BIM Data Content Guiding Takt Production Material Flow: IFC Meets MTS Supply Chain

Otto Alhava[1,*,†], Jyrki Oraskari[2,†], Tommi Arola[3,†], Tero Järvinen[4,†], Markus Järvenpää[4] and Bettina Ruottinen[5]

[1] Fira Oy, Teknobulevardi 3, 01530 Vantaa, Finland
[2] Chair of Individualized Production, RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen, Germany
[3] Rakennustietosäätiö RTS sr, Malminkatu 16 A, 00100 Helsinki, Finland
[4] Granlund Oy, Malminkaari 21, 00701 Helsinki, Finland
[5] Aalto University, Otakaari 24, 02150 Espoo, Finland

Abstract
The stagnation of the construction industry and the lack of productivity growth stem from the separation of design and construction. Although the industry uses various supply chains, it remains largely dependent on manual production and has fallen behind other industries. Inspired by takt production, this study aims to integrate design and manufacturing by streamlining the information flow from BIM/IFC to procurement, supply chain management, and construction. The research focuses on HVAC systems and aims to determine how the design, procurement, manufacturing, and logistics of ventilation products and materials can be integrated as a digital information flow using existing systems and technologies while complying with EU regulatory requirements. The study used a design science approach, modelling and optimising information flows and conducting proof-of-concept testing, which demonstrated the potential of automated data enrichment. In conclusion, the data content of the IFC design models is readily extractable and automated data processing routines can significantly reduce manual work.

Keywords
BIM, IFC, automated data processing, Linked Building Data, IFCtoLBD

1. Introduction

The stagnation of the construction industry and its lack of productivity growth stem from the separation of design and construction [1]. Although the construction sector is part of the manufacturing industry and relies on various supply chains of the construction product industry [2], [3], [4], [5], it remains predominantly based on craft production [6]. As a result, it lags significantly behind other manufacturing industries in terms of developing its production system. This lag is so pronounced that research has highlighted the need for a dedicated production theory for construction [7]. In contrast, manufacturing industries have already developed models for different product-specific production strategies and the corresponding implementation logic for production systems [8]. The advanced state of manufacturing is further demonstrated by the fact that each type of manufacturing system has its production theory (or theories) [9]. Since the 1980s, these theories have been successfully simulated and controlled through computerised real-time systems within various factory layouts [10], [11], [12].

This study is inspired by the growing adoption of takt production in construction [12], [13] and the ongoing development of its production system [11]. When implemented as an actual one-piece flow [14] takt production reveals upstream inefficiencies [15], which becomes more evident as takt

LDAC 2025: 13th Linked Data in Architecture and Construction Workshop, July 09–11, 2025, Porto, Portugal
* Corresponding author.
† These authors contributed equally.
otto.alhava@fira.fi (O. Alhava); oraskari@ip.rwth-aachen.de (J. Oraskari); tommi.arola@rts.fi (T. Arola); markus.jarvenpaa@granlund.fi (M. Jarvenpaa); tero.jarvinen@granlund.fi (T. Järvinen); bettina.ruottinen@aalto.fi (B. Ruottinen)
0000-0001-8820-0522 (O. Alhava); 0000-0002-4723-3878 (J. Oraskari); 0009-0004-0535-8295 (T. Arola); 0009-0008-4158-1581 (M. Jarvenpaa); 0009-0004-6532-1769(T. Järvinen); 0009-0008-0312-1023 (B. Ruottinen)

time is reduced [16]. In manufacturing, the successful application of takt production requires standardised work and flawless material flow management [17]. However, these two aspects cannot be realised without mastering product design, including all product details [18] and integrating design for manufacturing (DfM) principles [19].

Research has shown that building information models do not effectively support downstream processes beyond the design phase [20]. However, the manufacturing industry successfully addressed the challenges of integrating product and production design by digitalising information as early as the 1990s [11]. The models used in manufacturing must also apply to the construction industry, as construction itself is a form of manufacturing, albeit in much more primitive conditions compared to modern production.

External pressures, such as CO_2 regulation, labour shortages caused by an ageing population, climate change, and the adoption of artificial intelligence in other sectors, are driving the construction industry to adopt new technologies and methods more rapidly. The performance of the construction sector at the EU level is increasingly monitored through measures such as the Energy Performance of Buildings Directive (EPBD) and the Construction Products Regulation (CPR). Furthermore, the research team is motivated by findings from a national data flow architecture developed for the two extremes of supply chain types used in construction: Engineer-to-Order (ETO) [4] and Make-to-Stock (MTS) [2]. This architecture demonstrates that by standardising the data content of information models, it is possible to replace 2D drawings and elevate BIM to a systemic role equivalent to that of Computer-Aided Design (CAD) data in manufacturing industries. The research team strongly believes that the national data flow architecture [2] will also provide the means to enhance the construction industry's ability to respond to the new challenges posed by climate change.

1.1. Research Focus

This study aims to bridge the gap between the design carried out using Building Information Models (BIM) and the in-situ installation of HVAC products, employing the same methods applied in the manufacturing industry. This research focuses on integrating BIM design data with actual in-situ engineering design and product installation performed by subcontractors. Additionally, the study aims to establish a continuous data flow for a designer's 3D model and data content, supporting detailed design, procurement, supply chain management, logistics, and finally, installation. The objective is to systematically integrate design and detailed design, including product and material selection and quantity take-off, and transform current construction processes into design and assembly that align with the manufacturing industry's production logic.

The study is limited to building services engineering, specifically ventilation systems in residential buildings, to narrow the scope of data processing to an MTS supply chain and a manageable amount of design data. The research is based on the Finnish national data flow architecture defined for the MTS supply chains [2]. The study validates the current data flow through a case study of apartment-specific ventilation systems, analysing and modelling the design, supply chain and construction data management processes in two projects.
This study aims to address the challenges of data flow in the construction industry by answering the following research questions, thereby complying with EU regulatory requirements.

1. How can design, procurement, manufacturing planning and execution, logistics and installation be implemented as a digital information flow for HVAC installations in construction using existing systems?
2. What new methods and technologies are required to implement a digital information flow to meet EU-level regulatory requirements for HVAC installations?

The following section presents the state of the art. The third section discusses the research methodology. The fourth section presents the results, and the fifth section provides an analysis of the findings. The sixth section discusses the broader applicability of the results. The final section presents the study's conclusions regarding the achievement of its objectives and provides a summary of the findings.

2. State of the Art

2.1. Research Findings on BIM Utilisation in Construction Supply Chains

Research to develop the national data flow architecture revealed that the data content of HVAC BIM is not used in procurement, supply management, site logistics, or the actual installation process, i.e., construction [2]. This finding is consistent with the results obtained by Revolti and his research team [19], which showed that BIM is used only during the design phase but not in construction or facility management. Instead of leveraging BIM, downstream processes rely on 2D PDF drawings, from which the necessary information is extracted and calculated manually [2].

The national data flow guidelines propose standardising the design data incorporated in the BIM model to address this issue. The proposed solution involves exporting the design product data from the BIM model to a data platform (Engineering Bill of Materials, E-BOM), enriching the data into purchase items (Manufacturing Bill of Materials, M-BOM), and integrating it into an enterprise resource planning (ERP) system. Additionally, orders would be processed using the Pan-European Public Procurement Online (PEPPOL) standard, enabling digital call-offs for construction sites, electronic material flow management, and creating a digital twin [20].

However, a significant challenge in practical implementation remains: The national data flow architecture does not specify the technologies or methods required to enrich the BIM data content in a format compatible with ERP systems. This gap hinders the real-world adoption of the proposed digital workflow.

2.2. Level of Digitalisation in Construction Processes

Data transfer in construction processes is still primarily based on manually exchanging files between different systems and organisations. Existing standards, such as ISO 19650 [21], reinforce this practice [22], which recommends the use of a Common Data Environment (CDE) as a centralised source of information [23]. Although the construction industry has been using BIM for 3D design for over two decades, its level of digitalisation remains significantly underdeveloped compared to the manufacturing industry [24].

Manufacturing industries have successfully integrated product design, production planning, and manufacturing into a coherent model and production system [12], [25], [26]. The construction industry, which is also a form of manufacturing, has yet to achieve this level of integration. Instead, design, production planning, and manufacturing have remained separate in terms of organisation, business operations, and digitalisation. This situation is particularly evident in the way BIM is utilised in the sector.

The seven dimensions of design defined for the industry do not address procurement or supply chain management. These dimensions include geometry (3D), time management (4D), cost estimation (5D), environmental and sustainability data (6D), and facility management information (7D) [19].

2.3. Enabling Data Flow in Construction Processes

This study is based on the hypothesis that construction, as a form of manufacturing, does not fundamentally differ from other manufacturing industries. However, it has lagged over a century in developing manufacturing system theories, still relying heavily on craft production. If this hypothesis holds, then the construction industry's flow of information and digitalisation can be implemented using the exact mechanisms currently applied in automated manufacturing.

Manufacturing and its automation are based on integrating design software with various industrial-scale machining software, a development that emerged during the Third Industrial Revolution [27], [28]. At that time, the alignment of digital information systems in manufacturing enabled the digital control of production lines through CAD/CAM systems and their integration with customer interfaces, forming what became known as Computer-Integrated Manufacturing (CIM). Manufacturing industries distinguish between the design and production phases in terms of data content. In assembly-based manufacturing, the BOM is separated between the design and post-procurement phases, which rely on standardised components sourced from multiple suppliers. During the design phase, the bill of materials does not specify the supplier but only defines the general component type; the Engineering Bill of Materials (E-BOM) [29] is used for this purpose. As the designed product progresses to the production phase, decisions regarding suppliers and materials must be made. At this stage, the components or materials purchased are identified using supplier-specific part numbers, forming the Manufacturing Bill of Materials (M-BOM) [29].

2.4. Machine-readable data in construction and opportunities of Linked Building Data

Research conducted in the construction sector indicates that design for manufacturing (DfM) is mainly absent from construction processes [3]. This is evident in the limited use of prefabrication, which is applied only in specific product categories, such as prefabricated modular bathroom units, or in special projects, including large-scale, time- and space-constrained projects delivered using collaborative contracting models.

Due to increasing environmental requirements and the digitalisation of the construction order-to-delivery chain, various data contents, types, and formats must be effectively integrated. Some data are highly standardised, while other data remain unstructured. In construction design, native BIM software applications are used as desktop tools, each developed for specific design purposes, such as architectural, mechanical, electrical or structural engineering. These applications adhere to strict data standards, rendering free-form data enrichment using traditional database methods either impossible or highly challenging within native BIM software. The varying levels of metadata definition in BIM content can also be observed in the fragmented implementation of different types of machine-processing applications. Several tightly scoped solutions have been developed for machine-readable data processing, such as automatic door annotation [30] and automated verification of requirements for precast concrete [31]. By using these niche solutions, significant efficiency gains can be achieved in the design and construction process. In the latter example, the automated verification enables smart services by which stakeholders can assign measurable properties of the precast concrete modules to the requirements, thus allowing a computerised quality check [31]. The issue with these solutions lies in their point-by-point nature rather than forming part of a systemic approach. BIM data should serve as a starting point for enrichment within traditional information management systems without requiring native BIM software, as many stakeholders in the construction value chain are unfamiliar with BIM models. This approach would enable non-BIM-based information systems, such as enterprise resource planning (ERP) systems, to integrate more seamlessly with BIM-related data. Loading the content of BIM models into a graph database, where design data can be enriched through database operations linked to product databases, can enhance data enrichment and interoperability.

The World Wide Web Consortium (W3C) Linked Building Data group aims to develop standardised ontologies for the architecture, engineering and construction (AEC) industry and establish best practices for the sector. One of the key concepts is the modular use of ontologies to facilitate the publication and accessibility of information. Bonduel et al. demonstrated in 2018 that this applies to

IFC-based building data using building element attributes as examples [32]. Based on this, Linked Building Data (LBD) emerges as a promising technology that we explore in this study.

3. Research Methodology

The study employed the design science method. In the first phase, the research team modelled the information flows of an apartment-specific HVAC system throughout the design, procurement, supply chain management, logistics, and installation stages to validate the national data flow architecture. The research focused on typical new residential construction projects in the Finnish market.

This study analysed two completed projects using the MTS (Make-to-Stock) supply chain data flow architecture as a reference framework for the current and target states [2]. Data from the construction phase was gathered through interviews with site managers and HVAC installers, documentation of installation work, collection of 2D drawings used on site, and video recordings of the installation process.

Section 4.1 analyses and documents the results of the first phase. These results are compared with the MTS product data flow architecture [2], allowing the current state analysis of the HVAC system information flow to be visualised as a data flow architecture in Figure 1. In the second phase, the data flow architecture created an optimised data flow for the HVAC components and materials studied. Standardised design nomenclature enabled machine-readable data processing and compliance with environmental requirements. Optimisation was carried out by structuring the data content of the completed projects, which was then used to implement the target state system. The systematic solution developed in this phase, which facilitates the digitalisation of the entire ventilation system supply chain—from design to management and execution- was documented as a data flow architecture in Figure 2. The third phase involved a proof-of-concept test of the data enrichment process using the IFCtoLBD converter to generate linked building data and enrich it from IFC to M-BOM. The outcome of this phase was a digitalisation artefact that demonstrated machine-based data enrichment, presented in Section 4.4.

4. Case Study

4.1. Current Digital Information Process in Design and Installation of Ventilation System

In both studied residential construction projects, the main contractor used the design-build project delivery model to execute the project, and the ventilation design was outsourced to an external design company. The process followed by the principal contractor, designers, and subcontractors is illustrated in Figure 4, with references in this section corresponding to the numbered steps. The national BIM modelling requirements and process for HVAC design are defined in YTV2012 [33]. The YTV2012 requirements (1) were included in the fixed-term contracts that the main contractor entered into with the design companies. In both cases, MagiCAD software was used for the ventilation system design, and Solibri Anywhere was utilised for inspecting the federated model. According to the study, the main contractor responsible for design coordination during the HVAC design phase (2) had approved the HVAC BIM as compliant with YTV2012 based on an inspection of a representative floor. The YTV2012 does not define metadata requirements for HVAC products and materials, allowing designers to use their preferred nomenclature. As a result, the HVAC BIM (3) referenced specific manufacturer products. For the ventilation system, the designer used Lindab KVDPX silencers and SAFE ducts. By using actual products, the designer used their performance values as input data for system sizing calculations within MagiCAD (4). The HVAC IFC model was used in clash detection (5) within a federated model (6) alongside other design disciplines. Additionally, the designer provided the main contractor with 2D ventilation floor plans (7) in DWG format and control diagrams of the ventilation system, as well as equipment lists upon completion of the design phase. In the procurement phase, the main contractor tendered the ventilation as a lump sum contract (8) using 2D PDF drawings and ventilation system documentation in PDF format (9). The combined IFC model was included in the tender documentation; however, it was not referenced in the document hierarchy for contractual validity.

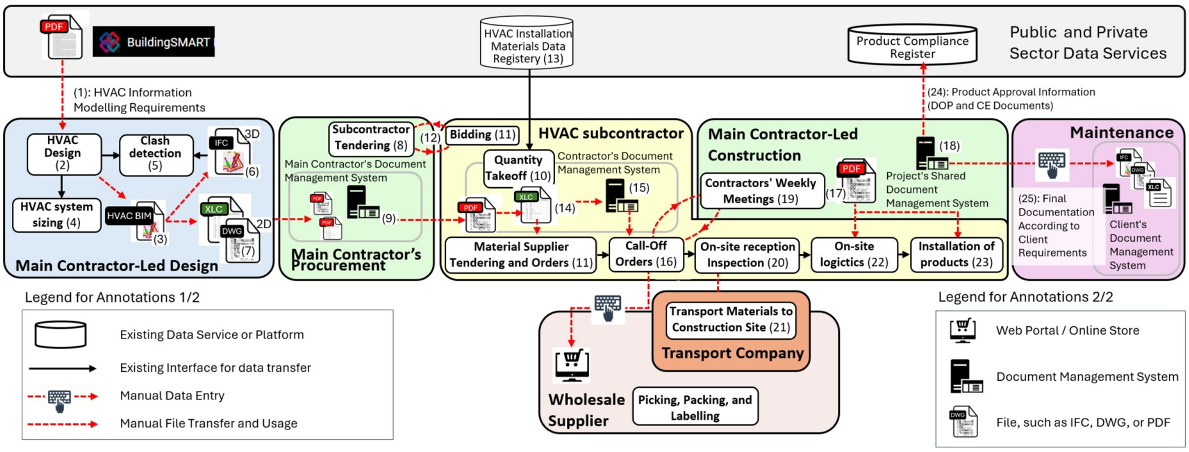

Figure 1: The information flow is based on the HVAC design, procurement, subcontractor's execution planning, installation, and handover in the studied projects

The HVAC subcontractor's estimator used 2D drawings to perform quantity takeoff for the ventilation system (10). The subcontractor separately tendered key components for the ventilation system, such as the ventilation system for the sample floor, communal areas, and air handling units, to different suppliers (11). During the tendering phase, the subcontractor proposed 12 modifications to the system to the main contractor, aiming to provide a more competitive offer. The ventilation system's products at the apartment level were sourced based on standard price lists as a single package. In both cases, subcontractors used JCAD for processing 2D PDF drawings and Mercus Broker for performing the quantity takeoff. The subcontractor's estimator added installation materials by using the HVAC Installation Material Data Registry (13) and enriched the ventilation system's MBOM manually. The estimator also estimated duct quantities by manually measuring standard apartment layouts and adding allowances for cutting. The final material quantities were recorded in an Excel file (14), with additional comments added at the row level. The file was stored on the subcontractor's file server (15).

After the HVAC contract was awarded, the quantity takeoff file was transferred to the production team, where the project manager initiated the material call-offs (16) via the supplier's web portal. The project manager cross-checked material quantities against any updated plans (17) following the contractor's tendering process. The main contractor and the client utilised a shared project document management system (18) to store design documentation throughout the construction phase. The main contractor provided schedule updates and discussed HVAC-related issues in weekly contractor meetings (19). Upon arrival, the subcontractor's site team conducted a delivery inspection (20) by verifying the number of packages against the transport company's waybill (21). As construction progressed, the installer manually collected materials from the floor storage area and the ground-floor warehouse and transported them (22) to the installation site. The quantities were based on the installer's manual takeoff (23) from printed drawings. When the materials ran out, the installer restocked from storage.

The installer followed 2D drawings (22) but modified components, materials, installation sequences and work methods based on experience to improve efficiency. Some changes also resulted from deviations in previous construction stages. At the beginning of the installation, the main contractor collected product documentation, including performance declarations and CE certificates, from the subcontractor via email. The designer approved the HVAC system products using the contractor's product data service (24). Finally, the main contractor submitted the HVAC system documentation to the client as required (25) and provided paper printouts of the client-specified HVAC equipment documentation.

4.2. Optimised Information Flow for HVAC Installation

The case study demonstrated that the design, supply chain management, manufacturing, and handover phases of the HVAC contract are executed entirely by manual data transfer using referenced 2D drawings. Each phase requires manual recalculations of component and material quantities, with a non-standardised BOM nomenclature used at each stage. Manual data generation and the absence of a shared metadata definition prevent the reuse of information downstream, rendering data enrichment impossible. To address the issue of information flow, the application of the design science research method was based on the data flow architecture for MTS products [2]. This architecture is suitable for modelling HVAC installations in residential buildings, as all components and materials required for HVAC installation are MTS products. Apartment-specific HVAC breakdown includes MTS components (such as fittings, bends, ducts, and silencers), on-site processed materials (ductwork), and installation materials. The principle of machine-based data enrichment developed in the study is illustrated in Figure 2, referencing the relevant steps indicated in parentheses. The data flow architecture defines the E-BOM data as represented by the HVAC product part nomenclature, which enables naming HVAC components and materials in the HVAC model (2) using general and machine-readable design names (1).

Following the data flow architecture, objects in native design software include standardised design names (2), which in Finland have been published in a machine-readable format on the national interoperability platform under the name HVAC product part [31]. When a designer uses standardised design names in BIM modelling, the BIM model can be extracted in the IFC format (3) as a machine-readable dataset, as it contains objects named with standardised design names and enriched with technical attributes. The HVAC Design phase generates data on HVAC objects, as described by designers, along with their technical properties (such as duct lengths), which serve as technical attributes (4). The apartment numbers are used as location information (4). This allows HVAC products to be extracted from the IFC model into a structured format and assigned to E-BOMs based on location (5). This can be implemented, for example, through IFCtoLBD conversion or batch processing using IfcOpenShell (6), which are described in more detail in the following sections.

In the manufacturing industry, decisions must be made regarding suppliers for individual components when transitioning from product design to production planning. This is partially automated in ERP systems, allowing supplier selection based on availability and price using rule-based logic. Since the procurement of HVAC materials in construction is typically carried out through project-specific tenders or seasonal contracts, automation requires that the supplier be preselected in the ERP system and that the supplier's product catalogue be available in the ERP (7). This enables the enrichment of E-BOM data into M-BOM according to the data flow architecture (8). For HVAC, the initial data for M-BOMs related to MTS products must be automatically retrieved from an HVAC product database, which in Finland is LVI-info (8). Data are retrieved using the TuoteTieto (TT) standard for automatic integration with procurement systems or a data platform, making supplier-specific product catalogues machine-readable. The TT standard and the product database are compatible with HVAC product parts, as the TT standard requires that each article include information on its corresponding HVAC product part ID. This means that each physical article in the product database has a corresponding standardised design name used in HVAC-BIM/IFC (2). This allows for the algorithm-based selection of an article for a specific E-BOM component using rule-based logic (7).

Standardised, product group-specific technical attributes are needed to refine the algorithm's selection to the correct article, as searching only by design name would return all product sizes for

HVAC ducts. Therefore, retrieving the duct diameter and designed material from the IFC model is necessary to ensure the selection of the correct product variant and unique identifier, such as the GTIN code. Since HVAC models do not include support structures for system installation, these components must be added to the M-BOM using installation materials for standard structures (9) and retrieved automatically from a package registry (10). This automated enrichment process produces M-BOM by location (8) without installation waste allowances. The M-BOM, with its quantities and locations, forms a ready-to-use dataset for procurement (11) and later for ordering, which is generated in the ERP system and sent to the supplier using PEPPOL standard messages (12) [34]. This allows the order to be transferred directly from the ordering system of the main contractor or subcontractor acting as the client (13) to the supplier's system (14). Orders can also be tendered using PEPPOL standard order-to-delivery messages (15) [34]. The location information is part of the material call-offs (16), which can be implemented through the PEPPOL message exchange. The supplier typically manages deliveries using a contract logistics provider (17) and an electronic shipping note (18).

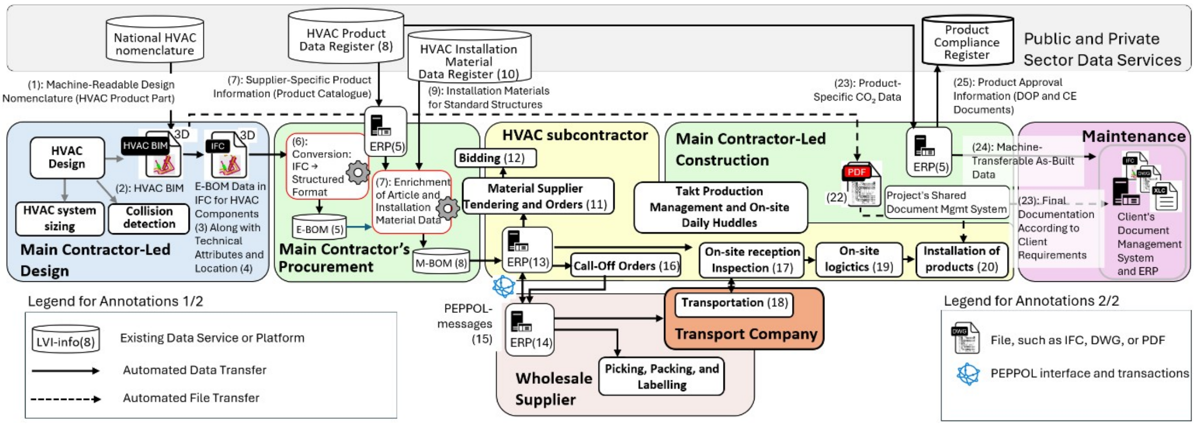

Figure 2: Enrichment of HVAC system data to product data using standardised design nomenclature in BIM and linked building data

The location data extracted from the BIM model is transferred through call-offs to the supplier, who marks it on packages. This enables site logistics to perform receipt inspection (19) and transport materials to the correct installation location while updating stock balances (20). Electronically maintained stock balances enable automatic notifications of installation readiness to the installer (21). The BOM data flow does not replace the use of 2D drawings during installation, so these must be provided to the installer along with the material listing (22). Using these data, the principal contractor can automatically generate the actual CO_2 footprint of the HVAC system by retrieving CO_2 data based on GTIN codes from the LVI-info product database (23) and producing an electronic handover report for the client (24). Since the bill of materials contains identified articles (GTIN) and their quantities, the materials used can be submitted electronically to the contractor's product data service for product conformity verification (25).

4.3. Enhancing the Digital Information Flow with a Machine-Readable Format

A machine-readable building climate report and material list, combined with the order-to-delivery chain of a construction project, impose significantly increased requirements on building services product data and data flow architecture. Product data management is carried out across various systems, primarily manually, without logical links to the data content of BIM. To address this, BIM must be converted into a machine-readable format to enable: 1) energy optimisation using different product and system combinations for the entire building, 2) real-time calculation of the carbon footprint based on actual products, and 3) integration of the order-to-delivery chain up to installation, allowing for the calculation of the realised carbon footprint.

A machine-readable data structure requires data from building services designers. Objects must be identifiable at the product part level, linked to building services systems, and include the necessary data content. The data content requirements are defined to ensure that designers understand the information they produce and can generate it with the correct quality. The IFC standard is inadequate for precisely identifying building services objects, as many components cannot be distinctly recognised using IFC alone. As part of the reform of the Finnish Building Act, the Rava3PRO project [35] implemented national standardisation of building services data, which has also been incorporated into the buildingSMART Data Dictionary (bSDD) platform [36]. This standardisation covers building services systems and product parts (more than 800 product parts and more than 300 system types), enabling machine-readable data for product identification and attributes. Standardising system types is significant when comparing portfolios across multiple buildings.

The information model used in this study was an IFC model based on the data content developed in the Rava3PRO project [35]. In this model, building services objects were modelled using HVAC product part standards, assigning property values to objects based on design nomenclature, which can be linked to product data in the next stage. As a result, handling product data within native modelling software was found to be unnecessary, as these tools are not designed for data management. The study explored methods for converting the information model into a machine-readable format. In the new data flow architecture, the E-BOM data content produced by designers is enriched within data platforms for relevant use cases. It was found that the data from the IFC building services model could be structured in two ways: 1) by converting part of the IFC model into a graph database using the IFCtoLBD software as a library, generating an E-BOM for the HVAC ductwork of the apartment, together with the location and technical attributes of each component in graph format, and 2) by using the LBD model. In the latter method, each component was enriched through an algorithm that took technical attributes and HVAC product part information as inputs and added the corresponding GTIN code and product name to the graph, uniquely identifying the sales article matching the design nomenclature.

4.4. Enhancing the Digital Information Flow Using Linked Building Product Data

The IFCtoLBD converter was developed to transform IFC model data (Industry Foundation Classes) into a more accessible format by representing building information using the W3C Linked Building Data Community Group (W3C LBD-CG) ontologies. The IFCtoLBD converter was used on the Jython framework, making it available as a Python library. It operates in three stages (see Figure 6). First, the IFC model is converted to RDF format (ifcOWL) using the well-known Express schemas published by buildingSMART. Second, aggregated value sets (IfcQuantitySet) and property sets (IfcPropertySet) are compiled from the ifcOWL data—finally, the program processes building elements, linking them with the collected and IFC standard default values. As depicted in Figure 3, hierarchical URI naming, simplified property naming, and a Linked Data representation with minimal complexity level have been adopted to facilitate further processing of property values. The implemented program uses a library to parse IFC models and directly accesses the model using SPARQL queries. A key advantage of this approach is that data filtering can be performed at the query stage, allowing the selection of specific elements and properties of interest. After this, the program reads the list of elements, creates a list entry for each building entity, and attaches the corresponding properties. The elements can then be categorised based on their value sets into product classifications, enabling tasks such as quantity takeoff. The ifcOpenShell [37] Python library was used as an alternative approach to process the IFC building services model within the software environment. The desired components were then selected from the IFC standard definitions, which included pipelines (IFCPipeSegment) and pipeline fittings (IFCPipeFitting).

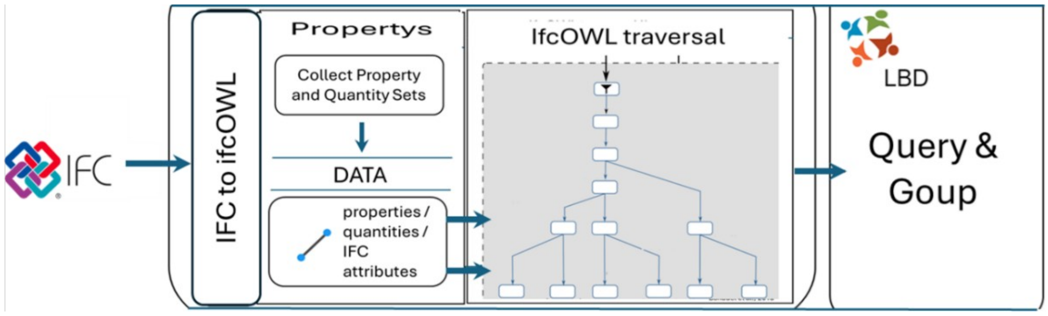

Figure 3: The use of IFCtoLBD as a Python library to get the property data.

All attributes entered into the model are machine-readable. Therefore, the global object identifier, part name, object type, and standardised design nomenclature were selected for the E-BOM output (Figure 4). A Python program was developed to recursively search for the required attribute data for each object in the model and organise them by the floor. The Python program was based on IfcOpenShell library commands, which allow model objects to be accessed using conventional programming methods. The final output was structured as a JSON file, which the Python program generated in the required order. The output format can be adjusted as needed, such as exporting the data as a CSV file or directly inserting it into an SQL database.

This process extracted a machine-readable E-BOM from the building services model in the desired format. This machine-readable E-BOM can now be analysed and enriched with actual product data to form an M-BOM, using the standardised design nomenclature as a reference. Typically, the HVAC components of the E-BOM are enriched with precise product details and location data. The contractor's procurement team identifies the product components and selects items from the product databases. The location data for building services components can be generated programmatically within a data platform if locations have been modelled in the IFC model using IfcSpace object types, for example.

Additional stakeholders also contribute to enriching the designer's E-BOM into an M-BOM. These include cost estimation and carbon footprint analysis teams, who add supplementary information to each object within the data platform, such as labour requirements, product costs, and all necessary installation components, including brackets, bolts, and connectors. The enrichment process was tested in the IfcOpenShell environment and the LBD graph database. Various product components in the design model were enriched using an algorithm that took technical attributes and standardised HVAC product part data as inputs. This required a separate API request to the HVAC product database in the IfcOpenShell environment and the LBD graph database. In this case, enrichment involved an API query within the procurement process to retrieve the GTIN code corresponding to the design nomenclature, detailed product information (such as carbon footprint), and the corresponding sales article for the model objects.

Seven different component types were tested within an apartment. Additionally, installation materials such as bracket arms, threaded rods, screws, and nuts had to be manually added to the M-BOM. This was achieved by creating a simple set of rules that accounted for the components of the apartment, such as silencers and bends, and the total length of straight duct sections. The rule set was converted into a calculation algorithm that assigned installation materials to components and ducts within the graph database, completing the M-BOM into an installation-ready format. The implemented data platform and algorithms demonstrate that the building information model can play a significantly more meaningful role in design, procurement, logistics and installation processes than it currently does. Since the data content of IFC design models can be easily extracted into a machine-readable format using existing programming environments, the automatic data processing routines could replace the need for manual interpretation of 2D drawings. This requires a clear understanding of data requirements and the ability to extract information in a format suitable for its intended use.

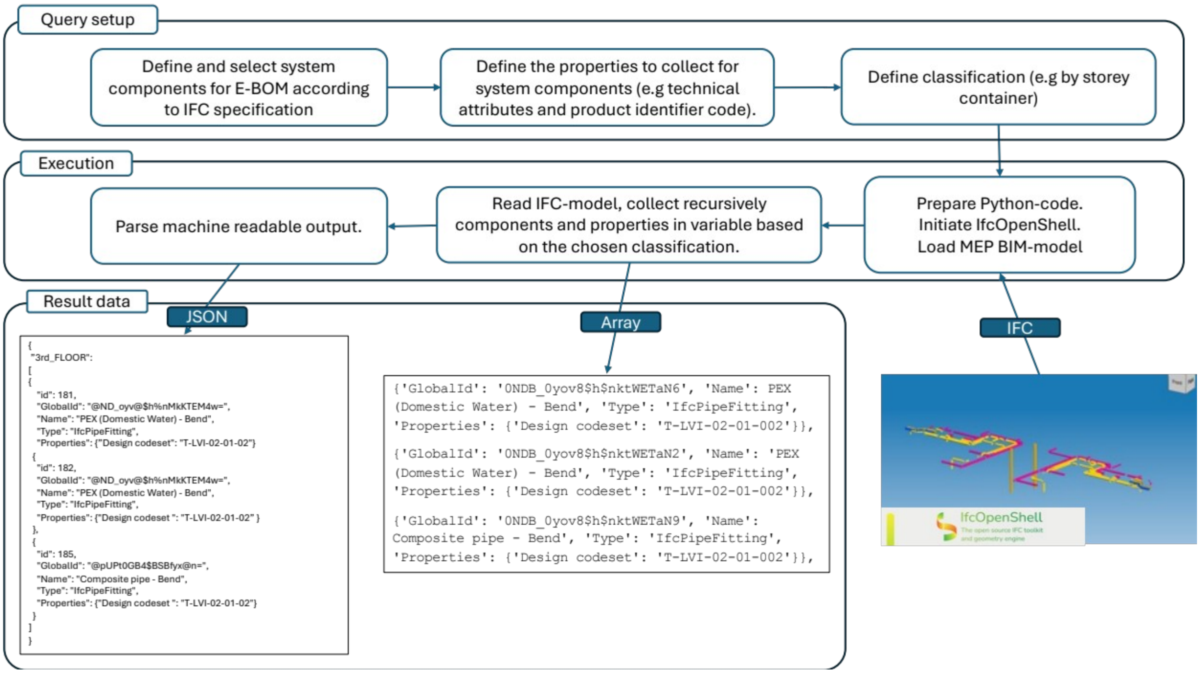

Figure 4: Example of IfcOpenShell process for E-BOM including design codeset export

Currently, the IFC design data are only minimally processed outside of design software; however, using a standardised product identifier simplifies further refinement in separate data platforms. Based on this experiment, enriching the building's M-BOM within an external data platform is feasible. However, the study has not yet implemented integration with construction ERP systems and actual procurement processes. Nevertheless, based on the features of the IfcOpenShell environment and the flexibility offered by Python programming, this is not expected to be a significant challenge.

The results also highlight the extent of unnecessary work caused by using 2D drawings, particularly in the order-to-delivery process. The proposed automation is likely to have a significant impact on improving industry productivity as it enables the automated management of material flow using BIM data as its foundation. The presented solution effectively paves the way for the digitalisation of the industry, transforming the supply chain one step at a time.

5. Discussion

A critical factor for successful data enrichment is the standardisation of the BIM model data content and the development of a culture of machine-readable data processing. The nationally used HVAC product part nomenclature enables BIM data to be structured in a format suitable for further use by various stakeholders. The IFC format, on its own, does not support efficient programming, data extraction, or integration with ERP or similar systems. Linked Building Data has proven to be an effective facilitator in this context.

The process involves two key conversions: the IFC-to-Linked Data Model conversion and the E-BOM to M-BOM conversion. Converting IFC data into a structured format requires filtering, extraction, and organisation, but these tasks can be automated through software. Enriching the E-BOM from standardised design nomenclature into a product-specific list is a complex process, as it requires defining technical attributes for each product category and refining selection criteria to improve accuracy in product identification.

The first significant productivity advantage of software-based IFC model processing is the ability to perform batch processing and automation, which enables data extraction and enrichment in the background. Batch processing is already widely used in ERP systems across other industries. The presented approach allows data processing as batch runs within data platforms and facilitates data distribution outside native software environments in an unrestricted format. Although IFC model objects can be accessed conventionally, the ability to automate machine-readable data transfer to where it is needed eliminates the need for manual data handling. This technical architecture for machine-readable data is essential for meeting the needs of the construction industry with a data-driven approach.

When data enrichment is carried out within a data platform, subsequent stakeholders can benefit from the information produced in previous phases. For example, scheduling teams can almost automatically generate an initial schedule version based on cost estimation data. Similarly, carbon footprint analysis can provide an initial environmental impact assessment by linking generic data to the machine-readable E-BOM. Once the material selections are finalised and the bill of materials is enriched with actual product data in an M-BOM, the carbon calculation can be updated to reflect the exact environmental impact. This provides real-time insights into project costs, scheduling, and carbon footprints.

Machine-readable data processing also represents a significant cultural shift that the construction industry must adapt to. A key starting point is creating the necessary infrastructure and standardising data content to enable seamless linking between BIM and external data sources. These external sources often belong to different standard families but are highly relevant to the digitalisation of construction production. Moving forward, it is essential to continue standardisation efforts, particularly for machine-readable BIM interpretation. The research does not aim to take a stance on where or in whose systems the enrichment of design data into product data should occur. In any case, the prevailing file-based data transfer model is set to become obsolete as digitalisation progresses within the construction industry. Given the significant benefits of automation and the investments required for its implementation, it is reasonable to assume that automation will fundamentally alter the existing division of labour in the supply chain and disrupt current business models.

6. Conclusions

Only a small portion of the potential of building information modelling is used in construction projects, and BIM models play a secondary role in the projects studied. Projects still rely on 2D drawings as their primary source of information, as if paper were still the only format for transferring data. Since PDFs are not machine-readable, even with optical character recognition, transferring data as files can be considered digitisation, but it is not digitalisation. The study demonstrated that BIM data content can be used similarly to models applied in manufacturing and that information can be enriched in a structured format. The test confirms that the linked data model is a viable approach for data enrichment within a data platform and, more importantly, that enrichment can be decoupled from native software and users. In summary, by using a standardised design nomenclature in the information model and leveraging IFC as the data source, it becomes possible to enrich the E-BOM data on a data platform into location-based M-BOM information, supporting both procurement and installation. In addition to the design nomenclature, enabling technologies such as IFCtoLBD or IfcOpenShell must be adopted to allow IFC data to be enriched into the data platform's information model.

The scope of the study was to test automation in extracting standardised HVAC product and material design data from BIM/IFC files into a structured format and enriching it from E-BOM to M-BOM. The test confirmed that machine-based data enrichment works for MTS products. Since construction widely utilises MTS-type supply chain products, this research finding presents opportunities for the construction industry to implement CIM architectures, integrate data across different systems, and automate processes such as manufacturing.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

References

[1] T. Zabelle, Built to Fail: Why Construction Projects Take So Long, Cost Too Much, And How to Fix It. Forbes Books, 2024.

[2] O. Alhava, B. Ruottinen, A. Peltokorpi, M. Siren, A. Aaltonen, T. Pitkäranta, Advancing Digitalization in Construction Through Automated Metadata Management and Machine Data Processing. Proceedings of the 41st International Conference of CIB W78, Marrakech, Morocco, 2-3 October 2024, ISSN: 2706-6568. URL: https://itc.scix.net/paper/w78-2024-11

[3] O. Alhava, T. Valkonen, B. Ruottinen, T. Pitkäranta, Digitalising designing of prefabricated ventilation elements. Proceedings of the 41st International Conference of CIB W78, Marrakech, Morocco, 2-3 October 2024, ISSN: 2706-6568.

[4] O. Alhava, T. Alaluusua, A. Pekkala, A. Peltokorpi, A. Aaltonen, T. Pitkäranta. Challenges and Opportunities in Digitalizing Concrete Element Supply Chains: Proposed National Model. Proceedings of the 41st International Conference of CIB W78, Marrakech, Morocco, 2024

[5] A. Peltokorpi, P. Uusitalo, M. Siltanen, O Alhava. Toimitusketjujen hallinta: Loppuraportti. Aalto-yliopisto, 2023. https://www.aalto.fi/sites/default/files/2023-04/Toimitusketjujen-hallinta-loppuraportti-2023-03-28.pdf.

[6] J. Womack, D. Jones, and D. Roos. The Machine That Changed the World: The Story of Lean Production--Toyota's Secret Weapon in the Global Car Wars That Is Now Revolutionizing World Industry. Simon and Schuster, 2007. ISBN-13: 978-0743299794.

[7] J. Riekki, J. Rannisto, J. Lehtovaara, O. Seppänen, and A. Peltokorpi. Achieving a 4-hour takt time–and driving change with it. In Annual Conference of the International Group for Lean Construction (pp. 1184-1195). International Group for Lean Construction (IGLC). 2024

[8] J. Miltenburg. Manufacturing strategy: how to formulate and implement a winning plan. CRC Press, 2005. https://doi.org/10.4324/9780367804947

[9] G. Chryssolouris. Manufacturing systems: theory and practice. Springer Science & Business Media, 2013.

[10] Y. Li, X. Chen, Y. An, Z. Zhao, H. Cao, and J. Jiang. Integrating machine layout, transporter allocation and worker assignment into job-shop scheduling solved by an improved non-dominated sorting genetic algorithm. Computers & Industrial Engineering, 2023

[11] C. M. Huettner, and H. J. Steudel. Analysis of a manufacturing system via spreadsheet analysis, rapid modelling, and manufacturing simulation. The International Journal Of Production Research, 1992, 30.7: 1699-1714. https://doi.org/10.1080/00207548108956629

[12] M. P. Groover. Automation, production systems, and computer-integrated manufacturing. Pearson Education India, 2016.

[13] Autodesk. Building Information Modeling in Practice, URL: https://images.autodesk.com/apac_grtrchina_main/files/aec_bim.pdf

[14] J. Lehtovaara, Takt Production and Decentralized Decision-Making: Improving Construction Production Flow with Novel Planning & Control Approaches, Aalto University, 2023.

[15] J. Liker. The Toyota Way, Second Edition: 14 Management Principles from the World's Greatest Manufacturer. McGraw Hill, 2020. ISBN-13: 978-1260468519.

[16] T. Fujimoto. The evolution of a manufacturing system at Toyota. Oxford Press 1999.

[17] O. Alhava, M. O'Loughlin, H. Haapasalo, J. Viitanen, and T. Pitkäranta. Rigorous 2-Hour Takt Reveals Upstream Underperformance, Proceedings of the 32nd Annual Conference of the International Group for Lean Construction (IGLC 32), 2024, 238-249.

[18] M. Rother, and T. Kata. Managing people for improvement, adaptiveness and superior results. McGraw Hill, 2009. ISBN-13 978-0071635233.

[19] A. Revolti, L. Gualtieri, P. Pauwels, and P. Dallasega. From building information modeling to construction digital twin: a conceptual framework. Production & Manufacturing Research, 12(1). (2024). https://doi.org/10.1080/21693277.2024.2387679.

[20] S. Liang, M. Rajora, X. Liu, C. Yue, P. Zou, and L. Wang. Intelligent manufacturing systems: a review. International Journal of Mechanical Engineering and Robotics Research, 2018

[21] International Organization for Standardization. ISO 19650-1:2018: Organization and digitization of information about buildings and civil engineering works, Part 1: Concepts and principles. Standard, International Organization for Standardization, Geneva, CH, 12 2018a.

[22] Ympäristöministeriö 1027/2024, ”Ympäristöministeriön asetus rakennuksen ilmastoselvityksestä ja rakennustuoteluettelosta”, 23.12.2024.

[23] X. Tao, M. Das, Y. Liu, and J. Cheng. Distributed common data environment using blockchain and Interplanetary File System for secure BIM-based collaborative design, Automation in Construction, Volume 130, 2021, 103851, ISSN 0926-5805

[24] M. Hannus, H. Penttilä, and P. Silén. Islands of automation in construction. Construction on the information highway, (198), 20, 1996.

[25] S. A. Irani. Job Shop Lean: An Industrial Engineering Approach to Implementing Lean in High-Mix Low-Volume Production Systems (1st ed.), 2020. Productivity Press.

[26] J. W. Hopp, and M. L. Spearman. Factory physics. Waveland Press, 2011.

[27] A. Sharma, and B.J. Singh. Evolution of industrial revolutions: a review. International Journal of Innovative Technology and Exploring Engineering, 2020, 9.11: 66-73. ISSN: 2278-3075.

[28] H. Lasi, P. Fettke, H.G. Kemper, T. Feld, and M. Hoffmann. Industry 4.0. Business & information systems engineering, 2014, 6, 239-242.

[29] H. C. Xu, X. F. Xu, & T. He (2007). Research on Transformation Engineering BOM into Manufacturing BOM Based on BOP. Applied Mechanics and Materials, 10–12, 99–103.

[30] S. Bigdeli, P. Pauwels, S. Verstockt, S. et al. Semantic Enrichment of a BIM Model Using Revit: Automatic Annotation of Doors in High-Rise Residential Building Models Using Machine Learning. Fire Technol, 2024. https://doi.org/10.1007/s10694-024-01655-0

[31] S. Kosse, O. Vogt, M. Wolf, M. König, and D. Gerhard, D. Requirements management for flow production of precast concrete modules, International Conference on Computing in Civil and Building Engineering, 2022, October, pp. 687-701, Springer International Publishing.

[32] M. Bonduel, J. Oraskari, P. Pauwels, M. Vergauwen, and R. Klein. The IFC to linked building data converter: current status. In Poveda-Villalón M, Pauwels P, Roxin A, editors, LDAC 2018 Linked Data in Architecture and Construction: Proceedings of the 6th Linked Data in Architecture and Construction Workshop London, United Kingdom, June 19-21, 2018

[33] YTV2012. *Yleiset tietomallivaatimukset 2012. Osa 1: Yleinen osuus*. Versio 1.0, RT 10-11066. Rakennustieto Oy, 2012. URL: https://kortistot.rakennustieto.fi/kortit/RT%2010-11066

[34] State Treasury, Nordic Peppol Construction Industry Forum. 2025. URL: https://www.valtiokonttori.fi/en/nordic-peppol-construction-industry-forum/

[35] Rava3Pro, national project and results, URL: http://www.rava3pro.fi/

[36] bsDD, buildingSMART Data Dictionary (bsDD), 2025. URL: https://www.buildingsmart.org/users/services/buildingsmart-data-dictionary/

[37] IfcOpenShell software, 2025. https://ifcopenshell.org/