

Despite these advances, several challenges remain. Further research is required to enhance the fusion and interpretation of data streams from automated progress monitoring, aiming to improve the quality of the Project Status Model within the DBTP. Additionally, the simulation's validation process demands a more substantial accumulation of high-resolution historical project status records.

There is also a pressing need to refine how we systematically derive actionable insights from simulation results. Doing so will substantially increase the utility of the information stored within the DBTP, turning data into decisions that can drive project success.

7. Pilot Demonstrations

One of the most important tasks of the demonstration task was to plan the demonstration activities in the different construction sites. Firstly, it was necessary to define the characteristics and the key attributes of the possible pilot projects. At the beginning, each construction company proposed one pilot project to perform the demonstrations; however, when the demonstrations approached, some of the construction sites were not available any more due to a series of setbacks, such as changes in the schedule or duration of some works. Thus, new pilot projects were required.

In this research, some important constraints appeared and made the demonstration phase more difficult:

- The average contract time of contractors, which is significantly shorter than the demonstration period.
- The long period before the demonstrations were scheduled to start, since some of the contractors can't foresee which projects will be at the construction phase so far in advance.
- The long bidding process period and uncertainty of contracts.
- The long demonstration period, which takes place over twenty-two months.

Therefore, it was decided that more than one pilot project would be needed per construction company.

As a result of this process, a framework with all the information needed to select the different demonstration projects was developed. This document was called the "**Demonstration Passport**" and it aimed to collect information about the building and the monitoring needs from the use cases; its purpose was to gather as much information as possible, to be able to prepare for any event and ensure a smooth demonstration between the partners and construction workers. It consists of structured templates for the partners to register thoroughly their information to be assessed at any time of the project. It is divided into four different sections: demonstration activities, building information, implementation, and other information relevant to the project.

This template was meant to be used by all partners; some of them must be responsible for filling in the information that others will later use as a common source of information.

Figure 44. *Demonstration Passport and its sections.*

Pilot Definition

The construction companies and project partners, **Fira, Spada and Acciona**, are located in Finland, France and Spain, respectively. This already gives the demonstration a broader range of applications since each company has its own practices and local context. Besides, the pilot projects provided for the BIM2TWIN project have different typologies of uses and construction technologies which also enrich the results. Each company has proposed different pilot sites due to the constraints already mentioned to host the demonstration of the different use cases developed by the technical partners; however, not all the sites were finally used as demonstration scenarios or to collect data.

Finnish Pilots

Fira provided different possible pilot projects, of which two were used intensively. The first one was the **Kivitasku pilot** (Figure 45), which is a new apartment building located in Vantaa, Finland.

The building is composed of three parts with their own access and a total of 136 apartments. Part A has six floors, and parts B and C have seven floors. The frame is made with precast concrete elements, while the foundations are in-situ cast concrete on the ground. The building has a large extent brick façade supplemented with some painted precast sandwich element panels. The roof is flat in shape with roofing felt made of bitumen.

The pilot was under construction during the first demonstration round with earthworks, most of the frame installations and some preparations of the inner phase made. The total duration of the project was about 15 months.

After the first demonstration, new raw data was needed, and Fira provided a new demo building. The **Postiaukio pilot** (Figure 46) also consists of a residential building, located in Helsinki, Finland. The building is composed of a total of 61 apartments on seven floors. In addition, there are commercial premises on the first floor. The frame is built with prefabricated concrete elements on a footing foundation. The bathrooms are prefabricated volumetric modules. The building is also attached to district heating. The façade is partly laid of bricks and partly plastered. The inner phase of the construction was carried out as takt production. A major part of the construction was done between the first and second demonstrations.

Figure 45. *Kivitasku pilot site.*

Figure 46. *Postiaukio pilot site.*

French Pilots

The pilot project proposed by Spada consisted of a restructuring and expansion of the "**Immeuble Favasuli**" building complex in Nice, France (Figure 47). The objective of this restructuring is to transform only the ground floor (and the basement) without touching the four upper levels which are not only made up of flats but also remain occupied by their occupants during the works. The very particular and delicate technical aspect of the operation on this site lies in the fact that it is necessary to raise the four occupied floors of the building during the period of the works. To do this, the original structure was reinforced with steel structures. Moreover, there is a monitoring system that continuously measures the position (and lack of movement) of the upper floors.

The works on this site were going slower than planned and only small demolition works on a small building in the backyard have been done; the only data collected was gathered before the first demonstration.

Figure 47. *Favasuli pilot site.*

Spanish Pilot

Acciona also provided several pilots, of which we used a Hospital in Valencia (Figure 48). This project consists of the rehabilitation and expansion of the Hospital. Two new buildings would be erected after demolishing the existing ones and will extend the height of the covered circulation galleries that connect all buildings. The construction methodology consists of reinforced, cast-in-place concrete for the structural part. The façade will be cladded, with interior masonry walls and external ventilated wall – metallic structure and ceramic plaques. Also, it will have interior partitions of dry walls.

Between the first and second demonstrations, the construction went from foundation works to the finishing phase and installations.

The aim of performing a series of demonstration sessions was to evaluate the behaviour of the DBT platform from the end users' point of view, considering the use cases developed by the technical partners and the Key Performance Indicators (KPIs) identified at the beginning of the project and to improve the functionalities and the platform itself. To that end, two rounds of demonstration have been carried out: the first one in February 2023 and the second one in September 2023. Both rounds involved the three construction companies, Fira (Finland), Spada (France) and Acciona (Spain), the platform developers and the technical partners.

Also, both demonstrations had a similar organising process which included performing the implementation in the real sites, executing the platform with real users and evaluating its behaviour through a survey. The group of users that evaluated the platform was formed by different professional profiles which enriched the final result; there were project managers, technical office managers, quality control technicians, security prevention managers, surveyors and engineers.

Figure 48. *Valencia pilot site.*

Validation of Results

First demonstration

The first demonstration session took place in February 2023, but the preparation procedures began way before. Due to that, many partners have visited different pilot sites on several occasions to deploy their acquisition equipment and collect raw data from the real sites. It aimed to show, for the first time, the status of each BIM2TWIN functionality, the platform and the dashboard to the users; they also should be able to operate it and see the potential of these tools.

The implementation plan included several activities to properly evaluate the DBT platform and its technical functionalities. First of all, the functionalities should be partially integrated with the platform and the dashboard, and each WP should have prepared a user guideline to perform the different developments. After that, a training session was organised for the partners to understand how to operate the platform during the demonstration sessions. Finally, each WP developed a survey to collect the users' feedback to improve their technologies.

This round of demonstrations was held simultaneously in the three construction companies. At that time, the dashboard KPIs were partially calculated and most of the input data came from real historical data or mock-up data. In each of the pilot sites were the pilot project partners (Fira, Spada and Acciona) and the designated partners, a group of partners who collaborated on the presentation of the developments.

Table 1. *Organisation of the First Demonstrations.*

Pilot Project	Pilot project partner	Designated technical partners	Dates
Valencia-Spain	ACCIONA	TECNALIA, IDP	14th – 15th of February 2023
Favasuli-France	SPADA	INRIA, CSTB	13th, 14th and 20th of February 2023
Kivitasku-Finland	FIRA	TUM	14th – 15th of February 2023

During the sessions, the different partners explained the DBT platform, the dashboard and the functionalities through presentations for the users, followed by a survey to establish measures for the platform and requests for functionalities improvements.

Figure 49. *1st Demonstration.*

Kivitasku - Finland

Favasuli - France

Valencia – Spain

The overall overview of this first round of demonstration was qualified as really positive by the end users; it has been remarked that it was very interesting to collect, digitalise and synthesise all the data involved in a construction site in one common platform using digital twins for construction management. Also, they all agreed on the great value of the functionalities proposed since this would simplify their working procedures, and they were convinced on the future viability and practicability of the DBTP. However, it has been noticed the necessity of more interconnection between the different technologies developed by the technical partners and the need of a more comprehensive storytelling of the project to convey a coherent message of the BIM2TWIN project. Having this in mind, the second demonstration session preparation started with these important conclusions: a special focus on the usage of the BIM2TWIN environment by the end users, and the integration and interconnection of all APIs between them and the DBT platform.

Second Demonstration

The second demonstration aimed to evaluate the BIM2WTIN environment considering all the remarks and improvements highlighted in the first round of demonstrations. The activities of this demonstration started immediately after the first one; several actions were organised to continue the ongoing work in developing the technologies and trying to integrate them with the other functionalities, the platform and the dashboard. Acciona, as the demonstration task leader, organised different meetings and workshops to coordinate all WPs, and also, some site visits were organised to collect new data, install new devices or do some on-site tests. As mentioned above, the speed of the construction process is not aligned with the BIM2WTIN project schedule; therefore, in this second demonstration, a new pilot project has been used to collect data.

This demonstration was decided to be performed as an online session which enabled to show the new version of the BIM2WTIN environment, the interaction between all partners with all construction companies, and the exchange of different opinions from different construction typologies and construction processes and methodologies; all partners were able to participate simultaneously in the same demonstration session, and each WP could present their work to all users and show their APIs in real-time. This demonstration took place between the 26th and 28th of September 2023 and it allowed site users to see how virtually operate the functionalities, the platform, and the dashboard, using historical data from the different pilot sites.

For this second round of demonstration, the format of these sessions was modified; it was decided to perform a coordinated presentation, showing the DBTP integrated functionalities, according to the different use cases, remarking on the connections between them. Also, each WP performed a virtual test of their API and finally, they gathered the users' impressions through a survey.

To coordinate all the functionalities with the platform, it was necessary to properly define the different workflows of the APIs and the dashboards for the final user.

The integration process was coordinated by creating a series of diagrams where each technical contribution could align with how end user should use the different functionalities of the platform, and organise the different information with the final user in mind.

Table 2. *APIs interconnections.*

Installed Devices	**Input Data**	**End User Action**	**Output Data - Results**
Where to Install the devices?	Where does the data come from? Where to upload the data?	Steps we should follow in the Platform	Where to download/see the data from? Is the data useful for other technical services?

The general impression of the users was that the BIM2WTIN project has been improved according to the first round of feedback collection and they validated the relevance of the core concept of the platform and its services. They also considered that the BIM2TWIN is very useful in its services and visualization tools, and it has a solid base with great potential for its use in the construction sector once refined.

8. Discussion

As we have seen in the previous pages, BIMTWIN has succeeded in developing several service components and interconnecting them. The project activities have progressed a long way in proving the feasibility of the Digital Twin Construction (DTC) paradigm, as outlined in the Introduction. This chapter summarizes the discussion around these developments and highlights the most important points regarding the observations and recommendations that can be drawn from this research project.

DBT Platform

The main component, the DBTP, was developed around **two important axes**:

- **Ensuring the semantic coherence of the information collected from the various services connected to the platform**: this point required significant effort to obtain a single data model covering the needs of each service. The ontology resulting from this work was produced over several cycles.
- **The use of a single technology to represent all this information and enable its exploitation**: the central data storage solution is based on a triple store.

However, to initiate the system for each of the sites for which the solution was deployed, significant coordination and adjustment work was required to integrate the input information (BIM and Planning) and make them interoperable. Once this preliminary work was properly done, the BIM2TWIN solution demonstrated its full potential by allowing one service to reuse the data produced by another service. It is important to emphasize at this stage the need for practices and supporting tools to ensure, in a native way, coherence between the tasks in the schedules and the elements associated with these tasks in the BIM.

The difficulties encountered in the task of aligning BIM and planning seems to stem from a lack of practice and perhaps a lack of properly adapted tools because BIM and IFC not only support the description of a building but also allow for a detailed description of the tasks and resources assigned to its construction. The problem here highlights the many-to-many relationship between work packages and physical building objects, but also the fact that a BIM model for construction can be quite different to a BIM model produced in a design process. They differ not only in the level of development (designs are usually LOD 200, whereas construction data will be at least LOD 30), but also in their aggregation – decomposition relationships. A long wall in a design model may be broken into a number of separate wall panels for production off site, shipping and installation; the finishes on these walls might also be quite different, with a commensurate impact on the need or modelling different layers of the wall that are applied at different times in the production process. Some work packages may need only a single surface of a single object representing the work package (such as a column surface for painting) whereas the rest of the object ma remain unaffected.

The project demonstrated that achieving our digital twin solution was not only a question of individual integration of Digital Twin Services (DTS) into the DBTP but the successfully combination of services to gain additional insights into the current status of the construction site. The services must profit from each other's results to produce more meaningful insights. As a consequence, this integration must be well prepared and requires prior work to identify the connection points among the services, and a clear definition of their requirements. In other words, the effort dedicated to the elaboration of a common data model (ontology) and the use made of the semantic technologies (the graph-based data base) have been decisive choices in enabling the integration of services and to be certain that the BIM2TWIN solution can be easily extended by adding new services, which will benefit from the existing information and will be able to use it to their full potential.

Degree of Automation

When thinking about digital twins, many people have fully automated systems in mind that reduce the amount of human work to the bare minimum. While it is feasible for other industries that produce the product to be twinned in controlled conditions in large quantities, this vision is not yet within reach for DBTs.

The construction industry differs from others because every construction project results in a unique building. Even though the same building design might be used multiple times, there will be differences in the location of the site, the possible delivery routes, the weather conditions, or the subcontractors and other stakeholders that are part of the project. For these reasons, it is not possible yet to implement a fully automated DBT that can cover many types of building projects from various construction companies in different parts of Europe. This makes it essential to weigh the costs of automation against the cost of the human work required to perform some processing steps manually. While some data can already be evaluated automatically, other data require human interaction for evaluation or can only be automated with disproportionately high costs.

Three main aspects were identified within the frame of BIM2TWIN, where significant manual effort was required to set up or operate the digital twin. First, the lack of a standard exchange format for schedules and resource assignments makes the automated interpretation of this information very difficult. There are significant differences between construction companies and even projects in terms of the scheduling methodology used, level of granularity, and other aspects. Also, for an automated linking of processes with elements from the IFC file, automated process interpretation is necessary. Second, the raw data collection often still requires manual intervention, e.g., for performing terrestrial laser scans. While there are methodologies on the horizon that investigate full automation, they still lack accuracy or come with high additional costs. Finally, data pre- and postprocessing steps, e.g., the global registration of point clouds with high accuracy, still require occasional intervention in an end-to-end pipeline. However, the advancements in research are gradually closing these gaps.

Service Integration and Cross-Service Interactions

Following the successful integration and demonstration of individual Digital Twin Services into the DBTP, the BIM2TWIN consortium sees great potential in combining an expanded set of services to gain additional insights into the current status of the construction site. To capture the status of the construction site holistically, it is not sufficient to analyse raw data in a siloed fashion. The services must profit from each other’s results to produce more meaningful insights. This is, however, a time-intensive task since it requires a prior independent integration of the services data, identification of the semantic and logical relationships between the data points, and a clear definition of the intelligent information processing requirements. Within the scope of BIM2TWIN, this was achieved only to a limited extent. Nevertheless, the strict data structures were identified as the essential basis for seamless interoperability between different services.

Process Monitoring Service

In order to closely follow the progress made on-site, different techniques have been used. The combined use of 3D scanners and 2D cameras was designed to test an alternative to inspection processes based on expert intervention. The aim was to determine whether using this technique would save time, improve quality, and increase productivity. The results obtained during the project showed that it is possible to develop a user-friendly solution that combines the use of 3D scanners and cameras for on-site acquisition with web-based tools for processing the data. This method gives good results for process monitoring.

The method based on image analysis alone also gave good results in terms of process monitoring. The solution deployed is totally device independent. It requires a web browser to allow access to the service. Nevertheless, the accuracy reached is not at the expected level. This is mainly due to the limited accuracy of the GPS data.

Quality Control Service

Even if the combined use of 2D and 3D instruments gives good results in terms of process monitoring, the accuracy of the acquisitions does not yet allow one to go beyond simple recognition (applying filters to dimensional tolerances would not make sense) and therefore does not benefit quality checking. Nevertheless, the market for these kinds of devices is booming and technical AI based solutions may emerge. The accuracy issues should be resolved in the medium term.

One important aspect with the solution developed during the project was the ability of this service to link KPI values to pictures and allow the sites managers to keep track of the default/cracks captured on-site. However, the surface control suffered from technical bottlenecks (devices not designed to be manipulated easily in "on-site" conditions, the need to balance between accuracy and size of the acquisition files, etc…). AI based solutions continue to be a very promising track but the method requires a huge amount of training data to be properly tuned, and that was not feasible in the scope of this project.

Occupational Health and Safety Service

The development around the OHS theme has produced interesting results by:

- Improving "structural" safety: By importing a BIM of a building under construction at a given time, it has been possible to generate a model called "SafeBIM", which detects hazardous areas in the structure under construction and automatically adds safety elements to prevent the risk of falls.
- Improving "active" safety: in addition to the hazardous areas identified from the BIM, analysis of the schedule also makes it possible to identify areas made hazardous by another team working in another place at the same time. For instance, the work of a teams made at a higher storey, just above another one at the same time could lead to hazardous situations. This "active safety" can be easily extended with the connection of the current solution to extra devices enabling a localised representation of workers' movements on the site. This tool could be linked to other sources of information (crane bucket movements, for example) to identify potential risk zones and create warning systems to minimise workers' exposure to risk.

Equipment Optimisation Service

The system developed during the project is capable of recognising and locating construction equipment. The combination of a simple acquisition system coupled with vision algorithms works well. One limiting factor, however, is the restriction of tracking to the camera's field of view, which requires strategic planning of the installation locations. This aspect should be considered to implement a re-identification process that enables continuous tracking of machines across different camera areas even if it remains a significant challenge to differentiate construction machines having similar visual characteristics.

It is also worth mentioning that such a solution can be complemented by using other sensors (IoT) to detect if equipment that is not in motion is still in use.

In summary, the system offers a viable and flexible solution that can transform the way construction companies monitor their equipment. It not only promises to optimize operations but also to improve safety standards and reduce environmental impact through more efficient use of machinery combined with data exploration and process algorithms.

One might achieve better results for the overall DTC system by considering the possibility of communication exchanges between independent BDTCs. In the case of construction equipment, a separate Digital Twin platform for the equipment itself could be applied to monitor and optimise its performance.

Proactive Production Planning and Control Service

The effectiveness of the predictive simulation system is highly dependent on the availability and quality of the project status and intent information stored in the Digital Building Twin Platform (DBTP). Our experience shows that integrating the system with DBTP is not only feasible but also creates a synergistic relationship, particularly when combined with automated progress monitoring, resulting in a closed-loop system. To date, the application of our system to a real-world project has yielded a 70% accuracy rate in simulation predictions. This level of precision has provided practitioners with greater confidence in their decision-making processes and encourages them to focus on optimising project management.

Despite these advances, several challenges remain. Further research is required to enhance the fusion and interpretation of data streams from automated progress monitoring, aiming to improve the quality of the Project Status Model within the DBTP. Additionally, the simulation's validation process demands a more substantial accumulation of high-resolution historical project status records.

There is also a pressing need to refine how we systematically derive actionable insights from simulation results. Doing so will substantially increase the utility of the information stored within the DBTP, turning data into decisions that can drive project success.

BIM2TWIN System Demonstration & Validation

The BIM2TWIN System demonstration and validation was a long phase of the project that started a few months before the demonstrations took place. Therefore, a great part of this stage was about coordinating the work developed by the different partners, planning the demonstration sessions, and always considering the requirements established at the beginning of the project.

One of the key points of the project was the pilot selection and all the constraints associated with it. To solve this issue, a demonstration passport was created; it was a framework that would allow all the information about the demonstrations to be filled in throughout the project and on-demand, with two main levels of information: the building information and the monitoring needs from the use cases. This would let to gather all demonstration information in one document. The demonstration activities were associated with different projects from the construction companies located in different countries. This enriched the final result, but also it required a great effort to manage expectations from the technical providers and construction sites, as they have different visions of the processes.

The main objective of the demonstration was to show the users the development of the B2T System, integrating all the APIs with the platform and showing the possible results through the dashboard and the 3D viewer tool. Throughout the different demonstration sessions, the users remarked on the necessity of having a flexible and easy-to-operate system to be adjusted to all particularities of the different construction companies. Also, all the functionalities and the platform should work as a unique entity sharing all the information between them; in fact, this is the innovative factor of BIM2TWIN, that all functionalities work collaboratively. Overall, users showed great interest in the topic and huge potential in the B2T system, which confirms the relevance of this project.

Conclusions

The BIM2TWIn project's research team has progressed a long way in proving the feasibility of the Digital Twin Construction (DTC) paradigm, as outlined in the Introduction.

In the broad picture, we have shown that it is possible to:

1. **Sense, interpret and provide users with information that builds situational awareness of the site, within a short time frame, and with little latency.** The situational awareness encompasses:
    a. construction progress,
    b. quality control,
    c. construction safety conditions
    d. performance of major construction equipment
2. **Predict outcomes of alternate production system plans and provide the results to decision-makers to support them in optimising the production control on site.**

Situational awareness concerns the current state of the project, while predicting outcomes concerns the possible future states. Knowledge of each of these empowers construction managers, who – it is reasonable to assume – can apply that knowledge to the goal of improving production flow, schedule conformance, construction quality, health and safety, and to reduce the environmental impacts of their projects.

Recommendations for the Construction Industry

Naturally, a research project such as BIM2TWIN cannot produce a commercial production control system, nor is it intended to do so. Instead, the project aimed to demonstrate how a variety of monitoring technologies and intelligent software applications could be applied in unison, as a cohesive system, to achieve Digital Twin Construction. The success in deriving the requirements, developing prototypical implementations of the system's components, in integrating them around the Digital Building Twin Platform, and in demonstrating their effective use in concert, leads to two recommendations for industry:

1. **Firstly**, we propose that the business value of DTC is to be found in the integrated system rather than in any single component. The reason for this is that situational awareness is only valuable if it is comprehensive. For example, knowledge of the status of the products on site is insufficient for adjusting the production system – we need information concerning the resources used to achieve that status, so that we can assess productivity and the quality of production flow. Companies in the Construction Tech industry are therefore advised to focus on providing comprehensive monitoring, evaluation and production planning systems, based on data from multiple monitoring sources and on AI routines for fusing/merging the data and interpreting it to provide useful information.
2. **Secondly**, the successes of monitoring project progress, quality and safety, although narrow in scope, suggest that construction companies should pay increasing attention to the developments in Construction Tech hardware and software, as these systems will be game-changers in terms of determining a

construction company's productivity ad hence their competitiveness in the market.

3. **Thirdly**, integration of information systems requires formal standards to ensure that the products of Construction Tech companies can plug-in to DTC information platforms and can be used interchangeably. The BIM2TWIN ontology is the first of its kind to define the specific information needs, including as-designed, as-planned, as-built and as-performed information. The BIM2TWIN ontology could serve as the basis for an industry wide ontology for DTC.

Potential Areas for Improvement

During the project, we deployed a solution implementing the principles of a digital twin for monitoring site activity. With the limited resources at hand, the system components developed in BIM2TWIN are at best alpha prototypes. Each could be greatly improved both technically, int terms of user friendliness, and in terms of overall system integration. Almost all the services we have developed and tuned using artificial intelligence technologies to perform shape recognition, position recognition or alternative planning calculation & predictions. But these algorithms need to perform extra learnings being thus able to recognise other building components, to be more accurate, etc.

Future Research

Around the main component represented by the BDTP, five technical services were not only developed but also connected to the platform so that each of these services could take advantage of the information collected or produced by the others. During our demonstration phases, we were able to prove the complementary nature of these services and the benefits of linking them together in order to provide the situational awareness that we had originally sought.

> There are undoubtedly practices that need to evolve to facilitate the transition between the design and construction phases and these practices should be supported by dedicated software solutions.

Nevertheless, there is still room for various improvements. If the construction lifecycle is considered, the BIM2TWIN project takes place between the design phase and the exploitation phase. The design phase produces the input files (BIM & Planning) that are needed to initiate our digital Twin. To take these input data into account, components have been developed enabling their injection in our system. But this has required time and effort to align the two sources of information. In the current practices, the teams that produce the BIMs and the construction plans, although they be employed by the same company, do not coordinate their work. As a result, the plans we handled, with described tasks, resources, and construction elements, had different identifiers for these elements than those used in the BIM. We had to align them manually. There are undoubtedly practices that need to evolve to facilitate the transition between the design and construction phases and these practices should be supported by dedicated software solutions.

The second challenge to be considered for future research is the transition between the construction phase and the exploitation phase. By tracking and recording all the events occurring during the construction phase, BIM2TWIN is in a position to produce a digital logbook of the project. All the data recorded are also contextualised thanks to the data model. One key challenge would be to think about the best ways to re-use this information when deploying digital twin environments for the exploitation phase.

References

Introduction

- Sacks R, Brilakis I, Pikas E, Xie H. S and Girolami M (2020). Construction with digital twin information systems. Data-Centric Engineering, 1: e14.
- Buchmann, A., and Koldehofe, B., "Complex Event Processing." - Information Technology, 2009, 51(5).

Chapter 1 – Digital Building Twin: The Platform

- T. Coupaye, G. Privat, F. Ottogalli, P. Raipin-Parvedy, A. Camus, and S. Bolle, "Thing'in – The Web of Things. The Thing'in research platform. Graphing the web of things, together!," White Paper, May 2018, [Online]. Available: https://www.thinginthefuture.com/IMG/pdf/thing_in_whitepaper.pdf.
- A. A. Akanmu, C. J. Anumba, and O. O. Ogunseiju, "Towards next generation cyber-physical systems and digital twins for construction," Journal of Information Technology in Construction, 26(July), 2021, 505–525, https://doi.org/10.36680/j.itcon.2021.027.
- R. Ackoff, "From data to wisdom - Presidential address to ISGSR, June 1988," J. Appl. Syst. Anal., vol. 16, pp. 3–9, 1989, [Online]. Available: https://www.scirp.org/(S(351jmbntvnsjt1aadkposzje))/ reference/ReferencesPapers.aspx?ReferenceID=713373.
- J. Schlenger, A. Borrmann, T. Yeung, J. Martinez, R. Sacks, and N. Bus, "Digital Twin Construction Ontology," November 2023, [Online]. Available: https://dtc-ontology.cms.ed.tum.de/ontology/.
- buildingSMART International, "Industry Foundation Classes (IFC)," 2024, [Online]. Available: https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes/.
- W. Huhnt, "Process modelling in civil engineering," Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE), 2009, 19(1), pp. 91–101. https://doi.org/10.2749/101686609787398317.
- V. Franz, "Unikatprozesse und ASIM-Aktivitäten - Bericht von der Arbeitsgruppe Unikatprozesse," Forschungsworkshop zur Simulation von Bauprozessen, 2010, pp. 5–16, Bauhaus-Universität Weimar Fakultät Bauingenieurwesen.
- V. K. Reja, K. Varghese, and Q. P. Ha, "Computer vision-based construction progress monitoring," Automation in Construction, 2022, 138, 104245. https://doi.org/10.1016/j.autcon.2022.104245.
- K. Mostafa, T. Hegazy, "Review of image-based analysis and applications in construction," Automation in Construction, vol. 122, 103516, 2021, https://doi.org/10.1016/j.autcon.2020.103516.

Chapter 2 – Progress Monitoring Service

- Arif, F., Khan, W. A., (2021). Smart progress monitoring framework for building construction elements using videography–MATLAB–BIM integration. International Journal of Civil Engineering, 19:717–732

- Golparvar-Fard, M., Peña-Mora, F., and Savarese, S. (2009). D4ar–a 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing, and communication. Journal of information technology in construction, 14(13):129– 153.
- Kim, S., Kim, S., and Lee, D.-E. (2020). 3d point cloud and bim-based reconstruction for evaluation of project by as-planned and as-built. Remote Sensing, 12(9):1457.
- Machado, R. L. and Vilela, C. (2020). Conceptual framework for integrating BIM and augmented reality in construction management. Journal of civil engineering and management, 26(1):83–94.
- Kopsida, M. and Brilakis, I. (2020). Real-time volume-to-plane comparison for mixed reality–based progress monitoring. Journal of Computing in Civil Engineering, 34(4):04020016.
- Bosché, F., Ahmed, M., Turkan, Y., Haas, C. T., and Haas, R. (2015). The value of integrating scan-to-bim and scan-vs-bim techniques for construction monitoring using laser scanning and BIM: The case of cylindrical mep components. Automation in Construction, 49:201–213.
- Yang Jun, Vela Patricio, Teizer Jochen, Shi Zhongke (2014). "Vision-based tower crane tracking for understanding construction activity". Available: Scopus - Document details - Vision-based tower crane tracking for understanding construction activity
- Joachim L., Zhang W., Haala N., Soergel U. "Evaluation of the quality of real-time mapping with crane cameras and visual slam algorithms" Available: Scopus - Document details - EVALUATION OF THE QUALITY OF REAL-TIME MAPPING WITH CRANE CAMERAS AND VISUAL SLAM ALGORITHMS
- Das Dipankar, Miura Jun. "Camera Motion Compensation and Person Detection in Construction Site Using Yolo-Bayes Model". Available: Scopus - Document details - Camera Motion Compensation and Person Detection in Construction Site Using Yolo-Bayes Model
- Jiyao Wang, Qilin Zhang, Bin Yang and Binghan Zhang (2023). "Vision-Based Automated Recognition and 3D Localization Framework for Tower Cranes Using Far-Field Cameras". Available: Scopus - Document details - Vision-Based Automated Recognition and 3D Localization Framework for Tower Cranes Using Far-Field Cameras
- San Cristóbal, J. R. (2017). The s-curve envelope as a tool for monitoring and control of projects. Procedia computer science, 121:756–761.
- Maciej Trzeciak, Kacper Pluta, Yasmin Fathy, Lucio Alcalde, Stanley Chee, Antony Bromley, Ioannis Brilakis and Pierre Alliez (2023). "ConSLAM: Construction data set for SLAM." Journal of Computing in Civil Engineering.
- Hu, Z., & Brilakis, I. (2024). Matching design-intent planar, curved, and linear structural instances in point clouds. Automation in Construction, 158, 105219.

Chapter 3 – Quality Control Service

- Akinci, B., Boukamp, F., Gordon, C., Huber, D., Lyons, C., & Park, K. (2006). A formalism for utilization of sensor systems and integrated project models for active construction quality control. Automation in Construction, 15(2), 124-138. https://doi.org/10.1016/j.autcon.2005.01.008
- Dong, A., Maher, M. L., Kim, M. J., Gu, N., & Wang, X. (2009). Construction defect management using a telematic digital workbench. Automation in Construction, 18(6), 814-824.
- Patterson, L., Ledbetter, W.: The cost of quality: A management tool. Excellence in the Constructed Project, ASCE (1989).

- Josephson, P.-E., Hammarlund, Y.: The causes and costs of defects in construction: A study of seven building projects. Automation in Construction, 8(6), 681–687 (1999).
- Paneru, S., & Jeelani, I. (2021). Computer vision applications in construction: Current state, opportunities & challenges. Automation in Construction, 132, 103940.
- Wang, R., Law, A. C., Garcia, D., Yang, S., & Kong, Z. (2021). Development of structured light 3D-scanner with high spatial resolution and its applications for additive manufacturing quality assurance. The International Journal of Advanced Manufacturing Technology, 117, 845-862.
- Tang, X., Wang, M., Wang, Q., Guo, J., & Zhang, J. (2022). Benefits of terrestrial laser scanning for construction QA/QC: a time and cost analysis. Journal of Management in Engineering, 38(2), 05022001.
- Kaveh Mirzaei, Mehrdad Arashpour. (2020). End-to-end point cloud-based segmentation of building members for automating dimensional quality control. Advanced Engineering Informatics.
- Milka Nuikka, P. R. (2008). Comparison of three accurate 3d measurement methods for evaluating as-built floor flatness. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.
- Pingbo Tang, A., Huber, D., & Akinci, a. B. (2011). Characterization of Laser Scanners and Algorithms for Detecting Flatness Defects on Concrete Surfaces. Journal Of Computing In Civil Engineering.
- Frédéric Bosché, E. G. (2014). Automating surface flatness control using terrestrial laser scanning and building information models. Automating surface flatness control using terrestrial laser scanning and building information models.
- YiTan, S. a. (2020). Automated Geometric Quality Inspection of Prefabricated Housing Units Using BIM and LiDAR. Remote Sensing.
- Chow J., Su Z., Wu J., Li Z., Tan P., Liu K., Mao X., Wang Y., Artificial intelligence-empowered pipeline for image-based inspection of concrete structures, Automation in Construction, 2020.
- Zoubir H., Rguig M., El Aroussi M., Chehri A., Jeon G., Concrete Bridge Defects Identification and Localization Based on Classification Deep Convolutional Neural Networks and Transfer Learning, Remote sensing, 2022.
- Wang W., Su C., Automatic Classification of Reinforced Concrete Bridge Defects Using the Hybrid Network, Arabian Journal for Science and Engineering, 2022.
- Chow J., Liu K., Tan P., Su Z., Wu J., Li Z., Wang Y., Automated defect inspection of concrete structures, Automation in Construction, 2021.
- Wang W., Su C., Fu D., Automatic detection of defects in concrete structures based on deep learning, Structures, 2022.

Chapter 4 – Occupational Health and Safety Service

- J. Teizer, J. Melzner, BIM for Construction Safety and Health, in: A. Borrmann, M. König, C. Koch, J. Beetz (Eds.), Building Information Modeling: Technology Foundations and Industry Practice, Springer International Publishing, Cham, 2018: pp. 349–365. https://doi.org/10.1007/978-3-319-92862-3_21.
- S. Zhang, F. Boukamp, J. Teizer, Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA), Automation in Construction 52 (2015) 29–41. https://doi.org/10.1016/j.autcon.2015.02.005.

- E.L. Chao, J.L. Henshaw, Job Hazard Analysis, (2002).
- B. Li, C. Schultz, J. Melzner, O. Golovina, J. Teizer, Safe and Lean Location-based Construction Scheduling, 2020. https://doi.org/10.22260/ISARC2020/0195.
- M. Bhatt, F. Dylla, J. Hois, Spatio-terminological Inference for the Design of Ambient Environments, in: 2009: pp. 371–391. https://doi.org/DOI: 10.1007/978-3-642-03832-7_23.
- M. Bhatt, C. Schultz, M. Huang, The Shape of Empty Space: Human-centred cognitive foundations in computing for spatial design, in: 2012 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC), 2012: pp. 33–40. https://doi.org/10.1109/VLHCC.2012.6344477.
- J. Teizer, K.W. Johansen, C. Schultz, The Concept of Digital Twin for Construction Safety, (2022) 1156–1165. https://doi.org/10.1061/9780784483961.121.
- K.W. Johansen, C. Schultz, J. Teizer, BIM-based Fall Hazard Ontology and Benchmark Model for Comparison of Automated Prevention through Design Approaches in Construction Safety, in: 29th International Workshop on Intelligent Computing in Engineering (EG-ICE), 2022. https://doi.org/10.7146/aul.455.c231.
- K.W. Johansen, C. Schultz, J. Teizer, Hazard ontology and 4D benchmark model for facilitation of automated construction safety requirement analysis, Computer-Aided Civil and Infrastructure Engineering (2023). https://doi.org/10.1111/mice.12988.
- K.W. Johansen, C. Schultz, J. Teizer, Automated performance assessment of prevention through design and planning (PtD/P) strategies in construction, Automation in Construction 157 (2024) 105159. https://doi.org/10.1016/j.autcon.2023.105159.
- K.W. Johansen, R.P. de Figueiredo, O. Golovina, J. Teizer, Autonomous Safety Barrier Inspection in Construction: An Approach Using Unmanned Aerial Vehicles and Safe BIM, in: ISARC Proceedings, IAARC, 2021: pp. 629–636. https://doi.org/10.22260/ISARC2021/0085.
- K.W. Johansen, C. Schultz, J. Teizer, Automated Spatiotemporal Identification and Dissemination of Work Crews' Exposure to Struck-By Hazards, in: Proceedings of the CIBW099W123: Digital Transformation of Health and Safety in Construction, 2023: pp. 1–10. https://doi.org/10.24840/978-972-752-309-2

Chapter 5 – Equipment Optimization Service

- Navon, R. (2005), "Automated project performance control of construction projects," Automation in construction, 14(4), 467-476, doi: 10.1016/j.autcon.2004.09.006.
- Sundquist, V., Gadde, L. E., & Hulthén, K. (2018). Reorganizing construction logistics for improved performance. Construction management and economics, 36(1), 49-65, doi: 10.1080/01446193.2017.1356931.
- Jiang, Y., & He, X. (2020). Overview of applications of the sensor technologies for construction machinery. IEEE Access, 8, 110324-110335, doi: 10.1109/ACCESS.2020.300196
- Xu, S., Wang, J., Shou, W., Ngo, T., Sadick, A. M., & Wang, X. (2021). Computer vision techniques in construction: a critical review. Archives of Computational Methods in Engineering, 28, 3383-3397, doi: 10.1007/s11831-020-09504-3
- Kosse, S., Pawlowski, D., & König, M. (2022, October). Industry 4.0-Based Digital Twin Approach for Construction Site Tracking Purposes. In International Conference on Computing in Civil and Building Engineering (pp. 671-686).

Cham: Springer International Publishing, doi: 10.1007/978-3-031-35399-4_47

- Glenn Jocher et al., ultralytics/yolov5: v6.1 - TensorRT, TensorFlow Edge TPU and OpenVINO Export and Inference: Zenodo, 2022, Available: https://github.com/ultralytics/yolov5

Chapter 6 – Proactive Production Planning and Control Service

- Abdelmegid, M.A., González, V.A., Poshdar, M., O’Sullivan, M., Walker, C.G., Ying, F., 2020. Barriers to adopting simulation modelling in construction industry. Automation in Construction 111, 103046. https://doi.org/10/gnhm8b
- Koskela, L.J., Howell, G., 2002. The underlying theory of project management is obsolete, in: Proceedings of the PMI Research Conference. Presented at the The PMI Research Conference, PMI, Seattle, Washington, pp. 293–302.
- Lappalainen, E.M., Seppänen, O., Peltokorpi, A., Singh, V., 2021. Transformation of construction project management toward situational awareness. Engineering, Construction and Architectural Management ahead-of-print. https://doi.org/10/gnhm5h
- Sacks, R., Brilakis, I., Pikas, E., Xie, H.S., Girolami, M., 2020. Construction with digital twin information systems. Data-Centric Engineering 1, e14. https://doi.org/10.1017/dce.2020.16

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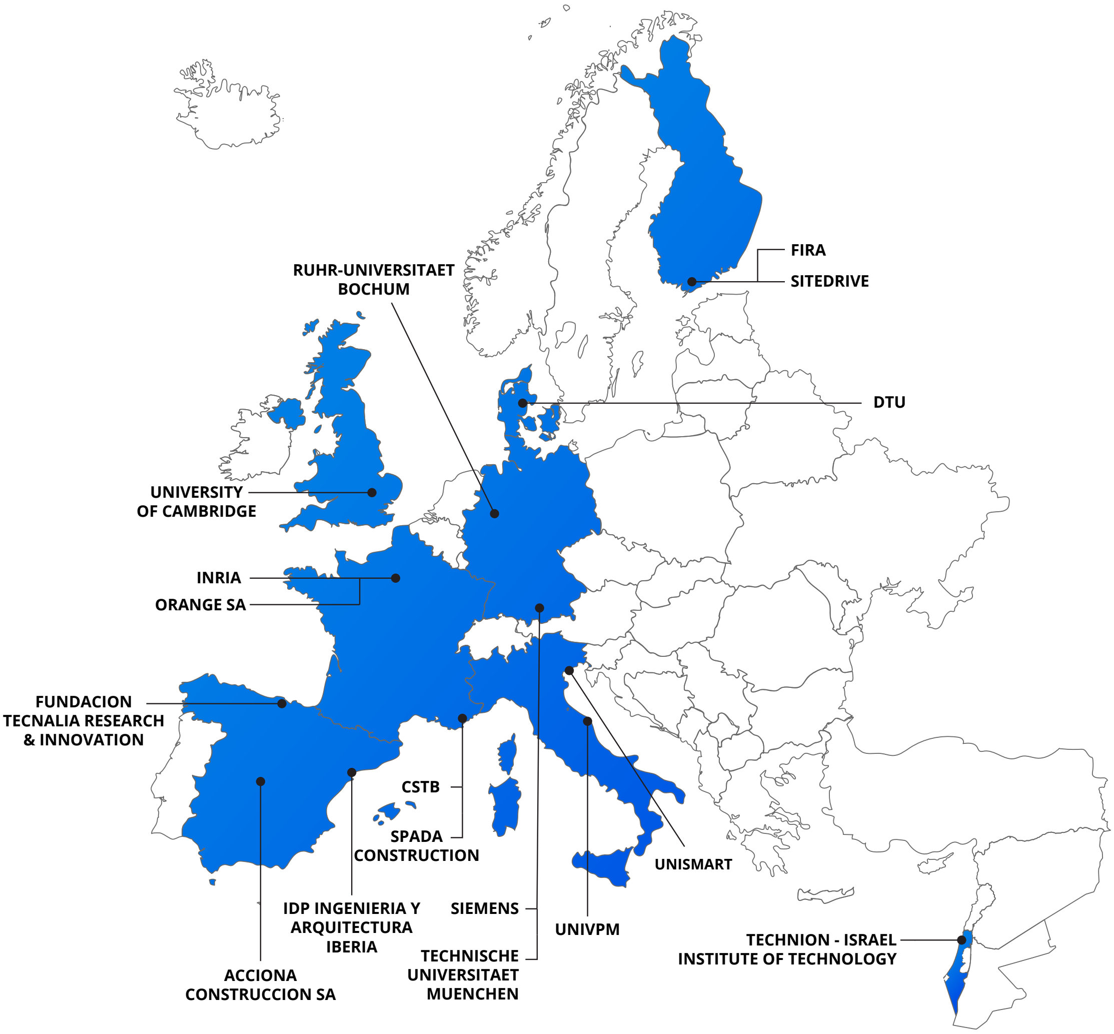

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