D4.5 VIRTUAL COMMISSIONING MODEL

Rehan Khan, DigitalTwin Technology

@AshvinH2020
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Contributing partners	(NCC), (UPC)
Reviewer(s)	[Agnieszka Łukaszewska] (FAS), [Sasa Klopanovic] (MFL)

ABSTRACT

This document describes the developed configuration management processes and illustrates them using the demonstration projects. The established process enables consistency among the requirements specified during the planning/design phase and the installations done during the as-built stage based on digital twin data. Additionally, the document also describes the developed conceptual configuration management process by identifying key areas of the process for the construction project's lifecycle. Finally, the demonstration is done for the configuration and quality management processes on the construction phase demo sites.

KEYWORDS

Configuration Management, Digital twin, KPIs, Quality control

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DISCLAIMER

ACRONYMS & DEFINITIONS

AECO	Architecture, Engineering, Construction & Operation
BIM	Building Information Modelling
CI	Configuration Information
CM	Configuration Management
CMT	Configuration management tool
DT	Digital twin
DTC	Digital twin construction
IoT	Internet of things
KPIs	Key performance indicators
PI	Performance indicators
PII	Project intent information
PSI	Project status information
QC	Quality control
RFID	Radio frequency identification
SCM	Software Configuration Management
WP	Work Package

ASHVIN PROJECT

ASHVIN aims at enabling the European construction industry to significantly improve its productivity, while reducing cost and ensuring absolutely safe work conditions, by providing a proposal for a European wide digital twin standard, an open source digital twin platform integrating IoT and image technologies, and a set of tools and demonstrated procedures to apply the platform and the standard proven to guarantee specified productivity, cost, and safety improvements. The envisioned platform will provide a digital representation of the construction product at hand and allow to collect real-time digital data before, during, and after production of the product to continuously monitor changes in the environment and within the production process. Based on the platform, ASHVIN will develop and demonstrate applications that use the digital twin data. These applications will allow it to fully leverage the potential of the IoT based digital twin platform to reach the expected impacts (better scheduling forecast by 20%; better allocation of resources and optimization of equipment usage; reduced number of accidents; reduction of construction projects). The ASHVIN solutions will overcome worker protection and privacy issues that come with the tracking of construction activities, provide means to fuse video data and sensor data, integrate geo-monitoring data, provide multi-physics simulation methods for digital representing the behavior of a product (not only its shape), provide evidence based engineering methods to design for productivity and safety, provide 4D simulation and visualization methods of construction processes, and develop a lean planning process supported by real-time data. All innovations will be demonstrated on real-world construction projects across Europe. The ASHVIN consortium combines strong R&I players from 9 EU member states with strong expertise in construction and engineering management, digital twin technology, IoT, and data security / privacy.

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1 INTRODUCTION

This deliverable report is part of Work Package (WP) 4 of the ASHVIN project titled "Control and real-time simulation of construction". Wherein the aim of the WP is the better management and control of construction site activities using digital twin (DT) data. This deliverable addresses T4.5: Configuration management, which aims to develop a configuration management process through the project lifecycle based on digital twin data.

1.1 Background

For the Architecture, Engineering, Construction, and Operation (AECO) industry changes are an innate part of the process during its complete lifecycle. The construction industry mainly operates on a project-based approach, going through several phases from planning, cost estimation, bidding, contracting, architectural layout, detail design and engineering, to the actual building construction and the final project delivery stage (Hao et al., 2008). Even though the size, scope, and complexity of construction projects vary significantly, one common element that is recurrent is change based on decisions on incomplete information, assumptions, and experience of construction professionals. Configuration management aims to describe and control the product from the planning to the realization (Zhang, 2014). Although configuration management is not extensively practiced in the construction industry in comparison to other industries, it offers comprehensive potential solutions.

Alongside as digital technologies transform project delivery with the asset information being structured and managed digitally, managing those changes through the different phases of a project is of vital importance (Whyte et al., 2016). Digital Twins as real-time feedback systems offer the possibility to link configuration information (CI) of the installed products to the digital replica of the physical asset. In the early construction phases, projects often go directly to design solutions instead of first acquiring required functions. Interconnection of information about functions, design solutions, and feasible realization methods can reduce the number of changes and improve efficiency during the production phase (Porwal & Hewage, 2013). Hence, the use of digital technologies to integrate and manage configuration information systematically and interrelate the information between the construction phases within a comprehensive digital twin system enables a more accurate representation of the physical asset (civil infrastructure) through its entire lifecycle.

Therefore, within this task of the ASHVIN project, the research focus is to develop a configuration management (CM) process to maintain consistency among requirements, design, configured items, and associated construction, operations, and maintenance data throughout the project lifecycle based on digital twin data. The development of a configuration management process and the demonstration is described to provide readers with an understanding of the Configuration management tool (CMT). The CMT aims to track as-designed/as-planned and as-built, as well as to allow for seamless commissioning. Alongside the CMT aims to enable asset information management for the CM process to ensure quality for the concerned projects.

1.2 Purpose and Intended Audience

The intent of this deliverable report is to develop a Configuration Management process to allow the relevant stakeholder to visualize, analyze, and compare the construction quality based on digital twin data. Additionally, an authorization process and hierarchy for the proposed changes and their impact are developed under this process. The configuration management process is set up in close collaboration with the demonstration projects and based on mature routines to cater to the Key Performance Indicators (KPIs) developed in T4.1.

This report is targeted at project managers, quality management teams, construction firms, and owners. The eventual purpose of the document is to facilitate better management and control of construction site activities using digital twin data. Thus, providing an incentive to public and private construction and technology companies to propel the digitalization of the AECO industry.

1.3 Innovation from Existing Market Solutions

The section describes the existing commercial solutions in the market and how specifically the CMT tool improves upon these solutions. For the domain of QA/QC using digital technologies can be vital for digital control of the construction site. Software such as the C2B platform (C2B, 2022) provides an automated solution for the QA/QC of a construction site with the As-Built model verification. The platform does progress control and deviation check by comparing the BIM model with the point cloud scan of the construction area through machine learning algorithms. In comparison what CMT aims to do is to include aspects of structural indications through the digital twin data measurements from the construction site. For instance: CMT aims to visualize & simulate concrete consolidation quality for the digital replica (3D Model) based on the real-time monitoring of column formwork vibrations. Another example: is to simulate the evolution of concrete compressive strength based on the temperature monitoring of slabs during post-tensioning. Additionally, Dalux Field (Dalux, 2022) as a product is used for construction management of construction sites. It allows for task and issue management for the quality management of the site. It also allows for site inspections and visual walkthroughs by stitching videos taken with a 360º camera.

From the perspective of configuration management to manage configuration information through the building's lifecycle. Commercial software such as EMT AIMS (AIMS, 2022) offer solution for information management such as EMT Assets (a web-based asset information management system, allowing you to track, capture, verify, and handover asset data for a construction project or maintenance scheme) and EMT Forms (a web-based system that allows the creation of digital forms & registers to capture, analyze and track information). What the CMT aims to achieve, is to incorporate multiple methods of information acquisition through DT data from the construction site such as (laser scanners, RFID, BLE Beacons & digital forms).

1.4 Outline of the report

The document is segmented into seven sections. The first section introduces the background and the purpose of the deliverable report. Subsequently, section 2 presents the relevant research and case studies for the concerned area. Section 3 presents the developed CM process. Section 4 introduces the demo sites under ASHVIN and subsequently, Section 5 manifests the utilization and applicability of the demo sites for the developed Configuration Management procedure. Lastly, section 6 summarizes the main contributions of the work and its practical value. Followed by section 7 which presents future research to build upon the work done.

2 BACKGROUND AND RELATED WORK

2.1 Configuration Management

Systems Engineering is based on various infrastructure processes that must be considered through the entire lifecycle including Risk Management, Quality Assurance, and Configuration Management (Brouse, 2009). Configuration Management as a management discipline is an essential part of systems engineering and aims to be applicable over the product/process lifecycle to provide an overview of the changes and control them to optimize performance, functional and physical characteristics (SAE, 2018).

During the missile race of the 1950s, numerous prototypes were built yet they remained under-documented or not documented at all, hence the CM process was developed by the US military to control documentation (Burgess et al., 2005). Configuration Management has been defined differently based on the core requirements of various industries. The process of software configuration management (SCM) is looked upon by the software industry as the best way to handle changes in software projects. It is defined as the practice of identifying the functional and physical attributes at critical points throughout the software's lifecycle and performing systematic control of changes to maintain software integrity (Babich, 1986). The US military describes configuration management's overachieving goal as: "to ensure there is documentation which completely and accurately describes the intended design, the actual product matches the documentation, and there are processes in place so this continues throughout the product's life" (DOD, 2013). Therefore, the processes, procedures, and users of the CM system are vitally essential to maintain the integrity of information all through the lifecycle by controlling changes.

2.1.1 Configuration Management Process Description

The typical Configuration Management Processes (Figure 1) include typical inputs, outputs, and activities (NASA, 2020). Inputs for the processes such as the CM plan developed under the planning phase guide the overall process for the program/project. Changes are inevitable to the baselines throughout the lifecycle and serve the engineering change proposals. The proposed changes should be intended to meet the requirements and interface documents. Subsequently, the approved requirements baseline aims to authorize the request for changes. The Designated configuration identifies the types of items that will need to be placed under configuration control.

Based on the inputs for the CM process activities are carried out to generate outputs. Fundamentally the five elements/activities of the CM process as shown in Figure 2 fuel its functioning.

- **CM Planning and Management:** At the inception of the project, the CM plan as a standalone document should describe the criteria for each technical baseline creation, technical approvals, and audits to be used internally and externally.
- **Configuration Identification:** As a subsequent activity configuration identification systematically selects, organizes, and states the product attributes. The identification activity includes selecting the Configuration Items (CIs), determining the associated configuration documents, determining the appropriate change control authority, issuing unique identifiers for

documentation, and establishing configuration baselines. NASA has established four baselines (functional, allocated, product, & as-deployed) defining a distinct phase in the evolution of a product design.

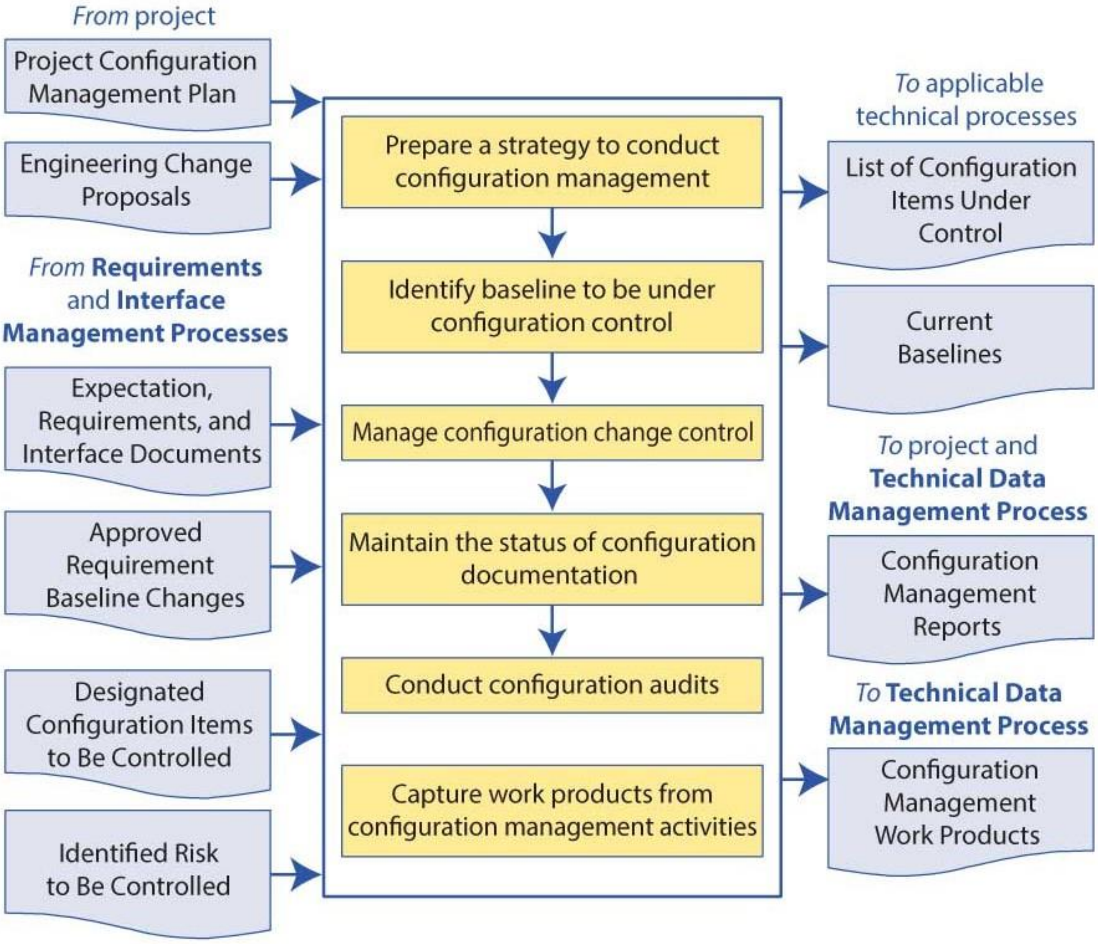

Figure 1: Flow diagram for CM process

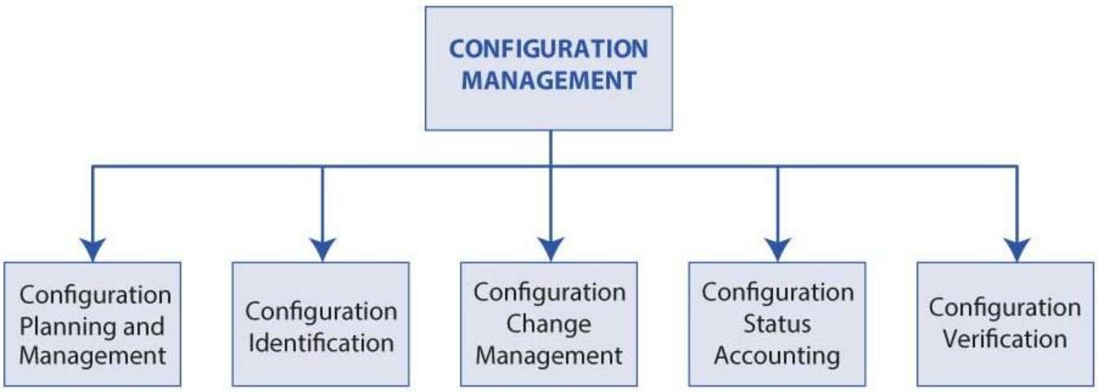

Figure 2: Five elements of Configuration Management

- **Configuration Change Management:** This process through a systematic proposal, justification, and evaluation of proposed changes manages approved changes and verifies the implementation. Engineering change as a type of CM change must be coordinated and approved by involved stakeholders.

- **Configuration Status Accounting:** Status accounting as an activity is vital to record and report configuration data necessary to identify CIs effectively.
- **Configuration Verification:** This activity is realized by inspecting documents, records, processes, and systems of operations to verify that the product has achieved its performance and functional requirements.

2.1.2 Application of Configuration Management

Although the initial development of configuration management was to control documentation for missile manufacture by the US military, it has been applied to industries where managing changes is essential. The CM approach is extensively used in the software industry for software development to organize, control, and manage evolving software systems (Estublier, 2000). Likewise, it has been widely used in safety critical systems such as nuclear and aerospace (Burgess et al., 2005; Whyte et al., 2016). CERN introduced CM in the 1990s (Hameri & Nitter, 2002) and are reflecting on their approaches to configuration management, challenges, and areas of improvement. Hence it was recognized as an ISO 10007 quality management process in 1995 (ISO, 2017). The traditional representation of CM through presentations and with a man at a drawing board represented the paper-based processes of the late 20th century, however, in the 21st century such processes are supported by digital systems.

2.2 Configuration Management & Quality Management in Construction

Quality management in construction means that projects are completed within the specifications set out in the Scope of Work. Typical factors to be considered in determining quality are keeping up with the project schedule and meeting the owner's requirements within budget. Also, whether the specifications laid out in the job contract have been fulfilled. The most common factors affecting quality are the use of damaged and low-quality materials, supplier and vendor failures, subcontractor mishandling and last-minute changes, etc. During construction setting up quality, processes are down to establishing: quality assurance and quality control. Quality assurance (QA) is based on a process-oriented approach rather than examining the end result. It takes into account planned and systematic activities executed in course of a job to fulfill the project's quality requirements. Quality control (QC) is more productive than process-oriented, focussing on the final outcome of a project. Measuring QA and QC requires two distinct approaches and involves varying project stakeholders (FTA, 2009).

Configuration management is not extensively practiced in the AECO industry, therefore only a few studies consider the application of CM in the AECO sector. CM as a project management approach can be used for BIM model management, by managing BIM change control documents for practical cases to facilitate BIM implementation during the construction phase (Hu et al., 2016). Research work by (Ashkezari et al., 2022) proposes a project configuration framework that integrates design failure mode & effect analysis with fault tree analysis to improve project configuration by applying quality management techniques.

Hence the application of CM in this research study, the construction primarily integrates quality management as part of the CM process by considering project risk, cost, and quality, with further possibilities to integrate configuration information in construction projects.

2.3 Digital Twin in Construction

Digital twins are promoted by solution providers as a panacea for everything from system requirements verification to maintenance of deployed systems. A DT of a construction site supports the management and control of the construction site. Digital twin construction (DTC) begins with real-time information streaming from the construction project enabling a closed loop of construction control. Figure 3 lays out the DTC workflow based on a DTC information system. Within the DTC information system, the generated information describes the "as-built" and the "as-performed" state of the project thus delivering the Project Status Information (PSI), unlike a federated BIM model delivering the as-designed and as-planned states of a project i.e., the Project Intent Information (PII) but not the as-built nor the as-performed states (Sacks et al., 2020). Additionally, a specialized *Evaluate Conformance* function compares the actual to the intended, the PII to the PSI. While conformance evaluation can be automated using various AI methods, it is likely that this function would solicit user input for value judgments in many instances and will draw on standard design knowledge. The output of this function is knowledge about the project's status and termed Project Status Knowledge (PSK). Therefore, the developed DTC process incorporates four distinct Plan-Do-Check-Act cycles at different time resolutions through real-time feedback from monitoring technologies to manage worker safety and for quality control.

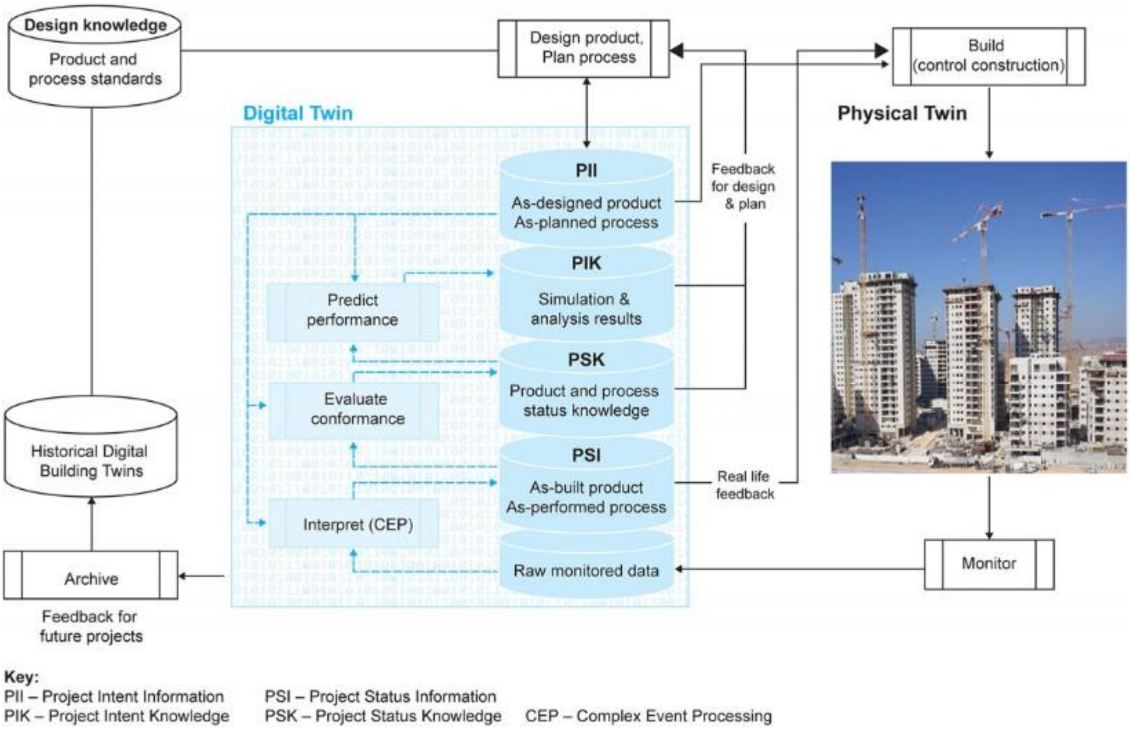

Figure 3: DTC workflow process (Sacks et al., 2020)

2.4 Configuration Management based on DT

CM is the detailed recording and updating of information to manage changes in a project to ensure the physical implementation of a product is consistent with the requirements and documentation that describes what it is supposed to do. Therefore, in the era of 'big data,' this be done using DT data through the management of configuration information. The management of CI is a continuous process to ensure that the product description is updated and accurate through real-time information flow of the changes/modifications made in the physical asset (construction site). Additionally, the CI should be available to all relevant stakeholders throughout the product lifecycle (Schönbeck et al., 2020).

Likewise, configuration management as a process can be central to digital twins. Poor configuration management would slowly result in the physical asset deferring from the digital asset. With full configuration management digital integrity is maintained, therefore as the physical asset gets built, specifications request the right information in the right configuration so that you have the exact representation of the physical entity as a digital asset. Therefore, CM is crucial to DTs by providing a complete picture of the Asset- configuration, data, documents as well as visual representation and ensures trustability by keeping the DT current thus providing foundations for analytics and engineering changes during the operation phase (Bentley, 2018).

2.5 Case studies

The practical application of CM in civil engineering and construction projects has been presented in the past on a number of case studies:

2.5.1 Crossrail

London's Crossrail is the largest construction project in Europe, with an original budget of £ 15.9 billion aims to hand over a physical and digital railway. It involves the upgradation of existing rail networks; construction of new stations; boring 42 km of new tunnels across central London from Paddington Street to Liverpool Street Station; installing, extending and commissioning a wide array of underground electrical and mechanical systems; and delivering the associated information to owners and operators (Whyte et al., 2016). CM is used on the project to ensure a consistent, validated set of asset information as a project deliverable. Digital system is used for data management with an estimated 2-3 million records in asset databases, 1 million model & drawing records, and a quarter of million GIS records. Henceforth there is a significant variety of linked data in the form of asset information (and all the associated variables such as author, approver, dates, and versioning); digital documents such as operation and maintenance manuals, plans, requirements, 2D designs, parametric building information models, and geographic information.

While physical assets in Crossrail include rail tracks, trains, shafts, and buildings. The contractor is responsible for providing labels for the identification of assets alongside equipment/serial numbers on all equipment. Labeling of assets allows them to be tracked and related to other assets in the form of 'powered by' and 'controlled by' relationships. Contractors control the associated information until they deliver the 'as-built' information to Crossrail. Thereafter Crossrail locks down the asset information associated with configuration items, and equipment/serial number labels to control further changes internally. Crossrail applies configuration control at the 'as-built' stage so that configuration changes before handover are consistently maintained for the owner. The challenges are as follows:

- *Complexity and culture of delivery* – There are conflicts and interfaces among the many processes and the current industry procedures for changes in program baseline, design management, and as-built drawings.

- *Multiple change processes* – The CM team concluded that having multiple change processes which are common in the industry is not ideal. In some change process, the same person is assessing the impact of change and deciding whether it should be accepted or rejected.
- *Establishing a requirements-led orientation* – There is a need to have assets conforming to asset information. For example, the red-line procedure covers the process of annotating changes on drawings for construction. The site contractor highlights approved, post-design changes from the original drawings to be reflected by an inspector of the built asset. These records are later used to update 'as-built' drawings before handover to the operator (Crossrail).

All this large volume of asset-specific information has an interface specifying how asset information is to be identified, named, labeled, stored, synthesized, and managed. By following a standard structure, and definitions the aim is to organize asset information within the digital system and to hand it over to operators to be resourceful for future operation and maintenance. Asset labels, equipment labels, and serial numbers are used to represent configuration items based on hierarchies of location, function, and classification. Hereafter this system supports metadata searching and explicit linking of asset groups.

2.5.2 Gas pipeline in Korea

The research study by (D. Y. Lee et al., 2017) considers the application of CM during the engineering phase of the pipeline project for efficient management of the changeable information. Since April 2009 Korea has been importing 1.5 million tons of Liquified Natural Gas annually from Russia, therefore the researchers investigate the application of CM for improving the technological efficiency of domestic companies.

The application of CM for pipeline projects is based on three elements: design requirements, physical configuration, and facility configuration information.

Breakdown of design requirements: The requirements are referenced in the Design Basis Document of Application for Approval by several major pipeline projects. The design requirements for are divided into seven categories: Codes and Standards, Piping Joints, Loading Conditions, Environmental Factors, Material-related Considerations, Thermal Insulations, and Sizing of Piping Systems. Each has its own components.

Breakdown of physical configuration: It includes information about real facilities and their components. It has design and construction results. The classification of piping (i.e., a mechanical component) infers the possibility of linkage between design requirements and physical configuration. The piping of physical configuration is largely divided into four categories: Pipe, Valve, Control and Monitoring, and Miscellaneous.

Components of facility configuration: It includes most of the engineering information except for design and physical configuration. Primarily the elements of facility CM include basic and detailed design information. They have several types of information but the three major components are purchase specifications, drawings, and procedure documentation. Although there is no standardized breakdown of facility configuration information as it is just basic/detailed design information like property data, it should be linked with proper components of design and physical configuration.

In this study, the tagging of piping data was done for the linkage of correlated data. Additionally, each inquired data has two properties file attributes (name, format, location, size, creation, and modification date) and registrants (registrant ID and company code).

The application of CM in this study enables to link all engineering information assigned tags in three main elements. An example shown in Figure 4 gives an understanding. Only a portion of piping data among the large amount of data such as ‘Physical Configuration for Piping’ and ‘Design Basis Document/ Code & Standards for Piping’ are extracted. All the extracted information is managed through linkage with each other on the basis of the tag system. All through the lifecycle from design to the maintenance stage the information can be easily traced and confirmed.

Figure 4: Application of CM for piping-related engineering information.

To demonstrate real-world design changes a comparison of work procedures is presented in the study. When a public employer requests a design change due to budget reduction, it can affect the elements of CM which are design requirements, physical configuration, and facility configuration information. The two alternatives reducing the diameter from 32 inches to 30 inches and the length of pipe from 100m to 60m are compared. The stakeholder architect will have to review design requirements based on codes and standards and change facility information such as design drawings and specifications increasing the possibility of errors due to inefficient communication (ex: Error due to notification of incorrect revision number). Whereas if the architect runs the design changes through the change management system applied by CM, they can identify design changes without additional communication so that the vendor can produce the pipes according to design changes. Therefore, the results allow an automatic linkage method of detailed information among the 3 CM elements.

2.6 Configuration Management Procedure based on DTs

The section presents the concepts and research that are related to key areas identified for the CM process developed for the ASHVIN project presented in Section 3. The description is essential for the readers for the sematic understanding of the CM process and the configuration management tool as well which is demonstrated on real-life construction projects.

2.6.1 Function specification

The specification of information about the required functions is essential for end-product performance as well as lifecycle management. The product specification should be done explicitly defined during the planning phase or the early design phase of construction projects (Chun & Cho, 2015). Otherwise, it can lead to low efficiency in the production phase and inadequate end performance of the product. Subsequently, in the operation phase, the evaluation of functions can help the clients to develop and standardize their functional requirements (Ding et al., 2017). In a survey among project managers regarding the availability of configuration information in practice, almost all respondents considered information on functions to be present in all construction phases. Additionally, the respondents ranked structured management of functional requirements as the most important for a high quality of the end-product, followed by documentation of functional requirements. Thus, the information about function is the controlling basis for all other key areas of configuration information and should be available throughout the project process (Schönbeck et al., 2020).

Consistency through lifecycle stages is vital for the CM process, and essentially the first step is to specify the requirements as per the function. Some of the industry practiced methods for digital information specification are described below:

2.6.1.1 CoClass

CoClass is the Swedish digital classification for all built environment. The objective of CoClass classification is to provide a common language describing the basic functional parts of the built environment, at all scales of complexity. Additionally, it can be used in all software and all information deliveries during the entire lifecycle (CoClass, 2022). Therefore, CoClass is created for digital information management and efficient asset management for all sorts of buildings and civil engineering works. The value proposition of CoClass is illustrated in Figure 5.

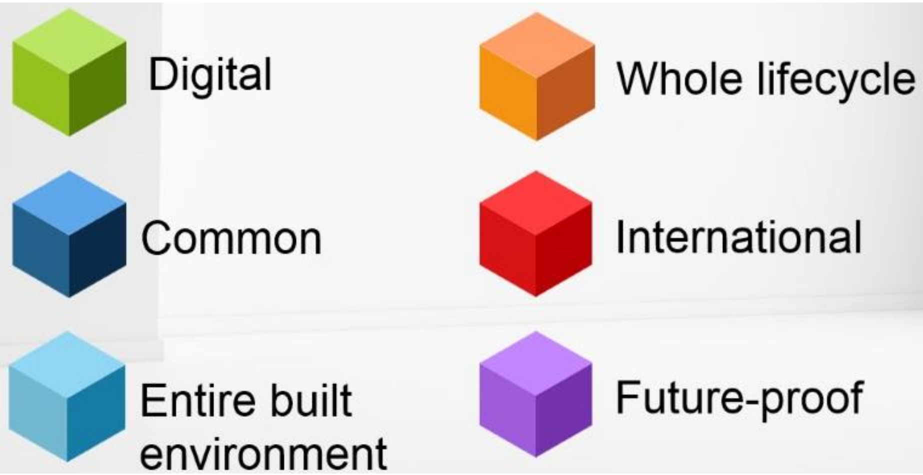

Figure 5: CoClass value aspects

The development of CoClass is based on a series of standards such as IEC/ISO 81346 (classification and reference designation in process plants) and ISO12006-2 (organization of information about construction works). The connection to the standards is as follows:

- ISO 12006-2 grants the general structure
- IEC 81346-1 grants the rules for regulation for reference terms
- IEC 81346-2 grants classes for construction elements (components) and for built space
- ISO 81346-12 grants classes for construction elements (systems)

CoClass uses 81346 standard series the designation of reference terms, thus CoClass is used to identify and designate individuals. Figure 6 illustrates an example of identification based on CoClass for wall construction.

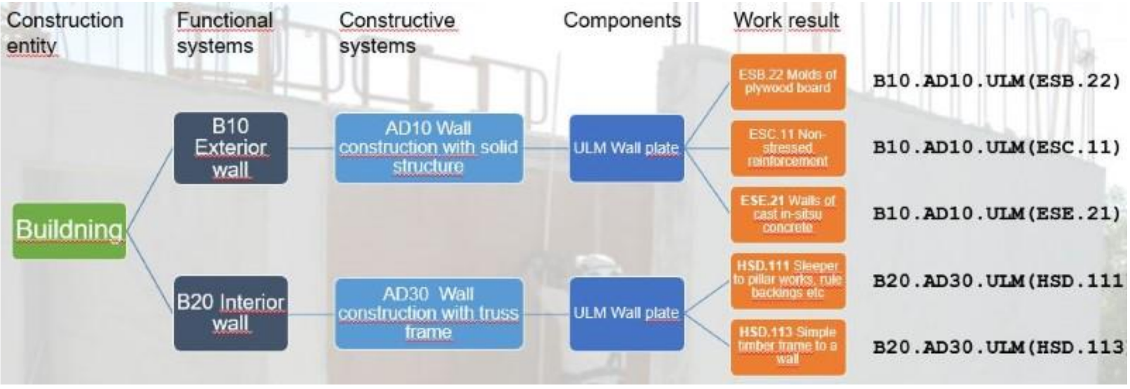

Figure 6: Classification- A wall construction example

In summary, CoClass gives a common ground for communication throughout the lifecycle. As an example: As per the client's requirements, an architect creates a model of the building using CoClass to assign a classification and a unique ID to each room and element. The ID represents the location of the element and the architect can enter additional functional properties for that element (in the case of a window the dimensions, material U value, etc) using CoClass for the structuring. When other stakeholders such as engineers, and consultants do the light and sound calculations they use the same data directly classified earlier by the architect using CoClass. They complete the requirements and transfer them through tender documents to the contractor. Using the same ID, the contractor can look for manufacturers as per specified requirements. During the installation, they can use the same ID to know the location of the installation. Subsequently, post-construction all this data can be handed to the client for the operation of the building. This essentially illustrates how CoClass can be used throughout the building process from initial idea to operation & maintenance.

2.6.1.2 GTIN

Statsbygg (Norwegian construction authority) has demanded that all products included in a building/delivery must be identified with GTIN (Global Trade Item Number). GTIN is a global unique identification key that uniquely identifies a product/merchandise. GTIN is typically included in the barcode that is scanned at the checkout point in the stores but is also used in other parts of the value chain (GS1 Norway, 2021). The objective for the construction industry is to be able to use GTIN to look up databases to retrieve and ensure uniform documentation and information of the individual products included in the building. Four product groups have been chosen for GTIN use as they represent different situations as shown in Figure 7. These four main categories of products are standard off the shelf products, ready-mix concrete, precast concrete elements, doors & windows. The principles for the selected groups can be transferred to other product groups. Many products already have GTIN, but some product categories are particularly challenging. Especially products that are produced based on specifications for the individual project.

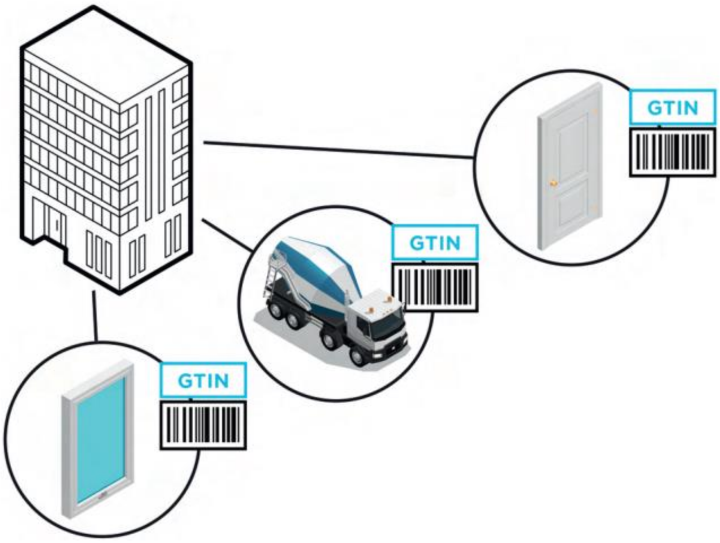

Figure 7: Products identified for GTIN

As GTIN is a unique number, it can be used by all actors in all phases of the building's life cycle from planning to decommissioning. GTIN can be connected to objects in BIM models for linking information. There are many ways to connect BIM objects to product information:

- GTIN as a property of BIM objects. This ensures that the individual object instance in the model has a direct reference to the product type it represents in the physical building.
- A generic code system that is added as a property to the BIM object, can among other things be used to connect to documentation in a product register including GTIN and product documentation.
- The object's instance's unique model identifier, Global Unique Identification (GUID). GUID is something the software itself establishes and the code, if generated correctly, should be unique.

A connection between BIM objects and GTIN can be made when the product is installed on the construction site. This can be done by reading the product with a barcode scanner connected to a tablet where the BIM object is identified. This method can be part of the executive quality assurance process. The most used GTIN consists of 13 digits and is therefore called GTIN-13 as shown in Figure 8.

Figure 8: Example of the structure of GTIN-13 with 6-digit GS1 Company Prefix

GTIN is already being used as an industry standard in many European countries to support the digitalization of construction. Therefore, by applying them to building products, stakeholders can ensure access to consistent, accurate, and trusted data at every step of the supply chain. Additionally, the integration of GTIN with BIM supports construction digitalization. Therefore, the use of GTIN standards can be one of the methods for the specification of information for the CM process to track it over the construction lifecycle.

2.6.2 Change Management for Construction Lifecycle

Changes during the construction lifecycle are inevitable resulting in delays in completion, overspending, and quality defects. Research by (Erdogan et al., 2005) explores change management in construction at two levels: organizational and project level by classifying change based on nature for different management techniques. (Sun et al., 2006) developed a change management toolkit for construction projects to include aspects of predicting the change and change by rescheduling workflows.

From the perspective of CM, initiation of configuration change starts with a request containing information about the change and the importance of its implementation. The implementation of changes requires updating of configuration information, as well as assurance that the functional requirements of all stakeholders still are fulfilled (ISO, 2017). It is recommended to define a set of criteria that are used along with an authorization process to decide whether a change proposal is approved or rejected. The assessment criteria should define the need for change, the stakeholders it impacts, and the impact of the change (including cost, schedule & resource impacts). Furthermore, the change management system should allow to document/audit the changes, and control the change. A disciplined change management process is critical for systems engineering. A generalized change control process in response to an engineering change proposal as shown in Figure 9, can be applicable to the construction project's lifecycle as well through the design, construction & operation phases to manage changes (Blanchard & Fabrycky, 2005).

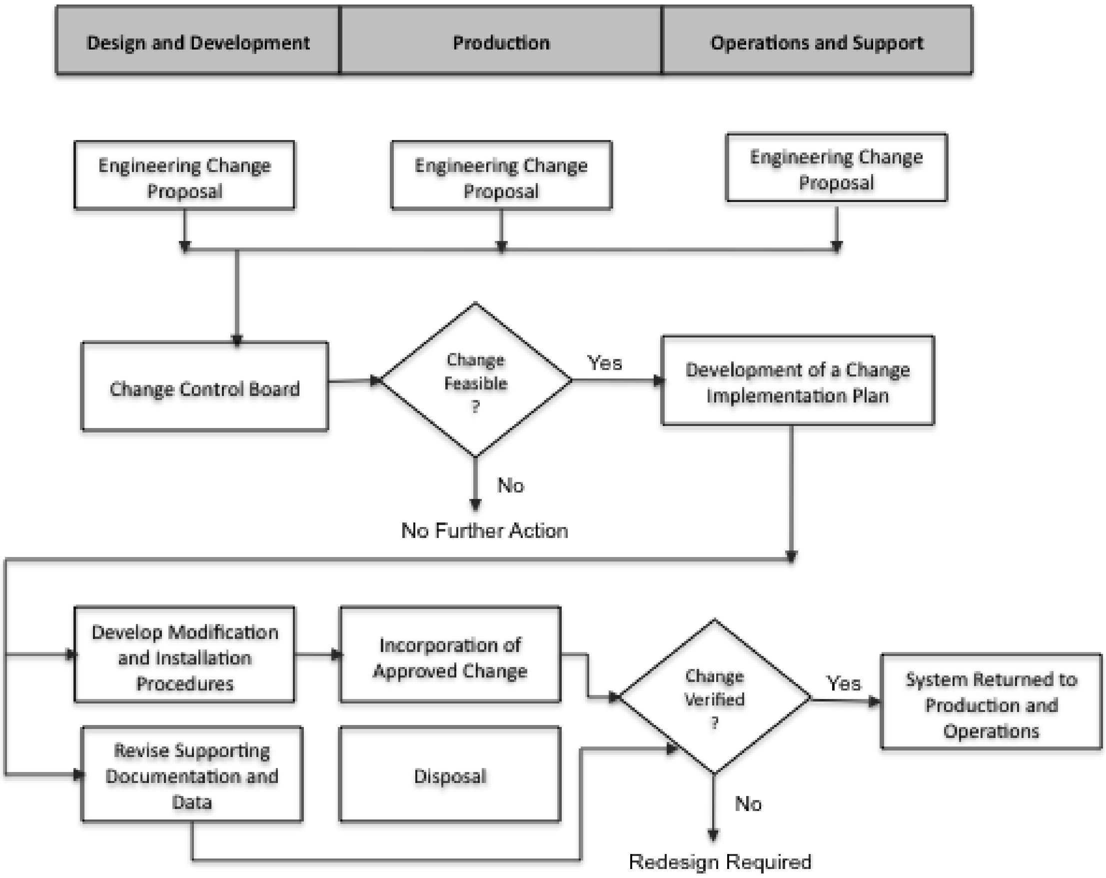

Figure 9: Configuration change control process

As the proposed ASHVIN CM process shows in Figure 10, the information on configuration changes is interrelated to all other key areas. The developed authorization process for change approval is elaborated in section 3.

2.6.3 Verification through Digital Twin data

Implementation of configuration management in safety critical industries such as nuclear and aeronautics resulted in significant efficiency and reliability by providing accurate information to support decision-making. With the integration of configuration management and digital twin results in digital integrity. Therefore, as the physical asset gets to build the specifications request the right information in the right configuration to have an exact replication of the physical as a digital asset. Thus, providing a foundation for analytics and engineering change in operations. Some methods to collect digital twin data to fuel the CM process for construction are:

2.6.3.1 RFID

Radio frequency identification (RFID) has been widely in the construction process to improve efficiency, manage assets and reduce thefts. An RFID system is composed of a transceiver (called a reader) which is a two-way radio transmitter that emits a signal to labels or tags. The tags contain a microchip to store and process information and an antenna to transmit information to the reader. However, the environment and working conditions are very different for each construction process, needing a particular RFID system for each context. Several uses of an RFID system in construction range from equipment & tool management, workforce management, tracking of materials, and construction site monitoring (Valero et al., 2015). Research by (Majrouhi Sardroud, 2012) advises the use of RFID for automated material management to create a system including a list of material flow, dead inventory, and actually used materials. With alerts in case, the materials arriving at the site are incompatible with the purchase order. A solution based on RFID tags has been used to record prefabricated units' transportation and their installation at construction sites (RFID journal, 2013). (Chin et al., 2008) integrated RFID and four-dimensional computer-aided design to assess progress on structural steelwork in two real-world high-rise construction projects.

By means of RFID tags placed on building elements, digital data is generated and provides the DT platform with real-time associated information. The RFID tag is activated once the scanner is nearby by identifying the building element and its properties resulting in CI that can be managed and tracked.

2.6.3.2 Bluetooth Low Energy (BLE) Beacons

The use of Bluetooth beacon technology offers solutions for indoor resource monitoring. A BLE monitoring system: BLE beacons, a gateway, a web service, and cloud-based storage. (Dror et al., 2019) presented the use of fixed beacons and mobile gateways to fix beacons on walls or ceilings during the building's construction, while apps installed on-site personnel mobile smartphones serve as gateways. The beacons require neither infrastructure nor an external power source. EYE beacon (EYE Beacon, n.d.) produced by Teltonika is used for asset tracking, permanently mounted on building elements, and connected to signal gateways allowing for asset tracking. The customer filtering feature also allows customers to group and name assets by a specific attribute or meaningful property to business operations. Deutsche Telekom presents an IoT-assisted system to forward construction digitalization, by using a combination of IoT, Bluetooth beacons, and a mobile app (Deutsche Telekom, n.d.). By attaching tiny beacons to shell elements and automatically sending information to smartphones, the cloud-based data can be accessed at all times.

In terms of DT data, the use of beacons can facilitate real-time information from the construction site by broadcasting information. For instance, a beacon fitted on a window with predefined information related to the window fitted just before installation of the window aids in establishing consistency between the requirements and the actual construction. With further possibilities to track associated changes being carried out in which the beacon can be refixed to the new window installation with historical configuration information.

2.6.3.3 LiDAR/3D scanning

3D Laser scanning as a technology aid in the transfer of data to digital module and processing to create spatial objects. Studies comparing the terrestrial laser scanning (TLS) based QA/QC approach with the conventional QA/QC approach for construction projects identified the former to be more efficient due to a reduction in data collection time (Tang et al., 2022). (Nguyen et al., 2021) advocate the use of laser scanning for the vertical assessment of surface flatness of the wall/column/beam for the quality control procedure with the purpose of avoiding obsolescence costs of construction rework. Researchers (Tran et al., 2021) developed a comprehensive framework for automated geometric QA/QC of as-built prefabricated 210 façades based on the comparison between as-designed BIM and as-built BIM generated from TLS data. Henceforth, for the domain of construction quality management the captured 3D data can be used for quality control during excavation planning, accurate placement of concrete, beams, & other parts, surface flatness analysis, and compliance with health and safety regulations.

2.6.3.4 Digital Forms

The CM process can get digital twin data through a web-based system for the creation of digital forms and registers, allowing track, capture, verification, and handover of asset data for a construction project or maintenance scheme. This method developed by Enable my Team (Enable My Team, n.d.) digitalizes the QC process. Mapping of form configuration to a PDF template once the data is captured is done to client-approved templates. A case study of Alstom Riyadh Metro used Enable My Team for the digitalization of rail inspection data. Wherein hand-written forms were previously completed during inspection of every fastening and turnout along kilometers of railway track to be manually entered into the management system after inspection. EMT Forms directly captures the data during each inspection and automatically uploads this data into a centralized cloud database.

The digital forms can serve as input for the configuration information database. While the inspection of installations in the buildings and the elements are being done by the QA/QC team, the use of this digital form will enable them to input the information of the element that is installed. Subsequently, it can be stored on a cloud database verified against the requirements and design specifications.

2.6.3.5 Mechanical sensors

2.6.3.5.1 Accelerometers

Acceleration is defined as the change in velocity over time (Freedson et al., 2005). Accelerometers measure acceleration multiple times within a given frequency and summarize this as a count over a pre-specified time period or epoch (Evenson & Terry, 2009) Use of accelerometers in combination with gyroscopes such as the MPU-6050 sensor can be used for real-time monitoring of the development cyber-physical systems of smart construction (Hasan et al., 2022). Research by (Gkoumas et al., 2021) advocates the use of accelerometers with monitoring systems for the optimized management of Europe’s transportation infrastructure.

2.6.3.5.2 Thermocouple

Temperature is one of the important factors that ensure the quality and safety of construction. (Posada et al., 2022) propose the use of thermocouple-based monitoring of concrete maturity process for slabs to enable an automated pipeline for DT-based structural modeling. The use of an automated real-time monitoring system of construction site environment temperature for data analysis and trend monitoring can support construction site management (Jiang & Hua, 2013).

3 PROCEDURE

The section elaborates on the developed configuration management process of ASHVIN and its sub-processes.

3.1 Configuration Management Process

Configuration management's basic purpose is to keep the physical implementation of a product consistent with the documentation that describes how to build it and what it is supposed to do. The proposed conceptual CM process is developed based on ISO 10007:2017. The ISO 10007:2017 standard describes configuration management during the lifecycle of a product. The guidelines describe key areas of configuration management that can be applied to construction projects (ISO, 2017). The standard provides guidelines from where five key areas were identified that can apply to the CM of construction projects through its lifecycle based on digital twin: specification, verification, digital integrity, change management, and operation & maintenance (O&M). The CM process developed under the project is to cater to the ASHVIN DT platform and the configuration management tool as illustrated in Figure 10. In the figure, the key areas are the headings and the relevant information below. Additionally, the arrows represent the interrelation between the key areas.

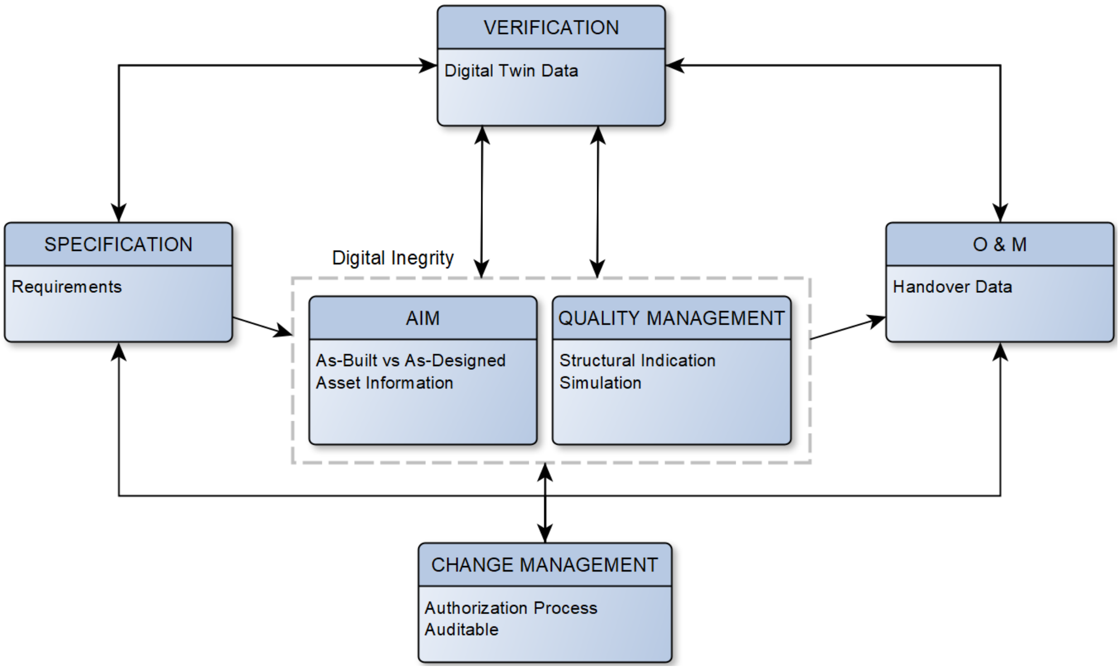

Figure 10: ASHVIN CM process conceptual model

The CM process initiates with function *specification*, for construction projects the planning and early design phase is essentially when the requirements of the project are specified as per the clients' requirements, function cost, and other relevant factors. Subsequently, during the construction phase, *digital integrity* has to be maintained throughout the process as in the case of a digital twin for construction, full configuration management through real-time feedback from the site would ensure accurate representation of the physical asset thus leading to *digital integrity*. This can be done through asset information management (AIM) and quality management for the construction process based on digital twin measurements. Further *verification* is done to ensure that the production (construction) is as per the specification using digital twin data which is also linked to the level of digital integrity. Additionally, change management controls and audits all the changes during the product's lifecycle alongside an authorization process to assess the change and them approve or reject it. Lastly, all this information is handed over to the operation & maintenance phase to assure efficient operations based on historical and digitally trusted information.

In summary, through higher digital integrity based on DT data the physical asset gets built as per the right specifications thus linking the information to the right configuration and vice versa the representation of the physical asset is more accurate through better CM as the specifications request the right information in the right configuration. For this research study only selected key areas of the CM process are described in detail in the deliverable sections: specification (2.6.1), verification (2.6.3), and digital integrity (5).

3.1.1 Specification

The specification of information at the initial project planning phase is vital, therefore for the ASHVIN CM process for the current study, there is no specific method developed. However, the CM process aims to integrate existing methods such as CoClass and GTIN explained in detail previously (see section 2.6.1) for the specification of information as per the functional requirements. The CoClass representation is also related to *D1.2: Ontology for the ASHVIN digital twin platform* of ASHVIN wherein the representation of construction works are done as per ISO 12006-2 and IEC 81346.

3.1.2 Change Management

In the previous section, the concepts for the change management process are described. Subsequently, the developed authorization process under ASHVIN is described in the following section.

3.1.2.1 Authorization Process

This task also aims to develop an authorization process to assess the impact of changes during construction and obtain approval from an approval level of authorization. The authorization hierarchy is developed based on the demonstration site i.e., demo#5 Kineum office building in Sweden (see Section 4.1). The input for the authorization hierarchy was provided by project partner NCC who are the demo site owners as well.

Figure 11 demonstrates the authorization hierarchy for approval of changes during the design and construction phases. In the case of the authorization process, during the design phase, if there is a change request, the originator (the one that has the request) puts it into the system as a request. The next step is that the design manager (or design coordinator) reads the request and, if necessary, adds information. The request is always sent to the project manager if it is a cost-driving question. If it is something related to aesthetics, the request is sent for approval by the architect. For the same request, many demands of approval can be made. Moving to the construction phase, financial responsibility has been handed over from the project manager and the cost estimator to the site manager, who will take care of the approvals. Wherein depending on the cost impact of the change the final authorization can lie at different hierarchical levels. The authorization is decided by the cost cut-off, the higher the percentage the decision will be taken by the higher management levels. For the cost cut-off, a value range has not been fixed as it varies from company to company depending on the company size and its internal budget strategy.

For this particular demo site although there is a Dalux system for logging and approving requests. Dalux Field software allows for management changes by logging requests and providing approvals to ensure that all issues are resolved as needed to manage and mitigate risk/avoid costly re-works. But in a recent internal study, it is found that this feature was very seldom used. Usually, the approval is made through e-mail or a telephone call. As it is often something that needs to be solved quickly, a phone call directly to the site manager is often the most common. Unfortunately, this means that the request is not logged digitally, and thus not who made the request and why. Therefore, an authorization process facilitated by digital twin data can streamline the process as long as the feedback is real-time and is fed directly to the managers and workers on site.

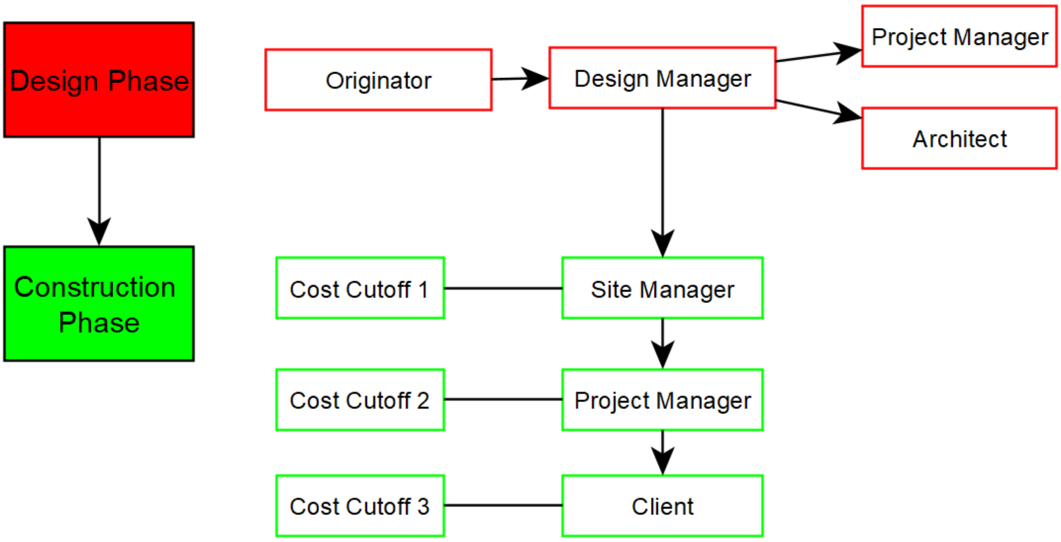

Figure 11: Authorization hierarchy

3.1.3 Verification

For the CM process, the verification aspect is based on the use of digital twin measurements from the construction site for the verification of configuration information and maintaining consistency among requirements, design, configured items, and associated construction, operation & maintenance data, and other enablers through the project lifecycle. Aspects of the verification process based on DT data are explained in subsequent sections of the report.

3.1.4 Digital Integrity

The key area of digital integrity is based on asset information management and quality management of the construction site based on the use of digital twin data for the verification that is demonstrated on real-life demonstration sites of ASHVIN in section 5.

3.2 Key Performance Indicators

One of the key areas for the developed CM process i.e., verification through DT data is presented in section 2.6.3 and herein the actual DT data available on the construction phase demonstrations of ASHVIN are related to the project KPIs which is also used for the verification through digital twin data part in the CM process.

KPIs are used to determine the goals and measure the performance of construction projects. Within the ASHVIN project, a set of KPIs is developed for planning and controlling construction site activities, ranging from supply chain logistic planning, resource allocation, to site layout planning to allow site managers to steer all planning and control activities towards productive, resource & cost efficient, and safe construction (Łukaszewska, 2021a). The KPIs are productivity, resource efficiency, cost, and safety. Besides they constitute of performance indicators (PI) that are quantifiable and measurable sub-criteria of KPIs. With regard to configuration and quality management, the previously mentioned KPIs can be applicable to demonstrate the goals of the construction project. Table 1 illustrates the spectrum of activities that can be used for the assessment of the KPIs for the CM process based on DT information systems.

Table 1: KPIs for CM based on DT data

KPIs	CM process (DT data)
Productivity	• Positioning of building elements (laser scanner, RFIDs) • As-Built model verification for progress control and deviation check (point cloud scans, 360º cameras)
Cost	• As-Planned vs As-Built Information (digital forms, RFIDs) • Rework costs (laser scanner) • Asset information management for LCA (CM database, logbook)
Resource Efficiency	• Wastage from concrete casting (mechanical sensors)
Safety	• Strength of structural components (mechanical sensors) • Deviation from design (cameras)

The above-mentioned processes for the overall configuration management of construction projects advocate real-time feedback based on digital twin measurements from the construction site. Hence, they can be used to evaluate the KPIs developed in D4.1 of the ASHVIN project. Also, some of the processes are demonstrated on the demo sites of the project for this deliverable report.

4 APPLICATION ON DEMOSITES

The ASHVIN platform and technologies are aimed to be implemented on ten real-world projects covering buildings, bridges, viaducts, and industrial structures (Łukaszewska, 2021b). The demo sites (construction phase) chosen for the demonstration of the configuration management tool are described briefly. Subsequently, this section presents the CM process application implemented for the demonstration on the specific demo sites based on the site conditions, accessibility, and the DT data.

4.1 #5 Kineum office building in Sweden

The Kineum case is a high-rise building (see Figure 12) located in the city of Gothenburg, Sweden. The project started in 2019 and ends in the summer of 2022. It comprises of 30,000 m^2, 960 – 1400 m^2 per floor, and 27 floors. Once completed with a height of 110 meters it is supposed to accommodate office spaces and a hotel with a nonstandard element façade with triangular glass units and a glazed roof.

Figure 12: Construction process of Kineum project in Sweden

4.1.1 Applicable DT data and Challenges

The Kineum building has the same floor plans for all of its 27 storeys. The level considered for the ASHVIN's demonstration plan is level 16 of the building. For the case of the Kineum site, one of the DT data gathering methods was through a Spot robot equipped with a Leica BLK360 laser scanner to scan the progress of the site on certain areas of the building floors. The resulting point cloud file is obtained in the propriety '.b2g' format. Although it captures the as-built of the construction site in the form of a collection of data points that can be converted into a BIM model. From the perspective of configuration management, the asset tagging of the converted 3D model would still be required. Therefore, for the CM process to ensure that the quality of installations is as per the specified requirements would primarily require the asset information for verification.

4.2 #6 Office building in Spain

The #6 demonstration project of ASHVIN are office buildings located in Barcelona (Spain) and are part of project@22 also known as 22@Barcelona and the “Innovation District” (‘Districte de la innovacio’). The objective of the 22@Barcelona project is to improve the urban, social and functional structure of the central areas alongside contributing to Barcelona’s transformation from the City of Industrial Civilization into the City of Knowledge Civilization. The project aims to convert the industrial area of Poblenou into the city’s technology and innovation district, as well as to contribute to leisure and residential spaces.

Mile is an office building project of 38,093 m^2 divided into three complexes: MILE-Badajoz, MILE-Llul, and MILEÁvila. The access was provided for the specific module of MILE-Ávila (see Figure 13), a cast-in-place reinforced concrete building of long-spanned post-tensioned slabs, consisting of eight levels and a total area of 16,524 m^2. From the structural perspective, the construction of this building is dependent on the slab deformation, and the limit states of the serviceability, and it has to be constantly controlled.

Figure 13: MILE office building as a rendered image (Provided by BIS structure) and during construction

4.2.1 Applicable DT data and Challenges

The construction site is located within an urban area with stringent conditions related to space and time. Due to limitations in space and implementation of traffic cuts the concrete casting is continuous, to overcome these hurdles. There are many ways through which data collection is carried out at the site such as the use of laser scanners, drones, tracking of crane movement, and measurement of concrete temperature during post-tensioning of slabs. Additionally, there is use of accelerometers to measure formworks accelerations during the vibration of concrete columns. The casting and vibration are carried out as a continuous process to maintain the construction workflow. The current monitoring method relies on visual and time-consuming feedback by project managers, which can be subjective. Therefore, with this method poor workmanship cannot be detected well on the spot; rather, the concrete is inspected and repaired after it becomes hardened. Hence retroactive quality control to achieve real-time quality assurance of concrete is necessary, which can be achieved through a monitoring and warning solution for concrete placement and vibration workmanship quality, especially in the case of a construction site where casting is continuous.

5 APPLICATION ON DEMOSITES

This section presents the CM process application implemented for the demonstration on the specific demo sites based on the site conditions, accessibility, and the DT data.

5.1 Demosite# 5 Gothenburg: Quality check during production

This section details the demonstration of the CM process for demonstration site #5 wherein the quality of product installations during construction is assessed whether it is as per requirements based on the DT data. The selected floor for demonstration is the 16th floor which serves as a hotel.

5.1.1 Quality control

Quality defects are identified and collected by different stakeholders and through different methods depending on the stage of the building project. During the construction process, quality defects are usually collected by the main contractor by means of internal quality inspections at different checkpoints in the program of works, incoming material inspections, and internal and/or external audits (Alencastro et al., 2017). Installations of quality products as per industry standards and the client's requirements are vital for the performance of the building and are essentially dependent on the quality management plan for the specific site.

Windows and doors are an important part of the building envelope and account for 20 to 30 percent of the whole building's heat losses (Ma et al., 2015). As per regulations, the most essential properties of doors and windows are related to function. Heat and sound insulation, fire resistance, and safety are the most important functional properties. Functional properties also include air-tightness, the level of rain-proofness, and wind load resistance, for which the required levels are usually stated in the agreement (Profin, 2020). Assessment of these functional properties can be done through various tests as visual and tactile inspections can only give a rough estimate. Additional steps for the quality assessment include quality of surface treatment of doors & windows, and quality of castings & frames. Meeting the requirements set for the mentioned functional properties is the most vital aspect of quality control for doors and windows.

Implementation of digital quality control for building elements such as windows & doors ensures that information is accurate, unambiguous, up-to-date, available, and provides feedback to improve production. As digital information allows linkage to other documentation and digital process, gradually introducing digital processes into building management leads to higher productivity (Synek, 2019).

5.1.2 Demonstration plan

In demo#5 the process of quality management is based on requirements specified in the contracts. The specifications for the demosite are done according to AMA (Allmän material och byggbeskrivning). AMA stands for General Material and Work Description and is a reference series intended to serve as a basis for the production of technical descriptions. The series simplifies the process of formulating material and execution requirements for all parts of the construction work. AMA is available online, as e-books, and as printed books. As an example, the specifications for the door are shown in Table 2.

Table 2: Door specification for hotel rooms

Element	Parameters	Specifications
Door unit	Door type	Internal laminated wood door, DL
	Dimensions	10Mx 20M
	Sound requirement	R w 35 dB
	Fire requirement	EL 30-SaC
	Security class	SK 3
	Locking system	Day lock

Due to the ease of the demonstration, a selected area of floor 16 (see Figure 14) of the Kineum building is chosen for demonstration, which is essentially a hotel space. In total there are 200 guest rooms among which a majority of them are similar in terms of layout and specifications. Within the ASHVIN project, partner NCC is the demo site owner as well as the assigned main contractor for the Kineum office building. To summarize the quality check process implemented at the site, for an instance for a window starts with an initial check of the order confirmation provided by the supplier. Subsequently, the next check for the requirements is done when the products are delivered to the site. The final inspection is done once the products are assembled by the relevant personnel as per the function requirement (ex: the fire engineer checks if the marking on the window glazing or the text strip on the window frame to make sure it is correct). The inspection is mostly done manually by the quality engineer at the site and the configuration information is recorded both on paper & on the Dalux software. Therefore, the aim of this demonstration is to streamline the above-stated quality check process based on DT data from the construction site and the digital asset/representation of the site on the ASHVIN digital twin platform.

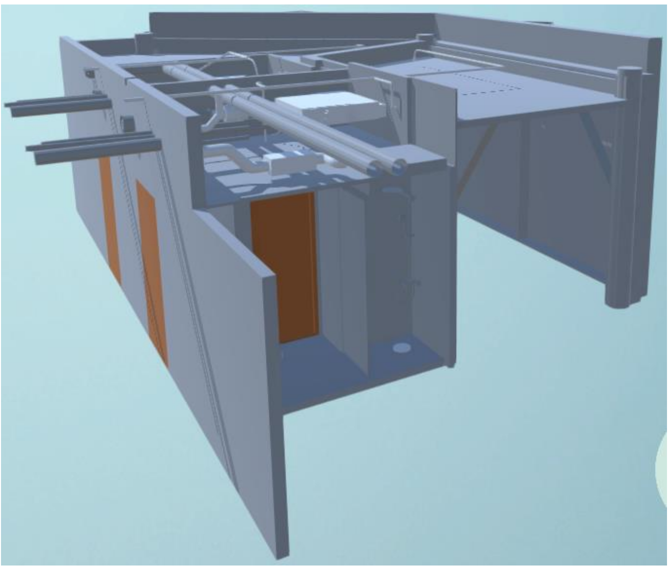

Figure 14: Selected section of the floor for demonstration

5.1.2.1 Change requests and reasons

The section elaborates on the reason for changes, provided by project partner NCC (construction company). In section 3.1.2.1, the change request and authorization process implemented by NCC was explained, hence this section explains the most common reasons for those changes (doors and windows).

In the case of windows, the most common reason is the change of maker/manufacture: as the contractor does not know who will deliver the windows till the construction phase and thus the standard measures and the fastening details can vary. Another reason is fire classification changes during the design phase when the fire engineer inspects the drawings. NCC evaluated their internal data and assed that for the projects that have reported 100929 requests in Dalux Field, 4311 requests (4%) were related to windows and the common issue were:

- Inadequate seal
- Poor window panes
- Areas with rust on the window
- Inadequate assembly/missing screws
- Areas with mortar on the windowsill
- Scratches / missing paint
- Skew assembly

The most common reasons for changes in the case of doors are: addition of doors, change of fittings, and in some cases change in fire classification and thus the change of material (to steel door). Likewise, out of the 100929 requests, 6946 requests can be associated with doors in the construction phase (7%). The most common requests treat:

- Inadequate seal/joining
- Fire door lacks marking
- The door automation not working or not connected, or the magnets/anchorage is not mounted
- Door stops missing
- Fitting not complete
- Door damaged during production

5.1.2.2 As-Designed and As-Built

“As-built” models are usually assembled reactively, following execution, and their purpose is to provide owners with models for the operation & maintenance phase-called the Asset information model (AIM) in ISO 19650 (ISO 19650, 2018). The use of the DT system to get feedback from the construction site for early detection of deviations between the as-designed and as-built products can shorten the reaction time. Evaluation of the current state (as-built) in comparison with the intended state (as-designed) at any point in time involves value judgments and must answer questions relating to the product (e.g., “Is the wall in the right place and of the right dimensions? Is the door built of the right materials, and are the necessary openings present?) (Sacks et al., 2020). As-built modeling ensures the construction site is as per the requirements and is the most important source for the quality management and configuration management processes. The as-built information can be gathered from the construction site in various forms as illustrated in section 2.6.3 of this document. Figure 15 illustrates the as-built and as-designed model comparisons of demo#5, to compare as-intended vs as-installed information types.

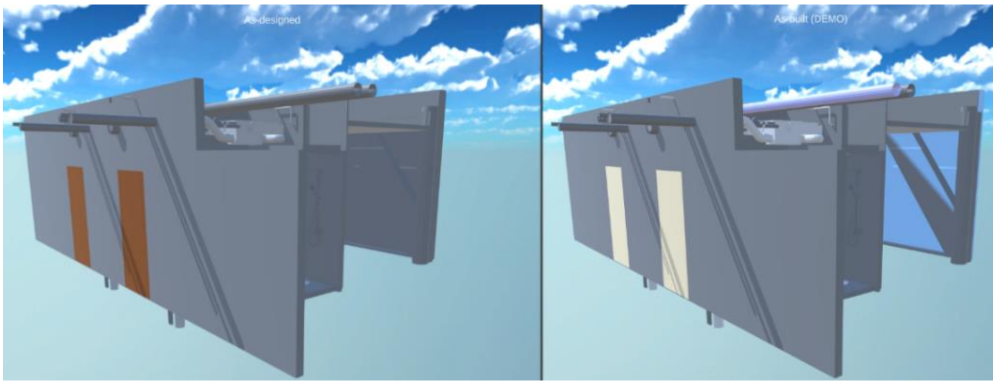

Figure 15: As-designed and As-built on the ASHVIN DT platform

For the purpose of demonstration, there is digital twin data available in the form of laser scans of the site. However, due to no asset information in the 3D model created from the point cloud, the process of verification between the requirements and the actual installed products is cumbersome. Therefore, for this demonstration, a CM database is created based on actual information from the site to carry out an as-designed vs as-built evaluation. The database contains configuration information for different building elements (door, curtain wall & pipes), which is explained and demonstrated in the next section. Additionally, it is assumed that the DT data from the construction site is gathered through digital forms, wherein the QA/QC team enters the configuration information for a particular asset during the inspections.

5.1.3 CM process demonstration

The demonstration of the CM process is primarily based on the created CM database, which is further segregated into initial and as-built databases. The parameters for the selected elements i.e., doors & curtain walls are provided by ASHVIN project partner NCC and these parameters were used for the quality check process at the Kineum construction site. Since the quality assessment is done for a hotel space, the objective is function over aesthetics. However, depending on the type of requirement the particular activity has (function or aesthetics), the inspection was done rounds to make sure that work has been done as intended with the right quality for the 200 rooms.

Figure 16 depicts the parameter verification for one of the curtain walls. The comparison is done between what is intended at the site (as-designed) and what is actually installed at the site (as-built). For the curtain walls, the aspect of thermal bridges is important and has an impact on the building's performance. Quality assurance with respect to thermal bridge effects initially takes place by optimizing details based on the calculation of the thermal bridges. Hence in the initial project planning phase, the characteristics of the building components in relation to the thermal bridge parameters are described and at the time of installation, an inspection is done to assess if they fit the description. Therefore, parameters such as thermal transmittance (U-value), supply air temperature, heat exchange, and ventilation are included in the CM database. Primary performance criteria for curtain walls for resistance to water penetration and air leakage are vital as well. However, these properties can be analyzed accurately only in laboratory conditions through ASTM standard tests. The application of CM for the quality assessment of curtain walls along with the incorporation of change management through the building’s lifecycle phases is key to the building’s performance.

Likewise for the demonstration of the CM process for the door of hotel rooms (see Figure 17) function parameters such as noise requirement, fire requirement, and security class are highly important for the quality assessment. For the sound insulation, an assessment can be carried out in a finished residential space with a mobile measuring device. Heat insulation properties can be assessed in a completed building by means of, for example, thermal imaging. In the case of quality assessment of the surface treatment of doors, it must have a uniform overall appearance. The natural grain of the wood may be slightly visible, also no finger joints should be visible on the surface of a varnished or stained product. As an example: An architect designs a double-swing door and models it as an instance of a door class with appropriate property values in a BIM model. Once the owner approves the door design, it is digitally signed by setting a meta-data property to “approved for construction”. However, due to the large size of the door, the contractor decides to procure and install the door in two parts. Therefore, through the CM tool and the CM database it can possibly be modeled into two new instances “as-procured” (later to be designated “as-built”). From the perspective of quality assessment of doors, the CM process is essential for establishing that the functional requirements are met alongside aesthetics which is of significance for this demonstration site due to the space type (hotel). Therefore, the CMT would facilitate automated sensing of the construction progress and the associated configuration information from the construction site.

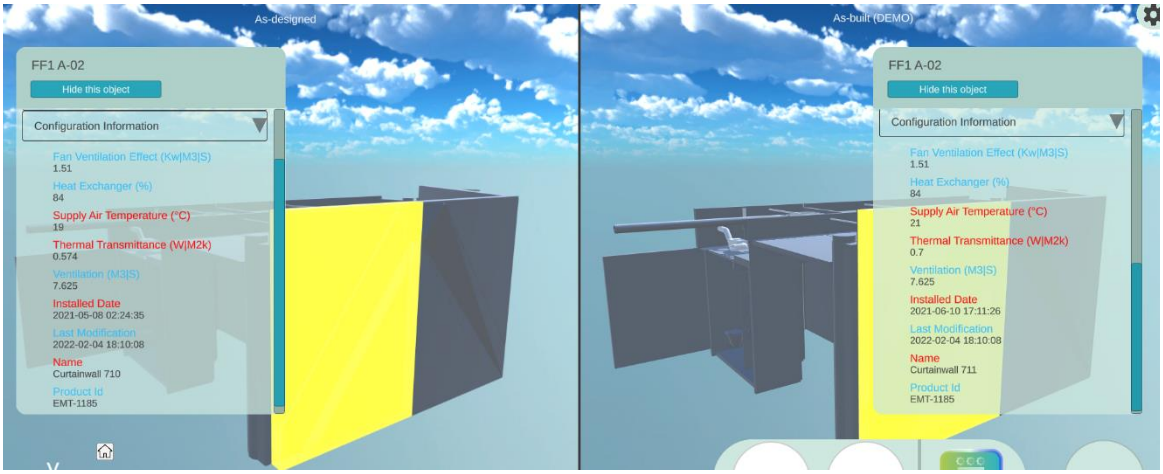

Figure 16: Configuration information for curtain wall

Figure 17: Configuration information for guest room door

5.2 Demosite# 6 Barcelona: Concrete Consolidation Quality

This section details the demonstration of the CM process for demonstration site #6 wherein the quality of concrete work is assessed whether it is as per acceptable requirements based on the DT data.

5.2.1 Concrete consolidation

Vibrating concrete is a necessity, as well vibrated concrete will be stronger. Right after the concrete is placed, it contains as much as 20% entrapped air depending on mix type & slump, form size & shape, amount of reinforcement, and the concrete placement method. Consolidating the concrete, usually by vibration, increases concrete strength by driving out entrapped air. A vibrator consolidates concrete in a two-part process. The first waves liquefy the concrete so it flows better and the continuing waves knock out air bubbles. Until both vibration stages are complete, the concrete isn’t fully consolidated (Suprenant, 1988).

For instance, it is desirable that all standard concrete columns receive a fairly evenly distributed allocation of vibrating energy. Too much or too little energy yields to the inefficiency of the energy resources or jeopardizes the quality of the concrete. Measuring standard elements, for instance, a set of columns allows controlling and monitoring the amount of energy devoted to each individual member of the set.

5.2.2 Tracking concrete vibration

Real-time monitoring of vibration quality of fresh concrete based on an IoT & convolutional neural network framework that measures vibration depth and captures concrete surface image endorses the use of digital technology for quality management in construction (Wang et al., 2021). Use of real-time 3D tracking and visualization of concrete vibration by using an ultra-wideband (UWB) tracking system to realize precise localization of the tip of an internal vibrator supports intelligent concrete consolidation. The tool of displaying vibration location and time in real-time facilitates the contractor to proactively address concrete consolidation issues (Gong et al., 2015). Furthermore, research by (S. Lee & Skibniewski, 2022) proposes a positioning-sensor-based solution for real-time management of concrete operations based on real-time warnings to managers by assessing the workmanship quality based on algorithms translating the position-sensor data.

The total amount of time can be tracked by adding vibrating sensors to key zones. Accelerometers can be coupled directly to the vibrating machine or indirectly to the formwork. In either case, acceleration will be detected while vibrating. Signals can be sent automatically to the cloud service and data can be treated afterward. For instance, casting one isolated column may last 20 minutes. Recording acceleration signals can help measure the proportion of time this isolated element is receiving energy related to the needed vibration. The amount of energy can be related to the vibration of the columns. This vibration can be measured during a casting episode. The total amount of time employed in vibrating a particular column is directly proportional to the energy required.

5.2.3 Demonstration plan

In demo# 6 one of the measurement plans was for measuring the acceleration during the vibration of formwork for columns. The concrete casting of this office building was continuous and sequential, also the accelerometer information is direct and concurrent with activity and no further data is collected once the activity is completed. Figure 18 shows the installed formwork for one of the concrete columns at the construction site. Subsequently, Figure 19 shows the finished concrete columns for level 4 after the casting of the columns is finished.

Figure 18: Concrete column formwork with installed accelerometers at demo# 6

Figure 19: Finished concrete columns

For the measurements, 5 accelerometers were installed on 5 columns between levels 4 & 5 of the buildings. Figure 20 illustrates the floor layout plan with the encircled installed accelerometers on the column formworks.

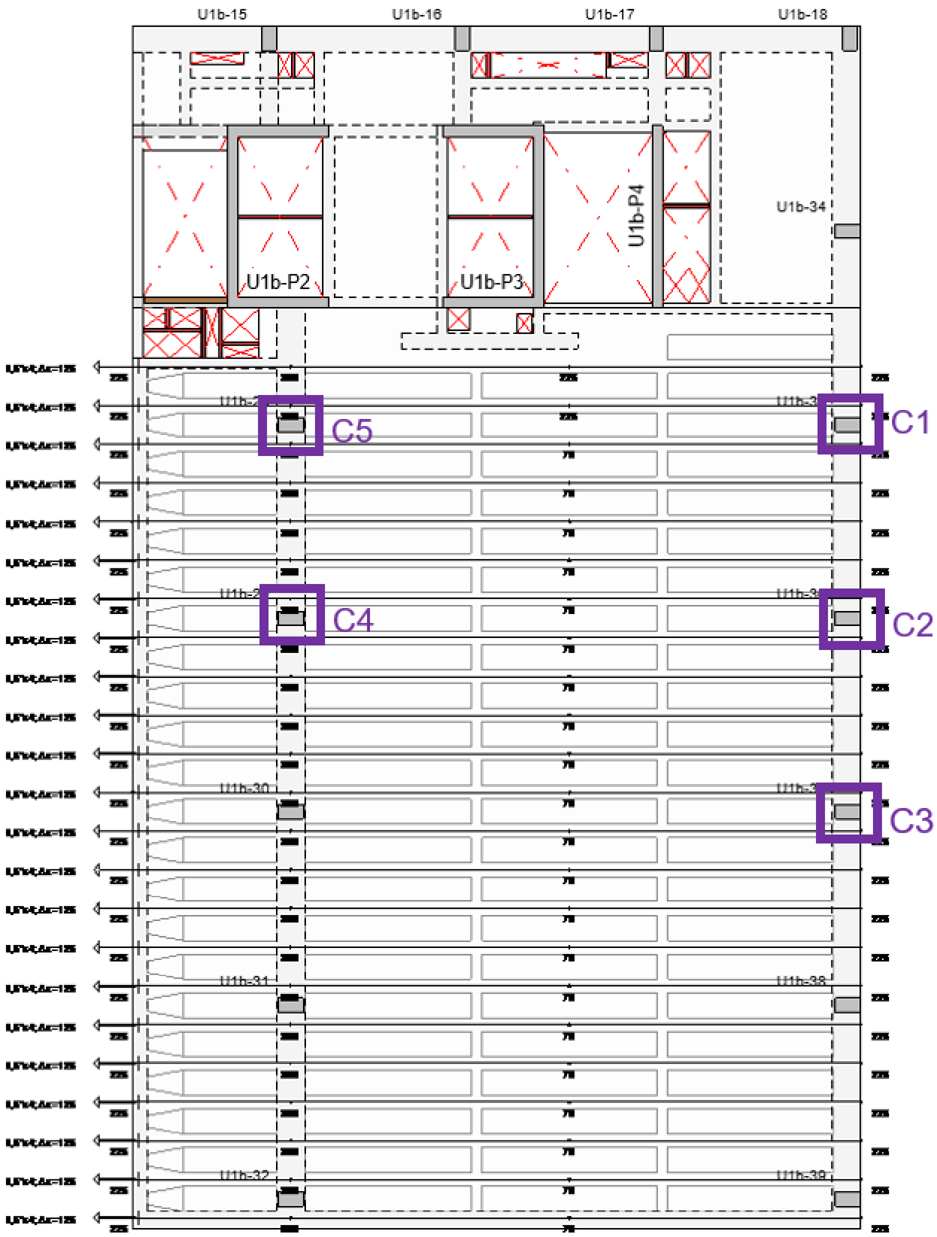

Figure 20: Layout plan with highlighted columns with accelerometer

5.2.3.1 Hardware Module

For the demo site demonstration, a high sensitivity MEMS acceleration sensor "Kenshin-kun" is used. It is primarily a vibration monitoring system with 3 axis acceleration + temperature measurement function with high sensitivity acceleration sensor. It has a temperature operating range from -20ºC to 60ºC with a measurement range of ± 2G.

5.2.3.2 Digital asset

The digital representation of the demonstration for the office building is created using the BIM file for the project, wherein additionally, the sensors are models placed on columns to represent the accelerometers on the column formwork. Only the part of the building concerned with measurements of DT data is represented and not the whole building as shown in Figure 21.

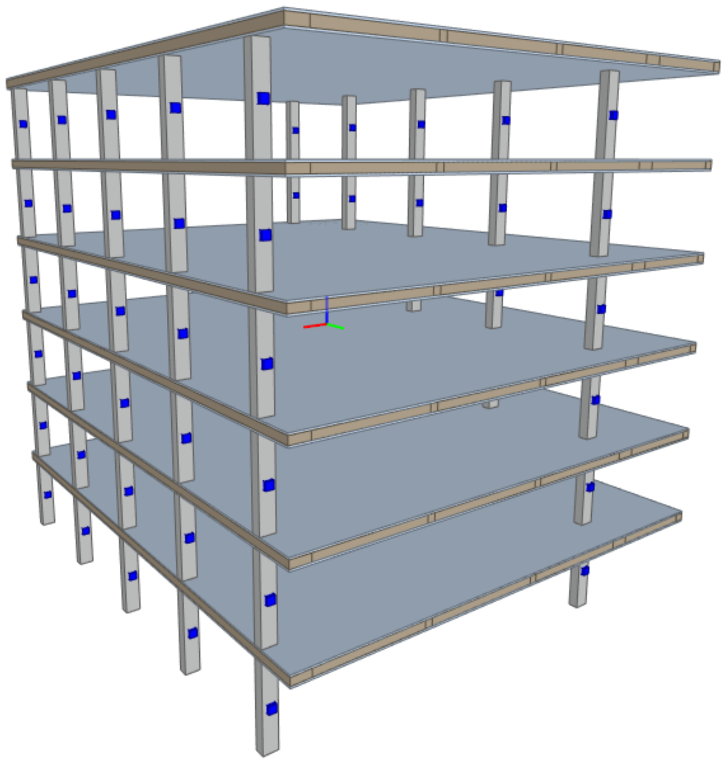

Figure 21: 3D model with the sensors (accelerometers)

5.2.4 CM process demonstration

The demonstration of the CM process based on the digital twin data is described in this section. For the demonstration, the configuration management tool is used as it is the designated tool for configuration management on the ASHVIN DT platform. As a process, it begins with the accelerometer measuring the acceleration of formwork during the vibration of concrete columns. Followings which the concrete work quality is assessed based on those measurements and a color spectrum is assigned to represent the quality of concrete consolidation work. The respective columns are then represented in those colors as per the quality as represented in Figure 22, thus giving the construction/quality manager an overview of the concrete quality work on the 3D model based on real-time measurements. Additionally, the CM tool allows for the measurements to be represented graphically with acceleration over time graphs for the highlighted columns (see Figure 23). The DT platform demonstrates information important for the construction manager alongside the graphs about the details of concrete consolidation such as temperature (sensed temperature sensors), concrete batch & mix. Figure 24 shows the vibration quality by highlighting the columns as per quality based on the vibration time, with red color indicating bad quality and green representing good quality.

As explained above the configuration management tool integrates IoT data into the ASHVIN DT platform to allow for the seamless integration of the representation of the physical asset with IoT data collected about the behavior of the physical object itself. In summary, this demonstration of the CM tool facilitates the construction manager to carry out a quality check of the concrete consolidation work for columns. As the tool analyses the concrete vibration and calculates whether these are within the acceptable range based on real-time accelerometer measurements.

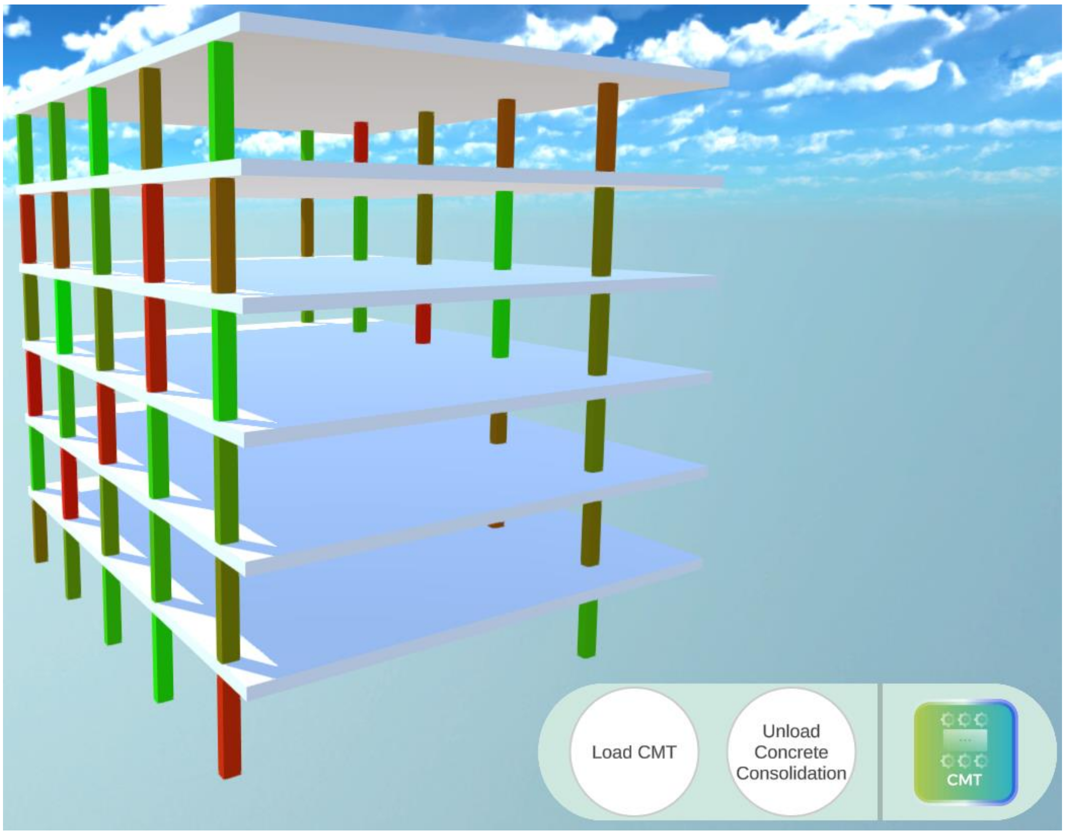

Figure 22: Highlighted columns as per concrete quality

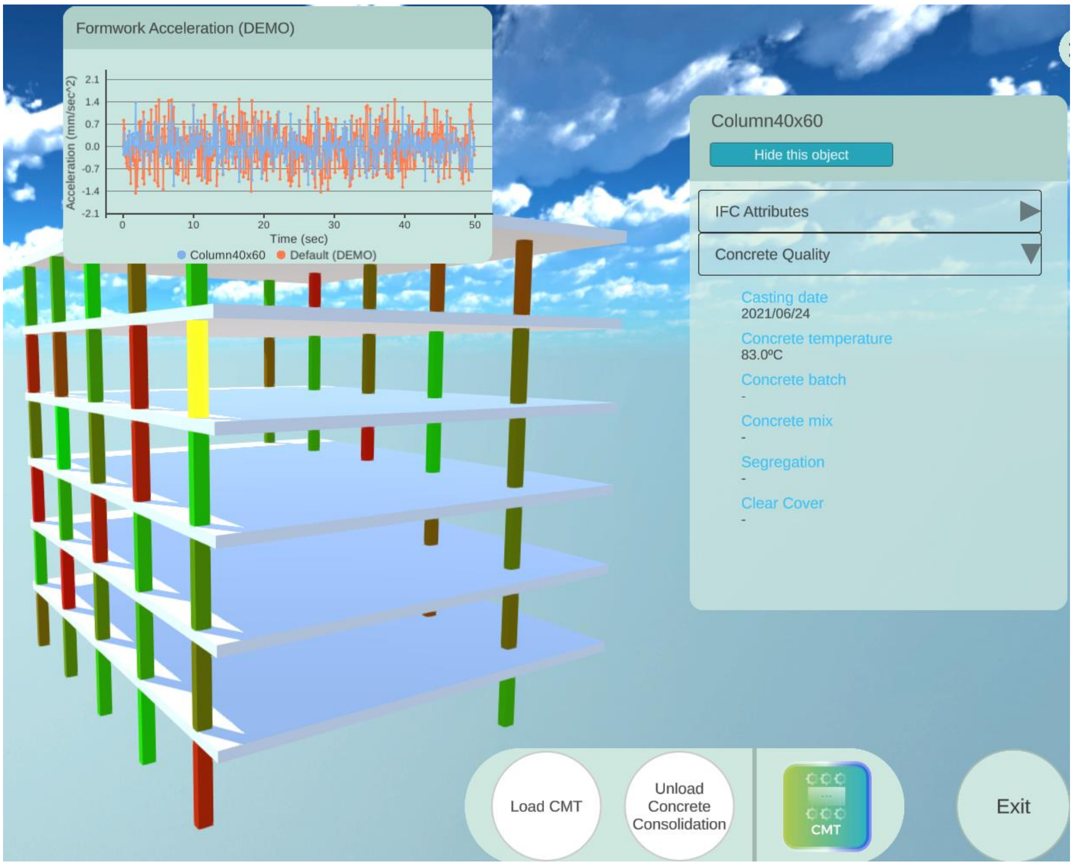

Figure 23: Visualization of DT data (accelerometers)

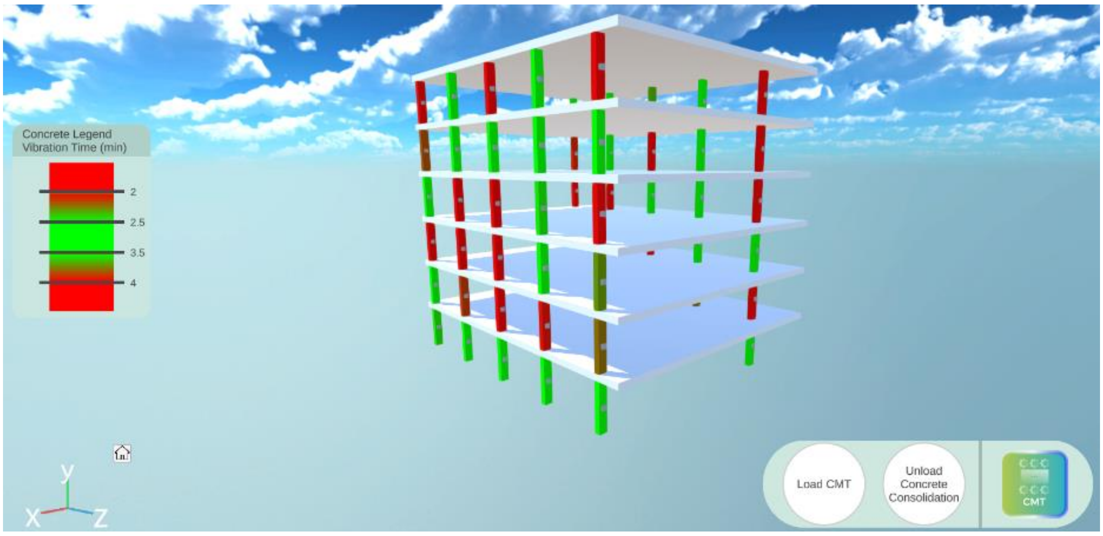

Figure 24: Vibration quality based on sensed data

6 SUMMARY

This deliverable intends to demonstrate the configuration management process for the selected demo sites (construction phase) based on near real-time feedback through digital twin data. The report presents a comprehensive literature review on the use of configuration management for the construction industry and in particular the use of digital technologies for the CM process. Although CM is not widely used in the AECO industry, the deliverable presents two case studies that apply CM. In this report, a conceptual model for the developed CM process based on five key identified areas is presented and applicable through the construction project's lifecycle. Additionally, each key area is described and how it can use different digital technology for the overall workflow of the CM process. To further affirm the CM process, it is demonstrated on real-life construction projects within the ASHVIN project.

Nonetheless, there are a few limitations to the research work done. For the demo#5 Kineum office building in Sweden, it was not possible to collect real-time data during the construction phase. Ideally, real-time data through IoT sensors and laser scanners would be valuable for the CM process. Thus, for the configuration information of products (i.e., doors and curtains) as per the installations and the actual installation done some of the parameters are assumed for the CM database. The majority of the parameters are provided by project NCC that are part of their quality assessment procedure. Ideally, the as-planned information must exist from the beginning and the real-time as-built must be used for comparison to ensure consistency is maintained among requirements and the configured items. Additionally, for the quality management on demo#6 ideally, a python script to analyze the concrete vibration quality using the accelerometer data for the data fusion layer would be essential for the implementation of quality management visualization and simulation on the ASHVIN DT platform.

ASHVIN is designed to develop the required digital twin solutions to impact the entire value chain of the construction industry, from digital service providers to construction labor. All ASHVIN innovation is targeted at improving productivity and resource efficiency. This deliverable and the configuration management tool would contribute to the ASHVIN's expected impact, by improving productivity and resource efficiency thus directly leading to an envisioned reduction of construction costs by 20% by supporting the decision process for construction projects. To summarize the deliverable addresses the lack of systematic management of configuration information. The research results from the study point to the use of configuration management based on digital twins to address many problems that come across in construction projects. The knowledge from the deliverable can be potentially used to further explore the application of the CM process in construction projects by the relevant stakeholders.

7 OUTLOOK

In regards to future developments some of the aspects that would be relevant and interesting are summarized as follows:

- Further development of the configuration management database to include specification of information for other building elements as well and allow the possibility to document changes made for the tracking of configuration information through the lifecycle.
- Development of features to use digital twin information through real-time feedback from the construction site.
- Incorporation of the As-Built model verification for construction progress and deviation check on the CMT through point cloud scans and BIM comparisons.
- Integration of a dashboard for the configuration and quality management processes for KPIs assessment.

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