Advancing Digitalisation in Construction Through Automated Metadata Management and Machine Data Processing

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Abstract
The primary objective of this study is to demonstrate that information flow can be successfully implemented in repetitive construction projects through BIM. Recent research has shown that BIM usage is often limited to the design phase and does not benefit procurement or construction. However, addressing the barriers to digitalisation during the design phase through effective metadata management makes BIM valuable and enables information to flow. The study employed the design science research method to develop a national data architecture, enabling MEP BIM information to be transferred to a data platform and enriched from design data (E-BOM) to procurement data (M-BOM). Enriching information was feasible for MEP parts and materials because the public sector has implemented a national interoperability platform. This platform previously published a national standardised MEP design nomenclature, which the research team enriched with product information using an algorithm-based solution. This solution leveraged data from the national MEP product registry through GS1/GTIN identifiers. The research team also demonstrated that MEP M-BOM data could be transmitted to suppliers via message-based communication using the PEPPOL standard. Furthermore, the proposed architecture makes it possible to perform CO2 calculations and electronic handover to the client. The research outcome forms a national reference architecture for make-to-stock products, making it applicable to other products and materials beyond MEP products. The architecture serves as a model for other production methods, such as precast concrete elements (ETO), electrical cabinets (ATO), and kitchens (MTO).

Keywords: BIM, E-BOM, M-BOM, digitalisation, supply chains, MTS, PEPPOL, GS1/GTIN

1 Introduction
The digitalisation of construction has faced significant challenges despite the widespread adoption of BIM across various types of construction. Although we design using 3D models virtually, the effects of digitalisation are not as evident on construction sites as they are in the society around us. We live in a digitalising era where various mobile applications and the automation of data processing enabled by digitalisation are visible to consumers in sectors such as electricity markets (e.g., Simion et al., 2023), food distribution (e.g., Quiroz-Flores, 2023), e-

commerce (e.g., Tang et al., 2021), and global trade (e.g., Antov, 2023). Research indicates that a critical manifestation of digitalisation, the digital twin of a product or process, is poorly defined or understood in the construction industry (Sacks et al., 2020). Simultaneously, the adoption of BIM is faltering (Dallasega et al., 2021). However, it is encouraging that, alongside this, construction research has been developing a model for a Digital Twin Construction framework (DTC). This model, introduced by Sacks et al. (2020), has been further advanced for creating simulation models (Yeung et al., 2022) and improving the quality of process information in construction using Digital Data Templates (DDT) and Digital Building Logbooks (DBL) concepts (Mêda et al., 2021). The most recent research aims to define the transition from Building Information Modeling (BIM) to Digital Twin (DT) technologies in building construction and facility management (Revolti et al., 2024). This study highlights the shortcomings of BIM and the resulting barriers that hinder the evolution towards DT. Expressly, Revolti et al. (2024) point out the following deficiencies: 1) BIM is used only in the design phase, not in construction or management; 2) BIM does not allow interaction with work processes and organisation; and 3) BIM is not 'error-free' and does not provide updated data in real-time.

Inspired by research on the DTC and the evolution from BIM to DT, the research team sought to explore how data from BIM models created with current MEP software can be practically utilised on a data platform by enriching it with product information. Given that the focus of DT research has shifted towards a shared understanding of what needs to be done to implement DT, the research team aimed to be at the forefront and investigate how a digital twin of a building can be practically realised using data from ongoing projects. The paradigm shift from "what" to "how" necessitates a change in research methodology, leading the research team to choose a design science research approach. Consequently, as the research was narrowed to include only the MEP products, it also focuses only on the manufacturing industry's Make-to-Stock (MTS) production strategy. This focus simplifies handling design and product data, as MTS products are pre-existing, and their information is available before the building's design and construction phases begin. For MTS products, the order penetration point (OPP) is closest to the customer, and the product information is static (Olhager, 2003), allowing for centralised information architecture, in comparison to ETO products which require decentralised information architecture (Alhava et al., 2024a).

The research team's primary goal is to develop a solution for digitalising the end-to-end information flow in the construction process. As this study shows, the dilemma is the discontinuities in information flow, which practically prevent MEP BIM model data from being used in procurement, subcontractor quantity takeoff, supply chain management, and on-site construction. The study forms a model for MEP information flow for MTS products, validated in three parts. This study seeks to enhance the understanding of the impact of industry fragmentation on digitalisation and explores practical methods to overcome these challenges. The study answers the following research questions:

- **RQ1:** How well does MEP design information flow from design to procurement, subcontractors, and further to suppliers and on-site personnel in repetitive construction projects?
- **RQ2:** What are the critical discontinuities in the digital flow of MEP design and product information in repetitive construction projects?
- **RQ3:** How can end-to-end information flow be implemented from MEP BIM models to electronic handover and as-built CO2 reporting required by the green transition using digitalisation?

2 Methodology

Our study, a collaborative effort conducted using the design science research method, was aimed at developing new knowledge to address the encountered problem through an innovative artefact (vom Brocke et al., 2020; Peffers et al., 2007). This approach, which involved a literature review, case study data, and interviews, generated information on how things can and should be constructed to achieve the desired goals for smooth information flow in the MEP supply chains. The study utilised data from projects involved in the case study and open interviews with participants in these projects, allowing them to share their views on the current state of information flow and its need for change. The interviews aimed to identify discontinuities in information flow and gather solution proposals from industry professionals working in various stages, functions, and roles within the construction process.

Through the case study, the artefact's functionality can be better understood in real projects (Hevner et al., 2004), which in this study means the digital information flow of construction with MEP make-to-stock products. The artefact was not just a theoretical concept but was tested and developed in the case study, ensuring its practical application. The artefact was developed based on observations from the literature, the case study, and interviews, making it relevant to real-world scenarios. It was tested in a suitable context. The artefact was divided into three components that were rigorously validated individually. This thorough validation process enabled us to confirm the effectiveness of the artefact in a shorter time frame compared to validating each component in the same construction project and introducing new methods, such as PEPPOL messages for the project organisation. All three components relate to residential construction at different stages (design and quantity take-off, procurement, and material management).

The case study consisted of three components. Two of them involved participation in two projects using takt production. The first residential project used a 4-hour takt, and the second residential building renovation used a prefabrication and just-in-time delivery schedule for a 2-hour takt (Alhava et al., 2024b). The third component of the artefact deals with the just-in-time delivery of MTS products, examining the use of electronic acceptance and internal logistics in the production of bathroom modules. Additionally, the artefact was reviewed at the LCI Congress on June 5, 2024 (Alhava and Järvinen, 2024).

3 Problem definition and artefact development

According to Anttila (2024): “Labour or materials cannot flow on the construction site unless the design information flows first.”

3.1 Theoretical background

Digitalisation opportunities, such as electric invitations for order fulfilment (call-off), material flow management, and tools to manage and update Bill of Materials (BOM), are often not utilised during construction. However, previous studies have shown that automatic data enrichment is applicable in the design and construction process as it is implemented in manufacturing (El-Haouzi et al., 2019). Since MEP systems are constructed on-site using parts and materials produced through the MTS production method, it is possible to standardise the MEP design nomenclature and create a parts list during the design phase. This is called an Engineering Bill of Materials (E-BOM) in manufacturing, used by the design engineer to represent the designed product structure. Before manufacturing can commence, suitable parts must be selected for the designed components, and the work sequence must be determined, creating a Manufacturing Bill of Materials (M-BOM) (Chang et al., 1997).

In Finland, a national MEP design nomenclature was published in 2023 on the state-owned national digital interoperability platform for digitalisation. Standardised nomenclatures for MEP design have been developed in the industry (Ministry of Environment, 2024a; Ministry of Environment, 2024b), which can be utilised on the koodistot.suomi.fi website (Digital and Population Data Services Agency, 2018). The code system defines metadata precisely, enabling the automated processing of standardised design identifiers. Correspondingly, the MEP product information is available in national product information registers in several EU countries. Finland's national MEP product information registers are LVI Info for HVAC products (LVI Info, 2024a) and Sähkönumerot.fi for electrical products (Sähkönumerot, 2024). National product information registries are transitioning from national product identification codes to globally recognised GTIN identification codes following the GS1 standard. The research team identified MEP nomenclature as a potentially valuable source for E-BOM and the GS1/GTIN product identifier as a viable unique identification code for M-BOM. The use of MTS products enables the execution of a repetitive construction project by production logic, following MEP designs and using the MEP products currently available on construction sites, allowing for the automatic transformation from E-BOM to M-BOM as described in El-Haouzi et al. (2019).

3.2 Current state

The current state is examined based on a review of the implementation process of repetitive construction projects in residential production, which, in its kind, is closest to industrial mass production in the construction business. Figure 1 shows the current state of the information flows and extensive use of PDF files in the MEP design, procurement, logistics, and installations.

The guidelines for residential production implementation, requirements for the use of BIM, and requirements for quality and its verification are regulated at the national level. The current state analysis included the requirements for MEP.

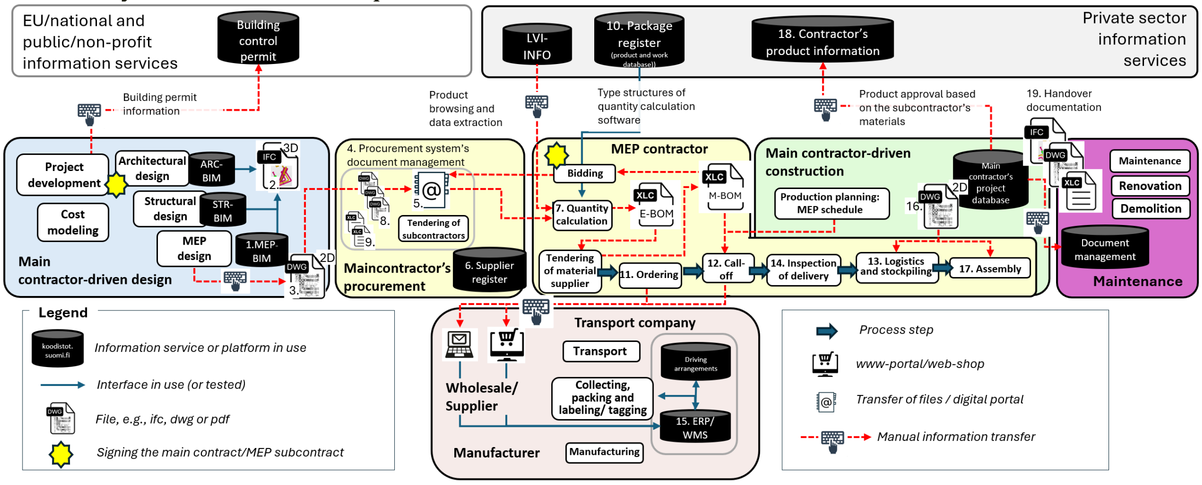

Figure 1. The current state of the construction process: information transfer by sharing files manually

3.2.1 Main contractor-driven design phase

MEP implementation planning (1.) receives input from architectural design spatial models, structural design system proposals, MEP system design's primary ducts/shafts and pipes, and reservations for technical spaces (RT 10-11066, series 1. p.11). The MEP implementation model during the design phase (RT 10-11066, series 1. p.12) encompasses at least the service areas of MEP systems, central units, ducts, pipes, terminal units, centres, conduits (cable trays and ladders), and lighting.

In residential construction, the 3D models of technical systems serve (2.) two primary purposes: 1) defining the geometry and dimensioning of individual MEP systems and 2) ensuring adequate space reservations for each system. The design of a technical system, such as a heating circuit and its associated ductwork, begins with the architect's geometric model of the entire building, into which the particular MEP system is integrated using components from the design software's library. The MEP system includes objects representing the system's central, transfer, terminal, and, to some extent, area components (RT 10-11069, series 4. p.7), and each subsystem can be dimensioned according to building regulations by separate MEP simulation software. In other words, the modelled system is functional from the perspective of the design software's calculation and analysis capabilities (RT 10-11069, series 4. p.7). Additionally, MEP designers produce 2D floor plans (3.) of the building, which depict different MEP systems separately. Designers also generate additional information from the MEP BIM model and tabulate it into separate files as attachments to the 2D drawings.

3.2.2 Procurement

In residential construction, the main contractor's bidding is based on storing the content of the project's MEP procurement package (2D plans and files mentioned above) in the procurement system's document management system (4.). From there, the companies participating in the bidding can access the 2D drawings and files in PDF format. The main contractor's procurement systems (5.) are document management and email/cloud storage systems for executing and tracking request-for-quotation and quotation transactions. The core of these systems is not information management for parts, materials, or labour (man-hour) requirements but rather the supplier register (6.) and tender/price analytics.

3.2.3 Subcontractors' quantity take-off and procurement

MEP subcontractors offer a subcontract that includes combined labour and materials (black-box bidding). Subcontractors' quantity take-off (7.) is based on 2D floor plans, typically created with each MEP system on its drawings (8.). In addition to 2D drawings, designers provided MEP system-specific supplementary information in various PDF documents, such as functional diagrams and equipment lists (9.). The information content of 2D drawings is significantly less comprehensive than the data available from the IFC model when calculating quantities of parts and materials.

Based on an MEP software analysis, subcontractors either manually count and measure the parts and materials from the 2D drawings and use Excel as a calculation tool or use 2D CAD software to re-digitalise the quantities from PDF by using 2D CAD software (Mercus Software, 2022a; Mercus Software, 2022b). Quantity take-off results in a CSV file in both methods, which is subsequently imported into the quantity take-off software where installation accessories are enriched to data using package registers (10.). Finland's national package registers are Granlund for HVAC products (Granlund, 2024) and Sähköinfo for electrical products (Sähkömaailma, 2022). These registers contain the standard structures of the technical systems and the necessary parts to construct them, organised as a rule-based data structure. The subcontractor generates either E-BOM using national design nomenclature or article-level M-BOM based on whether the subcontractor is tendering to different suppliers or distributors of the same supplier. The subcontractor tends to suppliers and uses CSV, email, or the supplier's webshop portal. The supplier completes the order as an M-BOM-level parts list using national product numbers or GTIN codes and confirms the quantities and delivery dates.

3.2.4 Call-off and logistics to construction site

As construction progresses, the subcontractor's foreman (or project manager) calls in materials based on demand in batches. Although the subcontractor could obtain the correct quantities of parts and materials for the call-off using their design and quantity take-off software, the quantities are recalculated manually on-site and per batch. The discrepancies in quantities arise because the main contractor (or the client) has updated the 2D plans and/or the actual implementation design has been determined on-site. Additionally, the foreman cannot include location information for the materials; therefore, materials are stored on-site without markings where they are intended to be used (13.). Subsequently, material deliveries are accepted manually, and documentation is based only on paper records. Similarly, random storage locations are used in storing on-site, and there is no inventory tracking at the storage locations even though suppliers´ delivery systems (Enterprise Resource Planning, ERP and Warehouse Management System, WMS, 15.) would provide digital interfaces enabling warehouse management also on-site. .

3.2.5 Construction of the MEP system

As a result, the MEP installer receives the same (or updated) 2D plan used as the basis for the quantity take-off (16.). The plumber or electrician must create the installation plan based on the 2D drawing (17.) and collect materials from the site storage or the wholesaler. The worker is usually responsible for selecting and transporting the necessary parts from the material storage location. Since the 2D drawings lack essential information on installation accessories, the compliance of the final installation with the requirements depends on the installer's professional skill. The responsibility for implementation shifts from the designer to the subcontractor, who selects the products and materials and develops the actual MEP implementation regarding the routing, dimensioning, and supports. Finally (17.), the worker measures locations, cuts necessary parts based on these measurements, and assembles parts, manually crafting a unique final product using 2D drawings.

3.2.6 Information Handover from Contractors to Client

The supervision of MEP systems and any necessary commissioning tests are carried out on a system-specific basis, with the client's inspector reviewing and approving the installations. The main contractor collects information from subcontractors about the products used and gathers the documents required for product approval, such as CE and Declaration of Performance (DoP) documentation (Ministry of Environment, 2024c). Product approval documentation is nationally stored in the Contractor's Product Information service (CPI, 18.) maintained by Rakennustieto Oy (Rakennustieto, 2024). The MEP designer reviews and marks the approved products that meet the design requirements in the CPI. Files are transferred as a batch from the CPI to the client's document management system alongside other (19.) handover materials obtained from the main contractor's project document management system and other sources, which are transferred as files either via transfer media or electronically to the client.

3.3 Artefact development (future state of the digitalisation in the MEP supply chain)

The foundation for the automation of information flow, i.e., information processing, lies in the standardisation and harmonisation of the data content in the existing design, procurement, delivery, and construction processes. The future state MEP supply chain is depicted in Figure 2. below. The starting point for data content standardisation, i.e., the definition of metadata, is the data content requirements for each phase considering the entire system's functionality. This leads to harmonising system-level data, ensuring the system's information is consistent, accurate, and up-to-date for all parties involved. System-level data harmonisation is a prerequisite for the transferability of information between systems and for its enrichment with structured data from other sources. In other words, metadata is defined, for example, for design, precisely according to the downstream requirements and information needs of procurement or the customer. The system and its components are illustrated in the figure below.

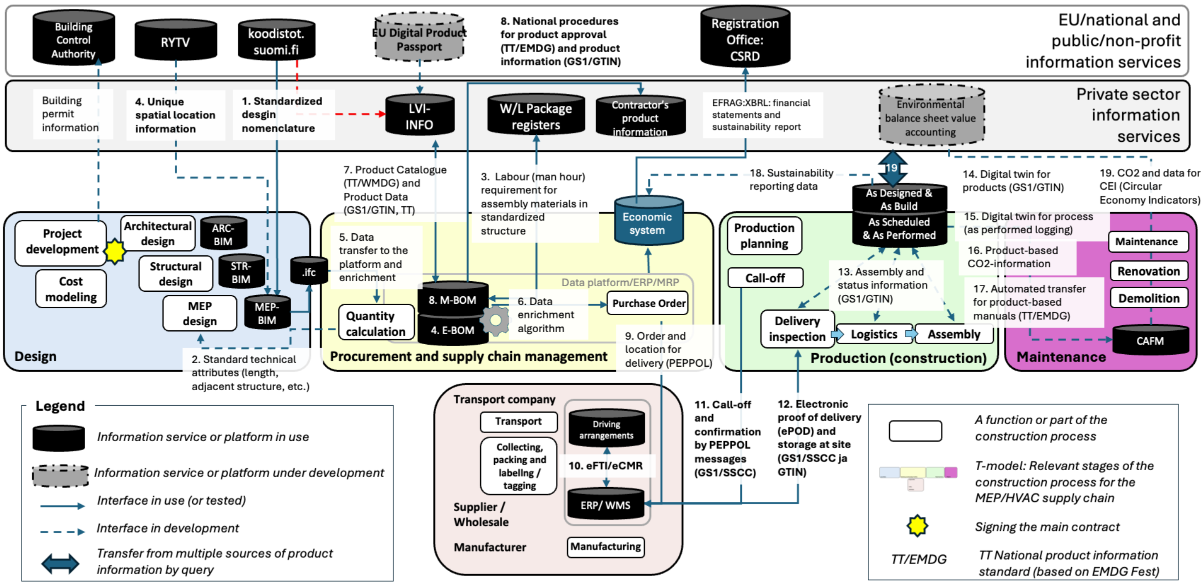

Figure 2. Functions, data warehouses, and data flows in the design-procurement-manufacturing-construction-maintenance process

3.3.1 Design

In the design phase, the goal is to plan a cost-effective building services system that complies with building regulations and requirements so that information about the system components, materials, and dimensions is obtained in a machine-readable format for further enrichment in quantity take-off. The design process involves dimensioning the MEP subsystems to ensure compliance with functional requirements. For MEP systems, standardised design nomenclature (1.) and the necessary standardised technical attributes (2.) required for E-BOM formation must be incorporated into the BIM objects.

The design should include installation-technical information in the model as attributes for different subsystems so that the necessary installation parts can be enriched for the relevant subsystem components using the package register (3.) during the quantity take-off. The design should also add a unique spatial location as an attribute (4.) for the object so that it can be machine-read from the BIM object's data into E-BOM data.

3.3.2 Quantity take-off and procurement

Quantity take-off is carried out by automatically converting the data from BIM objects of MEP systems into a structured form on a data platform (5). In automated data collection, BIM object attributes are transferred from BIM into a database table. These attributes include the standard technical attributes for certain object types (2.), the standardised location information (4.) (e.g. unique code for the location) with the accuracy required by the data platform's or ERP's/MRP's algorithm (6.) in order to create the M-BOM.

Package registers (3.) could enrich the data with the assembly accessories needed for installation. The installation-technical information from the BIM data about the part or adjacent parts (e.g., a wall type or whether the air duct is wall- or ceiling-mounted) is necessary to enable the utilisation of algorithms to enrich the data automatically. In this manner, the quantity and detail accuracy of the BIM models do not need to be increased. For example, the parts required for duct support can be enriched algorithms based on the information obtained from the BIM. The BIM attribute information should be enriched with an estimated wastage during installation. M-BOM consists of the order rows for each supplier from the data platform/ERP/MRP.

Quantity take-off generates information in a structured form indexed by locations. BIM objects should include unique spatial locations (4.). The location information is used to plan the material arrival, storage and internal logistics at the construction site. With the location information, the material supplier can also carry out the delivery for the installation site in an optimal manner by utilising automated collecting, packing, and labelling processes. This supports transferring the consolidation point of MEP materials from the construction site to the supplier. Consequently, on-site logistics is streamlined as proper deliveries are packed off-site.

Supplier's parts and materials have a unique product identifier that helps to identify the product. The goal of quantity take-off is to enrich E-BOM with product identification, resulting in M-BOM. Procurement personnel choose the materials from the supplier's product catalogue and enrich E-BOM into M-BOM by enriching the BIM object's data with a product identifier (7.) identifying the product as a particular supplier's exact product (e.g. purchasing article).

M-BOM includes product-specific (GTIN) information on all MEP subsystems and the parts and materials needed for installation, indexed by unique spaces. In the procurement phase, product identification information for the products intended to be used on-site is transferred to the contractor's commercial system (8.) using the product identification for the national procedures for the designer's product approval required by law. Procurement completes the order with the delivery location and estimated delivery times. The order is electronically transmitted from the procurement system to the supplier using PEPPOL-standardised order messages and data contents (9.).

3.3.3 Call-off to the construction site and logistics

The call-off process is implemented by grouping unique locations into blocks, executed according to the production schedule. Production plans and construction progress determine the delivery time frames, specifying the earliest and latest time when materials must be delivered to the installation site.

Based on the project's progress, the call-off (11.) for products and materials is sent to the wholesaler and transport company, which either confirms or rejects the delivery with updated details. The upstream must produce M-BOM data on the data platform in a structured form for the call-off, ensuring that each product is assigned a subcontractor, a unique location, the order number, and the wholesaler. Based on the locations and other product attributes (e.g., sizes and weights) in the M-BOM, the order is divided into transport units and loaded onto carriers, with machine-readable labels on both the transport units (SSCC) and products (GTIN). The supplier can automate the collection, package size selection, packing, and labelling using the enriched M-BOM information. The wholesaler can also electronically confirm the delivery time, transport units, and carriers to the site logistics team.

Site logistics electronically receives (12.) the delivery using the delivery number and receives each package based on the SSCC barcode. The packages can then be transported to the installation location or designated storage location based on the delivery labels. Product-specific electronic receipts can be generated using the GTIN codes from the parts list retrieved via SSCC.

If any deficiencies are registered, the inventory balance at the storage on-site is updated according to the number of delivered articles.

3.3.4 Construction of the MEP system

The installer or production planning team receives confirmation from logistics regarding installation readiness based on the electronic delivery inspection of the called-off materials. The installer retrieves the necessary parts and materials from the storage location and proceeds with the installation. The installer electronically confirms the materials used and their quantities using GTIN barcodes, reporting any deviations in quantities or implementation plans through the electronics systems. The installer reports (13.) the installation status as completed (or interrupted) in the scheduling software and reports deviations. The information generated from the installation includes the installation task, the installer's tax number, the parts or materials used (GTIN), the number of parts, the unique installation location, and any preset/adjustment values. This process generates as-built information on the parts and materials used (14.), which must be entered into the financial and procurement system as a basis for sustainability reporting.

3.3.5 Electronic handover and automatic carbon footprint calculation

The project's main contractor compiles the as-built information on the MEP products and materials used during the construction phase, creating (14.) a digital twin of the product. Simultaneously, the main contractor can develop a process twin (15.), consisting of data on who installed what, when it was installed, who inspected it, and how any corrections were made. For the MEP systems, the main contractor hands over the M-BOM data, including the unique information for each installed part and material (GTIN), quantity, unique installation location, preset/adjustment values, installation date, and implementing party.

During handover, it is possible to automatically (16.) calculate the carbon footprint using machine processing based on the product-specific CO2 information in a structured format. Additionally, maintenance instruction bases (17.) required for upkeep can be created using TT (LVI Info, 2024b) / EMDG (FEST, 2021) standards for machine processing, facilitating the transfer of product information, such as user manuals, into the maintenance document management system. Thanks to the structured format, the client or building maintainer can transfer the necessary information into the maintenance system either automatically through system interfaces or manually.

3.3.6 Sustainability reporting and accumulation of product information required by the circular economy

Company financial statements and (18.) sustainability reporting are conducted, for example, through the financial system using machine-readable formats such as EFRAG's XBRL (EFRAG, 2024). Sustainability reporting and billing information are compiled from the ERP and data platforms. The accumulation of information required by the circular economy, necessary for end customers, is achieved (19.) by enriching the data content of the product and processing twins with product-specific recycling information. The breakdown of the building's balance value, required by the circular economy, into different materials and parts for recycling purposes has not yet been standardised. However, efforts are being made to standardise these circular economy indicators information across different product groups.

4 Artefact validation

4.1 Validation process

The end-to-end digitalised MEP design, procurement, delivery, and construction process was validated in three parts, using two projects (residential and plumbing renovation), simulations, and the prefabrication of bathroom modules as case studies.

4.1.1 Artefact Component 1: Quantity take-off

The research team standardised the information content of the MEP BIM together with the teams from an MEP design company and the main contractor. The MEP designer created an MEP data model using an object library in which design items adhered to the MEP nomenclature (Ministry of Environment, 2024b). In the case study, the quantities of product parts and the lengths of ducts for the entire building's ventilation system were transferred to the data platform in a structured format using the design firm's software. The design data was separated from design software into a structured format on platforms, where it can be enriched to form product identification, technical attributes and labour requirements. Based on the study, the research team concluded that design items should be divided into two main groups: product parts and materials. Product parts are installed as-is and thus can be selected based on additional information using algorithm-based processing. Material information pertains to materials measured in running meters, for which the total usage of the part must be calculated separately to determine the required amount of material. The team enriched the parts list with location information and generated transferable E-BOM data for the system.

4.1.2 Artefact Component 2: Procurement

The research team transferred the E-BOM platform containing the selected MEP supplier's product catalogue information. The main contractor's procurement and IT team transferred catalogue information from the national MEP product data register using TT-standard (LVI Info, 2024b) for batch processing. The main contractor's team created processing rules to generate a quantity list by location using the design items from the E-BOM. A challenge in the enrichment process was the formation of rules, as the product identification did not include a data field for standardised design nomenclature at the time of validation. To address this gap in automated enrichment, each product in the catalogue must be classified in the ERP by adding a design nomenclature identifier. This is an illogical implementation from an information architecture perspective, as it would need to be applied separately to all procurement systems. The research team proposed adding a nomenclature identifier to the TT-standard. The research team investigated the execution of orders using PEPPOL messages and, based on the validation, determined that the data fields and contents of PEPPOL are sufficient for placing MEP orders via messages.

4.1.3 Artefact Component 3: Call-off to the construction site

Call-offs were made electronically, using location and takt production carts. Hence, the supplier received the installation location on the site per order and used automated collecting, packing, and labelling for precise deliveries. The supplier equipped the transport units with SSCC identifiers to enable machine reading. Site logistics transported the transport units received from the supplier to the correct apartments based on the installation location markings. Due to system limitations, SSCC barcodes could not be validated on-site; only the electronic proof of construction material deliveries could be verified. The digital receipt of MEP parts, identification of transport units, delivery inspection, unpacking to storage locations, and updating inventory balances were verified in the case of the factory-assembled bathroom modules.

4.2 Validation results

4.2.1 Artefact Component 1: Quantity take-off

The research demonstrated that an E-BOM can be generated from the BIM model using standardised design nomenclature identifiers and that parts list data can be enriched with location information and technical attributes (E-BOM). Standardised design identifiers can thus replace the custom nomenclature used by design offices and individual designers, which hinders currently the automated processing of BIM data. The research also indicated that defining a building space identification (unique spatial location) code system at the EU level is justified.

4.2.2 Artefact Component 2: Procurement

The validation of the artefact demonstrated that the E-BOM generated from the MEP BIM could be enriched into an M-BOM using algorithms, incorporating the location data required for call-offs and internal logistics at the construction site. The research indicated that PEPPOL is suitable for ordering MEP products. The study highlighted challenges in implementing the enrichment algorithm: 1) rule-based enrichment is difficult to achieve unless a standardised design nomenclature identifier is assigned to each item in the product catalogue, and 2) different types of products and materials have varying sets of technical attributes, which need to be standardised and integrated into the respective objects in the MEP BIM model.

4.2.3 Artefact Component 3: Call-offs to the construction site

The study verified that SSCC and GTIN information transmitted via PEPPOL messages enables electronic receipt of deliveries using a delivery number, receipt per container, inspection of product quantities, and storage using predefined storage locations and inventory balances. The validated system's data content enables internal logistics at the construction site, similar to those in manufacturing industries. The most significant shortcoming identified in the systems and data definitions during the study is the lack of location and delivery time window information in the ordering systems. The study did not find an applicable standard, and the scheduling software used at construction sites lacked an interface to automatically retrieve this information for making call-offs through the site's scheduling software.

5 Conclusions

The research confirmed the synthesis presented by Revolti et al. (2024) that "BIM is only used for the design phase and not in the construction and management phases" when examining the use of MEP BIM in repetitive residential construction projects. (RQ1) MEP designers used BIM for sizing and geometry, but the main contractor's procurement, subcontractor's quantity take-off, logistics, and on-site construction relied on 2D drawings. As a result, the MEP process's most significant discontinuities (RQ2) are using 2D drawings in the main contractor's bidding activities and construction. This forces the subcontractor to calculate quantities from 2D drawings, even though the data could be directly obtained from MEP BIM. Similarly, the use of 2D drawings prevents the utilisation of digitalisation downstream in the process, leading to the need to recalculate quantities manually when calling off materials, managing logistics on-site, and during installation. This explains a significant portion of the waste observed in MEP work by Seppänen et al. (2021). The digitalisation of the MEP process from end to end (RQ3) requires the standardisation of design data within the MEP model, the addition of spatial information, and the standardisation of product-specific technical attribute data to generate E-BOM information from MEP BIM. This information must be enriched on a data platform and added to M-BOM using standardised product information (TT/EMDG and GTIN standards). Achieving this requires harmonising product information, for example, using the GS1 standard family. Product identification enables the enrichment of carbon footprint data, provided that CO2 information can be retrieved from national product information registries (or, in the future, EU digital product passports). The study successfully addressed the research questions and developed a systematic solution for enabling end-to-end information flow from design to handover for MEP products.

5.1 Limitations and further studies

The study was limited to repetitive construction projects. In projects executed under different contract types, it may not be possible to appropriately select and standardise the nomenclature used, making it challenging to implement digitalisation in the manner the research described. The study focused solely on MEP products manufactured using the MTS (Make-to-Stock) production logic. As such, the proposed solution is not directly applicable to non-MTS products. For example, producing precast concrete elements requires design work, aligning it with manufacturing industries' Engineering-to-Order (ETO) production logic. Similarly, electrical panels are assembled from standard components, categorising them as Assembly-to-Order (ATO) products, while kitchens, which are produced based on specific orders, fall under the Manufacturing-to-Order (MTO) category. The standardisation of design nomenclature and the identification of product information will likely need to be implemented differently, depending on whether the production method is ETO, ATO, or MTO. The product-process matrix indicates which production system should be chosen based on the product range (Hayes & Wheelwright, 1979). Different products require different operating models to ensure the production system runs smoothly. MTS products belong to inventory-driven production, where products are manufactured to stock and delivered to customers based on order.

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