Challenges and Opportunities in Digitalising Concrete Element Supply Chain: Proposed National Model

Otto Alhava, otto.alhava@fira.fi
Fira Rakennus Oy, Helsinki, Finland

Teemu Alaluusua, teemu.alaluusua@aalto.fi
Aalto University, Helsinki, Finland

Antti Pekkala, antti.pekkala@fira.fi
Fira Rakennus Oy, Helsinki, Finland

Antti Peltokorpi, antti.peltokorpi@aalto.fi
Aalto University, Helsinki, Finland

Antti Aaltonen, antti.aaltonen@rt.fi
Confederation of Finnish Construction Industries RT (CFCI)

Tomi Pitkäranta, tomi.pitkaranta@sitedrive.com
Sitedrive Oy, Helsinki, Finland

Abstract
The introduction of takt production and the application of single-piece flow in the interior phase of construction projects has highlighted the problems in the frame erection phase of concrete element construction. Despite implementing flow production, the frame erection phase has become a bottleneck in shortening the lead time in residential building construction. The study confirmed that the design and implementation of the structural phase suffer from a lack of process and product information flows. Similarly, it was found that a contributing factor to the poor level of digitalisation is the centralised data architecture, which has been adopted in the industry using the Manufacturing to Stock (MTS) business model and strategy. As concrete element supply chains are based on a different production logic, Engineer to Order (ETO), the study defined significant differences in data architecture and operational mode of the information system. The study proposes a national or EU-level solution model for designing and exchanging product information for concrete element supply chains. Based on the case study, the research formed a national reference model for implementing decentralised data architecture and digitising inter-company data transfer. The study was conducted as part of a project by a national advocacy organisation in the construction industry aimed at digitalising the concrete element supply chain. The research results are significant in the studied market area, as they contribute to the implementation of digitalisation by demonstrating the implementation method of the data architecture for ETO supply chains and enable the same development in digitalisation for the element industry that the stock product manufacturing sector has already achieved in the digitalisation of the supply chain, wholesale operations, and the implementation of machine reading and automated data processing.

Keywords: distributed system, concrete element, digitalisation, supply chain, GS1, PEPPOL, ETO

1 Introduction
Problems in existing manual methods of identifying, tracking and locating highly customised prefabricated components have fascinated researchers for years (e.g. Ergen et al., 2007). Several technologies and frameworks have been proposed to solve the problem of off-site production, for

example, RFID tags (Ikonen et al., 2013), BIM-based architecture (Nissilä et al., 2014), centralised database (Ocheoha & Moselhi 2018), 4D BIM (Bataglin et al., 2020) etc. Also, the digital twin and Digital Twin Construction (DTC), along with appropriate workflows and information systems, have been introduced to cure the lack of data-driven construction management (Sacks et al., 2020 and Jiang et al., 2023). Yet, the research gaps identified in studies like Wang et al. (2019) remain the same: automatic exchanges and conveyance of the process information are missing, data utilisation in the supply chain is low, and the coordination mechanism for delivery and transportation is missing, not to mention the feedback loop from site to factory or design. In response to the aforementioned, this study aims to take a step from the what-level described in the DTC model to the how-level.

Problematic prefabricated components, like concrete elements, are engineering-to-order products (ETO), and their time to the customer is typically very long; production volumes of each type of component are small, and product variation is very high (Bellgran & Säfsten, 2010). Because of the high customisation involved, and it affects the supply chain, the status and location information of ETO components should be tracked individually for each component and accessed primarily by lower management to prevent any delays during production, delivery, and installation (Ergen & Akinci, 2008). As seen in Figure 1., the proposed solution for information management of ETO has typically been based on a centralised system.

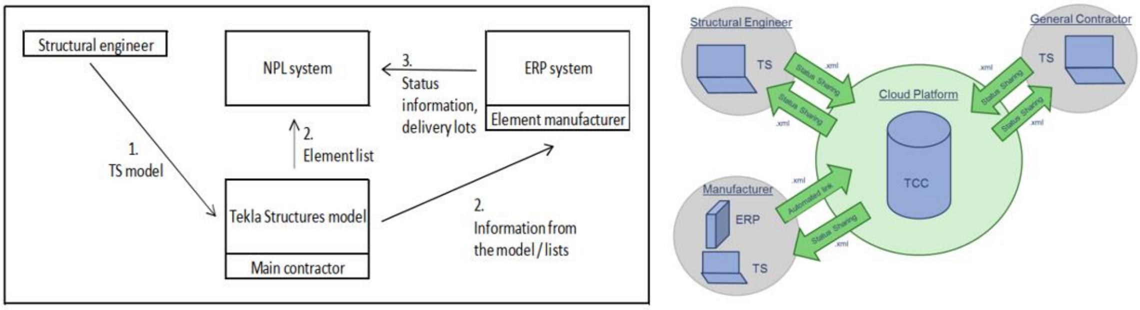

Figure 1. The proposed solution for Networking Platform for Logistics (NPL) is on the left (Jussila et al., 2012) versus platform-based centralised data architecture (Nissilä et al., 2014).

An alternative ETO supply chain information management solution is distributed data systems. As there are several definitions for distributed systems, a distributed system is a collection of autonomous computing elements that appears to its users as a single coherent system. This definition refers to two characteristic features of distributed systems: a) a distributed system is a collection of computing elements, each being able to be used independently of each other, and b) users (be they people or applications) believe they are dealing with a single system. This means that one way or another, the autonomous nodes can communicate with each other (Van Steen and Tanenbaum, 2016).

Distributed systems are widely used in Internet-based industries like retail, online selling, healthcare, transport and logistics, food services, technical sectors and humanitarian logistics. The same applies to supply chain standards like e.g. GS1 and PEPPOL. GS1 aims to create a common foundation for business by uniquely identifying, accurately capturing and automatically sharing vital information about products, locations, assets and more. The Global Trade Item Number (GTIN) is a global supply chain solution that identifies any trade item that may be priced, ordered or invoiced at any point in the supply chain upon which there is a need to retrieve predefined information (GS1, 2023). On the other hand, PEPPOL (Pan-European Public Procurement Online) is a standardised framework and network designed to facilitate efficient and secure electronic procurement across Europe and internationally. It is a set of standards and a network that facilitates electronic procurement and invoicing across Europe and beyond (Valtiokonttori, 2024).

In Finland, a national digitalisation project for business-to-business data transfer, led by the State Treasury, is underway. This project aims to expand the implementation of PEPPOL standard-based order-delivery chain messaging. As the State Treasury is an official member of the OpenPeppol Association, it established its Peppol authority function in the autumn of 2022 (Valtiokonttori, 2024). Since the PEPPOL standard is compatible with the GS1 standard family, examining the harmonisation of data contents is essential to promote national digitalisation. Simultaneously, in Finnish national product information registers (LVI-info, Rakennustuotetieto, and Sähkönumerot. fi), the GS1/GTIN product identification share has already exceeded 90% in MTS products.

Aalto University has been researching to promote the digitalisation of the construction supply chains since 2022 as part of the Building 2030 consortium's activities. In 2023, The Confederation of Finnish Construction Industries RT (CFCI) initiated a project to digitalise the supply chains of concrete elements and building services, of which this research is also a part. The project aims to create an industrial system in which different parties can autonomously implement their systems and choices. The supply chain systems must be autonomous but operate as a coherent system from the perspective of the entire supply chain. This requires 1) defining interfaces as open standards or using existing applicable open interface definitions. This is essential for interoperability, portability, and extensibility (Van Steen and Tanenbaum, 2016, p. 976-977). These three requirements are necessary to enable supplier- and system-independent implementation across the construction and construction products industries. Defining the interfaces requires standardising data content, i.e., defining metadata for all transferable information. Implementing a distributed system requires defining the data architecture. Ownership must be defined in addition to the jointly defined metadata for the supply chains, i.e., which party in which role must maintain which information and provide it over an open interface for use by other supply chain parties. This research aims to identify the components of the distributed system and validate it as a system.

2 Methodology

The research was conducted using the design science research method because the aim was to identify and delineate the problem and develop new knowledge to address it through an innovative artefact (vom Brocke et al. 2020).

3 Problem definition and artefact development

3.1 Current state

The supply chain for concrete elements is only partially digitalised. The use of the information model in the structural phase is nationally guided by the Common BIM Requirements 2012 Series 5 (COBIM S5, 2012). Structural design standards specify using unique element identifiers but do not address their format. The standard also guides the implementation of void provisions, clash detection, and the modelling accuracy of different structures. From the design and product information management perspective, the standard needs to address data content.

Parallel to Common BIM, the national BEC project produced in 2011-2012 a definition for 3D modelling, information modelling, and data transfer for concrete elements, which has risen to the status of a de facto standard. The project involved the concrete element industry, structural designers, and Trimble Solutions Oy, and the guidelines have been actively developed. They are widely used among designers, main contractors, and element manufacturers. The most critical de-facto standards for this research are the quantity takeoff from the IFC model (BEC IFC 2016), the Element Design Modelling Guide (BEC 2012), the Element Property Set (BEC PS, 2012), and Custom Properties (BEC CP, 2023). These standards define the element-type-specific information to be used in the structural phase information modelling to ensure that element design, manufacturing, and quantity calculation can be implemented using the information model with IFC as the transfer format.

Despite the national standardisation efforts and the extensive use of information modelling, 2D drawings remain the primary source of information for manufacturing and construction sites. In the supply chain, information exchange between organisations is predominantly based on email, phone calls, the use of WhatsApp, and shared project document repositories (Peltokorpi et al., 2023). As a result, situational awareness of production and delivery status is the most critical issue in supply chain management. The problem is exacerbated by the fact that the concrete element supply chain, as an ETO supply chain, accumulates errors that, due to the lack of real-time tracking, arise from deficiencies in initial data and design, manufacturing errors, loading and transportation errors, installation errors, lack of coordination, slow information exchange, and inadequate documentation (Alaluusua, 2023). One of the companies participating in this research conducted measurements from June to August 2022 to determine the number of errors and the disturbances they caused. The results of these measurements are presented in Table 1, showing that the errors identified in the studies above accumulate on-site.

Table 1. Number of Errors in the Structural Phase Measurements on Four Different Construction Sites. Measurement Period: 50 Total Workdays. Minor Disruption: Work becomes slightly more challenging or slows down a bit. Disruption duration is often less than 30 minutes. Harmful: Work slows down significantly or requires expensive measures—duration over 30 minutes. Severe: Work stops completely, requires costly measures, or poses a safety risk—duration over 2 hours.

Fault in	Severe	Harmful	Minor	Total	Share
On-site installation	2	4	12	18	12%
Element transportation to the site	10	13	15	38	26%
Other deliveries	5	3	0	8	5%
Measurements	0	1	2	3	2%
Crane and lifting	5	0	2	7	5%
Design	4	9	8	21	14%
Site logistics	0	5	5	10	7%
Precasting	9	11	22	42	29%
Total	35	46	66	147	
Share	24%	32%	45%		

The company commissioned a thesis to eliminate the root causes of the errors highlighted by the measurements. The key findings of the study were: 1) the overall level of integration in the supply chain is currently low between the main contractor and the suppliers, 2) the standardisation of the supply chain processes is lacking, 3) the exchange of information and workflow between different parties is inadequate, and 4) the primary method of transmitting information between the functional groups in daily operations is via email or phone call (Makkonen, 2023). These element-specific errors cumulatively caused a similar overall delay to that reported by Murguia et al. (2024) in their study on cladding.

3.2 Artefact development (future state)

3.2.1 Defining Unique Identification Information for a Product Unit (Concrete Element Identification)

The first and most crucial confirmation in the research is that each concrete element is fundamentally a unique item from the perspective of the whole supply chain depicted in Figure 2 below. Although buildings use multiple identical concrete elements that are interchangeable in theory, each must still be uniquely identified: a specific element must be manufactured and delivered to be installed in a particular location within the building structure. The need for unique identification of individual elements is also emphasised from the process information perspective: a specific element is stored in a curing location or awaiting lifting in an element rack at the construction site, and this information is necessary for managing the supply chain.

The need for identification is further highlighted by several similar but not entirely identical elements in production (even though, for example, they might overlap in the exact location on overlapping floors). From the manufacturing perspective, it is essential to identify which elements are identical and what deviations exist between specific units to plan production load efficiently and convey critical information to the factory's internal logistics and the workers at the manufacturing point. The study found that the planning software allows using two identification codes in the design phase (1). However, both are manufacturer-specific and not based on publicly available standards. Since the study aims to avoid vendor lock-in, the solution must be based on an open standard.

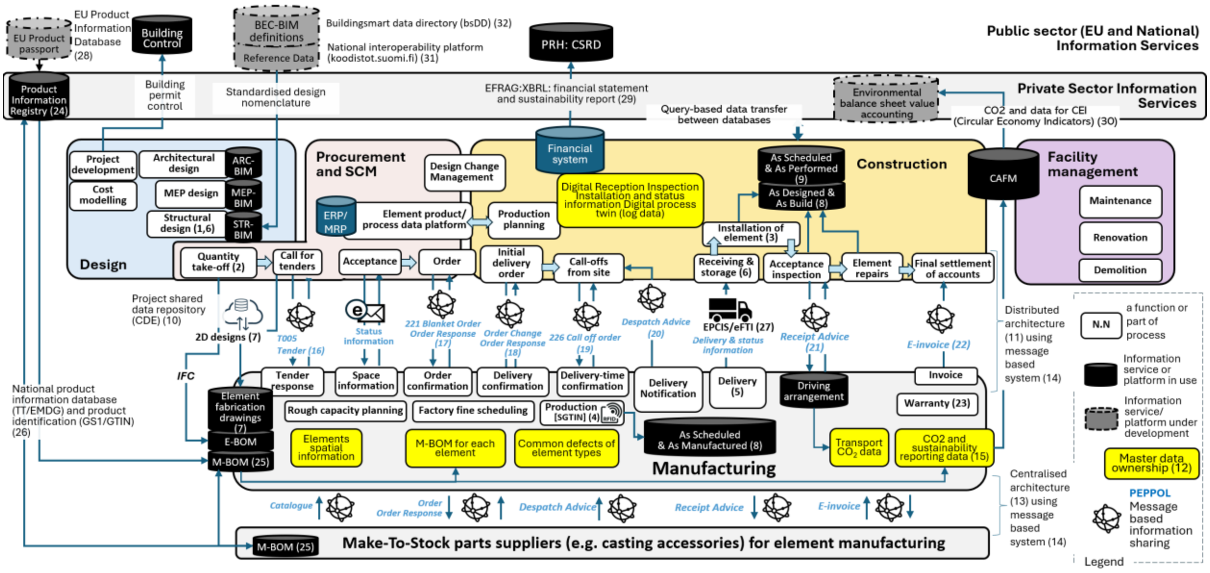

Figure 2. The data repositories of the element supply chain, the proposed standards in the national model, the data flows, and key process steps in the design, procurement, manufacturing, delivery, and element installation.

From the productivity improvement and quality control perspectives, errors must also be identified individually at the construction site for each element so the factory can make the necessary inspections and adjustments quickly to prevent the error from propagating in production or to correct defective elements before delivery. Once the unique identification information for the product has been defined to this level for all types of elements, suitable identification methods from the GS1 standards family could be selected (as presented in 4.1.1., Table 2 below). If quantity takeoff is performed at the element level and the design drawings of the elements are included in the request for quotation, these must be identified in the information model and plans with matching identifiers (2).

3.2.2 Defining Unique Identification Information for a Product Unit (Concrete Element Identification)

The efficiency of supply chains requires the automated processing of information. As a result, identification codes must be machine-readable, and during this research, the project aimed to find a suitable GS1 information carrier for this purpose. The barcodes, 2D codes, and RFID technology supported by the GS1 standard were compared. Since concrete elements need to be identified after installation (3) during the internal works phase, the logical choice for the information carrier is RFID (4) tags instead of manually written or barcoded machine-readable identification codes.

RFID technology is essential for machine reading under difficult site conditions while considering work safety. RFID does not exclude the markings made for humans, which are typically done with grease pencils or markers directly on the element at the factory. It also does not prevent the continued use of element tags that contain the same identification information in text and various barcodes. Based on the research, it was concluded that RFID codes solve the usability issues typically associated with installing different elements: RFID codes can be read even after the element is installed in its final position in the building. On the other hand, element tags usually need to be removed as they are attached to the reinforcement of the joints, resulting in the loss of the information they contain. The same happens to texts on the elements, as they usually have to be placed in areas covered by joints to be readable during delivery (5), unloading, and site storage (6). The most suitable technology for this purpose is passive UHF RFID, as it does not require battery backup, has a reading distance of several metres, and the data capacity is sufficient for the purpose.

3.2.3 Defining the Data Content for Design and Product Information Transmitted via Identification Codes (Metadata for Element Types)

Using a global standard for identification methods and solutions enables the utilisation of technologies and software used in other industries to digitalise the concrete element supply chain. The research demonstrated that the digitalisation of the supply chain essentially involves transmitting valid information using standardised data fields and formats to convey design (7), product (8), and process information (9). The unique product code is merely a key to transmitting related product, design, or process (i.e., event) information. Barcodes and RF codes are methods for rapidly and mechanically identifying unique identification codes.

In the concrete element process description workshops conducted as part of the research, a set of use cases and established documents were identified, through which information has been exchanged using email for file exchange, the increasingly popular MS Teams collaboration environment, and shared project document repositories (10). Replacing these with electronic data transfer requires identifying and standardising essential design, product, and process information.

In practice, the definition of this information is a prerequisite for applying software solutions used in manufacturing industries for the production, logistics, and installation of ETO (Engineer-to-Order) products to the construction sector and the element supply chain. A limitation arises in that more than mere product identification and recognition is needed for transitioning the concrete element industry and construction to digital data transfer. Product identification using a GS1 code allows for the retrieval of information related to a specific product unit (i.e., a specific element) using the identification code as a key, in the same way, that it efficiently enables the production of information that can be linked to that specific element using the identification code.

The use of RFID or barcode as an information carrier solves the issue of being able to assign this information through machine reading and, if necessary, automate the retrieval or production of information. However, adequate and business-relevant data transfer in the concrete element supply chain requires the next step: defining the metadata for product and process information specific to element types.

3.2.4 Distributed Data Architecture Implemented in the ETO Supply Chain

Another key finding from the process review of the partition wall element in concrete element supply chain information management is that crucial information for the process performance becomes highly distributed among various parties. This was also confirmed in the use case tests. The parties generate process information as concrete elements progress through the supply chain, but due to the manual operation method, it is not available in a machine-transmittable form. Information about different stages of the process remains isolated within the respective entity or part of the organisation. As a result, it is impossible to create an overall situational picture of the supply chain because the process data is fragmented. Consequently, it is also currently impossible to obtain information about the performance of the element supply chain. Different stages of the process require information such as the elements in loads, the loading sequence, and the targeted arrival times. In current processes, the transmission of this information in various formats, such as Excel/PDF files marked on 2D drawings or in CSV format, is agreed upon on a project-by-project basis.

However, supply chain efficiency requires that some information be available to other parties or even delivered automatically in case of changes and deviations. For example, if an element installation fails on-site, the manufacturing drawing of the element must be quickly accessible on-site so that necessary corrections can be made as soon as possible. The required up-to-date information is available at the factory, so the element drawing should be the manufacturer's production drawing, maintained and shared from the manufacturer's systems. Similarly, the factory should classify defects based on its manufacturing process. Otherwise, it is challenging to automate the handling of defect information. In this case, the factory would define defect types for each element type, and the downstream process would use these predefined defect types. As a result, the downstream process would produce standardised and comparable data to assess the efficiency of the supply chain. This is impossible because individual workers define the information themselves and primarily use WhatsApp or a punch list tool to report defects. In other words, the processability of information generated in the situation requires the factory to maintain the typical defects for the element type as items, making them immediately available for use on-site when troubleshooting and forming defect information. This ensures that defect situations are resolved quickly and that the information produced to address them is of the highest quality for further machine processing. This enables error isolation and data-driven productivity improvements in element production.

Based on the project and situational specificity of product and design information, the third conclusion related to the research architecture is that concrete element supply chain information management requires a distributed data architecture (11). Distribution is necessary to solve inefficient supply chain management and replace manual applications such as WhatsApp and email as information transfer methods. Project-specific solutions enable the erection of the building frame and the resolution of related issues through ad-hoc communication methods. Still, these ad-hoc procedures effectively prevent the industry's development. Projects only produce information on operational performance by manually collecting it, and no party can invest in data collection on their own because the information remains relevant only to the individual project, resulting in sub-optimisation due to the constantly changing parties and building types. Therefore, defining a distributed architecture (11) is essential to ensure that process information serves the development of the entire supply chain's operations and productivity

3.2.5 Master Data Definition Enabling the Distributed Data Architecture of the ETO Supply Chain

As part of the research, a case analysis indicates that a distributed architecture requires the definition of master data ownership (12). More than defining open interfaces and metadata is required to digitalise the ETO supply chain. The design, tendering, procurement, and production planning processes, as well as the actual manufacturing, storage, delivery, and installation processes, generate such a significant amount of both product and process information that it is essential to define which party is responsible for producing, storing, and maintaining each piece of information. Since some of this information needs to be transferred to another party, such as the client, upon project completion, the data owner must also provide a service to transfer the information at the end of the project in a structured format. Additionally, the operation of the distributed concrete element supply chain requires defining functions for retrieving information and metadata for storing information. According to the conclusions drawn from the research, master data management must include a) data ownership, b) metadata definitions, c) interface definitions for retrieving information (client pull), and d) the specification of which information must be automatically transmitted to another party (server push). Simultaneusly, the data architecture for the element manufacturer and the supplier of prefabricated components needed for the elements is centralised (13), as presented in the architecture of MTS supply chains (Alhava et al. 2024).

3.2.6 Message-Based Data Transfer Required by the Distributed Data Architecture

The fourth significant feature developed in the artefact is information management in the concrete element supply chain. As recent studies indicated, instead of adopting a centralised solution, it must be implemented as a message-based system (14). This conclusion practically follows the distributed data architecture itself. Compared to the other main production methods in the construction industry, the use of MTS products, which employs standardised product identification and centralised product information management through read-only type open interfaces, the design, product, and process information of ETO products cannot be managed with a similar centralised architecture. The amount of information explains the difference, the lifecycle of the information, and the number of users.

Product information for MTS products typically remains the same throughout the product's lifecycle, generally years. The same product and thus its article-specific product information is used in hundreds, if not thousands, of projects, resulting in many users for the information, and the data can also be stored in company systems. MTS products are also typically not individually identified beyond the article level, meaning MTS products are ordered and used based on quantities, and individual products do not need to be identified or tracked from manufacture to installation. For example, to calculate the carbon footprint (15) required by forthcoming EU legislation or to implement digital handover, it is sufficient to know how many articles were used and in which location within the building. The difference with element-specific identification is thus significant. In the concrete element supply chain, the amount of information related to an individual element is substantial, and both product and process information accumulate significantly for each component during the process. Simultaneously, the number of recipients for that information is only a few. Therefore, a centralised solution for data management is not applicable.

4 Artefact validation – Future State

During validation, unique identification cases were first created from the use cases identified in the project, and identifiers to be individualised were compiled based on these use cases. Product identification was compared to the guideline published by GS1 Norway (GS1, 2018). This information was adapted to the RFID technology supported by the GS1 standard family to ensure that the data capacity of the information carrier was sufficient.

To validate the data contents and data architecture, a conceptual model was first created and compared to the process descriptions made in the CESC project and published studies. Based on the process descriptions, use cases were selected to model the distributed data architecture and its operation in the case type. Example messages of the use case were compared to the PEPPOL standard messages (16) (17) (18) (19)(20)(21)(22).

4.1 Validation results

4.1.1 Defining Unique Identification Information for a Product Unit and Machine Reading

During the validation, the software's GUID was compared to the guideline published by GS1, resulting in the decision to follow GS1's three-level product identification method. According to the validation, this allows for 1) unique identification of individual elements, 2) designation of identical units during the manufacturing stage, and 3) differentiation of nearly identical units. In this way, the serial number can indicate the differences between nearly identical elements.

The validation also concluded that the element class used in Finland and the design software's GUID should be added to the RFID despite the unique identification containing redundant information. Table 2 provides examples of the identification code. The validation of the RFID use case on-site was delayed from the original schedule, so this part of the validation could not be carried out.

Table 2. GS1 application identifiers (AI) to identify engineer-to-order products. GTIN, MTO variation number and serial number form layer 3 GS1 identifier. Finnish element classification identifies all elements from a group of identical elements. GUID is the design object ID generated during the design phase by the concrete element design software

Fault in	Example
(01) GTIN	064000001000247
(242) MTO variation number	123456
(21) Serial number	12345678910
(91) Finnish element classification	V1001
(92) GUID	ba34cf17-0c4b-4c6f-929cae05aa74ad45

4.1.2 Validation of metadata for element types defined in BEC2012

The validation revealed that the national definition of concrete element design and manufacturing information, implemented as the national BEC2012 project during 2011-2012, already includes sufficient data fields by element type to initiate the digitalisation of the concrete element supply chain. Regarding the use case study, it was found that some of the element type-specific data content definitions made in BEC are not yet comprehensive enough for adequate machine processing. Although this de facto standard has been applied for over ten years, some data fields need to have defined formats, allowable value sets, or unambiguously defined options for data contents. This is because the data contents in the supply chain have yet to be processed mechanically but have always involved a human who compensates for the lack of automation. These metadata definitions, therefore, need to be supplemented as part of a national project. An example of insufficient metadata definition is in Figure 3.

Tekla Structures	Solibri/Tocoman BIM/IFC	Description
Primary Material		
Volume of Concrete Parts /m^3		Volume of concrete parts in the assembly (in-situ or precast); parts made from non-concrete materials are not included.
Weight / t	Weight of the element.	The weight of the element is calculated using the formula 2500kg/m^3 * volume of concrete parts + weight of the insulation.
Insulation	Wall element, insulation material.	Insulation material.
Insulation Thickness / mm	Wall element, insulation thickness.	Inner Shell Thickness / mm
Wall element, inner shell thickness.		
Outer Shell Thickness / mm	Wall element, outer shell thickness.	

Figure 3. The validation of element data revealed incomplete metadata definitions that need to be corrected for the project. Typical deficiencies include description, permissible values, value range, or permissible options.

4.1.3 Validation of the message-based data transfer and data architecture

In the use case tests conducted during the research, it was found that some design and product information can be transferred according to the schedule of project milestone meetings. Still, when a problem arises in the supply chain, information must be transferable for each element in a bidirectional manner between parties. Information is thus generated and needed reactively during the process. The most crucial difference is that the number of users of concrete element information is minimal compared to MTS products, and the lifecycle of the use of individual element products and process information is very short, only a few months from design through manufacturing to installation. After this period, most of the information will be transferred digitally to the client. At the same time, the manufacturer and builder will retain some of the information for warranty purposes (23). Using a centralised information management architecture is neither economically nor technically feasible due to the nature of the information management and the information lifecycle, and the most efficient implementation for information transfer is the same as in electrified order-delivery chains and invoicing, i.e., message-based.

4.1.4 Message-Based Data Transfer Required by the Distributed Data Architecture

Message-based communication requires standardising information and data content throughout the design, manufacturing, delivery, and assembly process and defining use cases to identify the associated transactions. The research identified 24 use cases and their related transactions. When studying the end-to-end process for only load-bearing elements, more than 50 necessary messages or message types were identified.

Therefore, the research delved into the usability of PEPPOL messages and preliminarily concluded that these messages could be utilised in some transactions. However, it was also found that the concrete element supply chain involves transmitting information not directly supported by the PEPPOL order-delivery chain message standard. An example of a validated transaction for element call-of is presented in Figure 4.

Peppol BIS version 3 - November 2023 Release
Peppol BIS Ordering 3.3
Peppol Order transaction 3.4 (T01)
INFORMATION REQUIRED FOR A CALL-OFF MESSAGE

Peppol message hierarchy level	Description	Comment	PEPPOL Syntax name	Peppol description
Header	Project number		cac:ProjectReference / cbc:ID	
Header	Ordering party		cac:BuyerCustomerParty	
Header	Selling party		cac:SellerSupplierParty	
Header	Delivery address ID		cac:Delivery /cac:DeliveryLocation /cbc:ID	
Header	Delivery address name		cac:Delivery /cac:DeliveryLocation /cbc:Name	
Header	Delivery address		cac:Delivery /cac:DeliveryLocation /cac:Address	
Header	(Delivery terms)		cac:DeliveryTerms	
Header	Shipping identification codes (e.g. SSCC)	pre-assembled load	cac:Shipment /cbc:ID	
Header	Ordering party order number		ubl:Order /cbc:ID	
Header	Order type: call-off		cbc:OrderTypeCode	
Header	Kommentti		cbc:Note	
Header	Delivery date		cac:Delivery /cac:RequestedDeliveryPeriod /cbc:StartDate	

Figure 4. Validation of Call-off Use Case Messages Implemented with PEPPOL BIS Ordering 3.3 and Order Transaction 3.4 Message Types

While the PEPPOL standard should be utilised within the concrete element supply chain, preparing to supplement the transmitted information with custom messages or message contents is also necessary. PEPPOL includes extensions that could be utilised. However, as was the case with the digitalisation of electricity sales and delivery concerning GS1, specific supply chain-related supplements will likely need to be defined for the concrete element supply chain regarding message transmission. Adhering to the PEPPOL standard is a prerequisite for using message operators, and thus, any extensions must be compatible with the PEPPOL standard.

5 Discussion and future research

As part of the research, the Bill of Materials (BOM) implementation for element factories was also validated. These correspond to Manufacturing Bill of Materials (M-BOM) used in the manufacturing industry because they are detailed down to the article level (25). Element manufacturers strive to use as many pre-fabricated components as possible in the elements, which are produced using a Make-to-Stock (MTS) production strategy. In other words, the MTS production strategy is integrated into the Engineer-to-Order (ETO) production strategy. The product information for the products used by element manufacturers is compiled in a national product information registry and is machine-readable using the TT/EMDG Fest standard (26), in the same way as MEP MTS products (Alhava et al., 2024). This will enable the element industry to calculate CO2 emissions automatically in the future, using the carbon footprint data provided by manufacturers. Therefore, it is logical that manufacturers will maintain CO2 data for the elements they produce in the future and make this information available to clients. The national product information registry (24) for the product data used by element manufacturers is maintained by Rakennustieto Oy (Rakennustieto, 2024). This further validates that the information management of supply chains executed with an ETO production strategy requires a distributed architecture.

During the research, it was also noted that a distributed architecture requires the active sending of event data. Further research is needed to validate an appropriate data transfer standard, which in ETO supply chains could potentially be the EPCIS standard from the GS1 standards family (27).

In future research, it will also be necessary to investigate how the upcoming EU product passport will impact the CO2 calculation and reporting for concrete elements (28). Companies are already required to report their financial statements in accordance with EU requirements, which will soon also mandate a sustainability report (29). The research should explore how to most efficiently implement the collection of reporting data within a distributed architecture. Additionally, the study should extend to cover data requirements for the circular economy and future CEI (Circular Economy Indicator) reports (30). It has also been suggested that the national digital interoperability platform (31) should include a nomenclature for concrete elements in the future, which would enable automation in the design phase using the same principles as with MTS products (Alhava et al., 2024). Alternatively, the BuildingSmart data directories could be used for data distribution (32).

From the research methodology perspective, this article successfully addressed a broad and complex subject, but a weakness of the study is the narrow handling of its parts. Based on the process descriptions of partition wall and facade elements previously done in the project's workshops, there are numerous different use cases for various parties, and the research covered only a tiny portion of these (even though it covered all essential parts for implementing the system and digitalising the supply chain). Since there are more than 20 identified types of elements, their design, manufacturing, and installation are expected to involve different data contents and deviations from the aspects covered in this study.

6 Conclusions

The research implemented the validation of a distributed architecture for managing design, product, and process information in the concrete element supply chain for ETO products. The validation demonstrated that the concrete element supply chain information transfer can be implemented using independent systems based on the same principles as other industries, utilising the GS1 standard family and the PEPPOL standard. The assumed impact of the research on the industry is significant, as it introduces a new information management paradigm that benefits the network and shifts the focus of research on ETO supply chain information management from a "what" framework to a "how" framework.

References

Alaluusua, T. (2023). Digitaalinen tiedonhallinta tahtituotantoa hyödyntävän rakennushankkeen toimitusketjuissa. *Master's thesis, Building Technology, Aalto University.*

Alhava, O., Ruottinen B., Peltokorpi A., Siren, M., Aaltonen A. and Pitkäranta T. (2024). Advancing Digitalisation in Construction Through Automated Metadata Management and Machine Data Processing. Proceedings of the 41th International Conference of CIB W78, Marrakesh, 1-3 October

Bataglin, F. S., Viana, D. D., Formoso, C. T., & Bulhões, I. R. (2020). Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: exploring synergies between Lean and BIM. *Canadian journal of civil engineering, 47(2), 165-177.*

BEC (2012). Elementtisuunnittelun mallinnusohje. *BetonielementtiCAD-project 2011-2012, BEC working group, Rakennusteollisuus RT, Helsinki, Finland. Available at*: https://www.elementtisuunnittelu.fi/Download /23982/BEC2012%20Elementtisuunnittelun%20mallinnusohje_v110.pdf [visited 15.5.2024]

BEC CP (2023) Custom properties, Version 1.1. *BetonielementtiCAD-project 2011-2012, BEC working group, Rakennusteollisuus RT, Helsinki, Finland. Available at: https://www.elementtisuunnittelu.fi/Download/24144 /BEC_CustomProperties.pdf [visited 15.5.2024]*

BEC IFC (2016) Betonielementtien määrälaskenta ifc-mallista, version 1.0. *BetonielementtiCAD-project 2011-2012, BEC working group, Rakennusteollisuus RT, Helsinki, Finland.* https://www.elementtisuunnittelu.fi/Download/24146/Betonielementtien%20m%c3%a4%c3%a4r%c3%a4laskenta%20ifc-mallista.pdf *[visited 15.5.2024]*

BEC PS (2012) Property Sets, Version 1. *BetonielementtiCAD-project 2011-2012, BEC working group, Rakennusteollisuus RT, Helsinki, Finland. Available at: https://www.elementtisuunnittelu.fi /Download/24145 /BEC_PropertySets.pdf [visited 15.5.2024]*

Bellgran, M., & Säfsten, K. (2010). Production development over time. Springer London.

COBIM S5 (2012). COMMON BIM REQUIREMENTS 2012 Series 5. Structural design. *Building Information Foundation RTS and Parties to the COBIM project 2012, VERSION 1.0 RT standards sheet, December 2012 RT 10-11070 (en)*

Ergen, E., Akinci, B., & Sacks, R. (2007). Tracking and locating components in a precast storage yard utilising radio frequency identification technology and GPS. *Automation in construction*, *16*(3), 354-367.

Ergen, E., & Akinci, B. (2008). Formalisation of the flow of component-related information in precast concrete supply chains. *Journal of Construction Engineering and Management, 134(2), 112-121.*

GS1 (2018). Guideline for Unique identification of products with SGTIN (serialised GTIN). Labelling with GS1 Datamatrix barcode and tagging with EPC / RFID Gen 2 UHF RFID tags. Release 1.1 - 27. June 2018. *GS1 Norway, Available at: https://www.gs1.org/docs/technical_industries/Construction /GS1%20Guideline%20unique%20ID%20for%20products%20in%20Construction%20v1.1%20-%202018.pdf [visited 15.5.2024]*

GS1 (2023). GTIN Management Guideline for Construction Products. *[Online] Available at: https://www.gs1.org/standards/gtin-management-guideline-construction-products/current-standard#1-Introduction [visited 15.5.2024]*

Ikonen, J., Knutas, A., Hämäläinen, H., Ihonen, M., Porras, J., & Kallonen, T. (2013). Use of embedded RFID tags in concrete element supply chains. *J. Inf. Technol. Constr., 18(7), 119-147.*

Jiang, Y., Su, S., & Zhong, R. Y. (2023). Digital Twin-Enabled Two-Stage Optimisation Model for Logistics-Assembly Synchronisation in Fit-Out Construction. *In 2023 IEEE 19th International Conference on Automation Science and Engineering (CASE) (pp. 1-6). IEEE*.

Jussila, A., Kiviniemi, M., & Talvitie, U. (2012). Piloting a new information-sharing method in a construction supply chain. *In 9th European Conference on Product and Process Modelling, ECPPM 2012 (pp. 707-712).*

Makkonen, S. (2023). Improving process flow in the frame erection phase of a residential building. *Master's Thesis, Construction Management and Economics, University of Tampere, Finland.*

Murguia, D., Rathnayake, A., Jansen van Vuuren, T., & Middleton, C. (2024). Measuring Construction Productivity across Projects: Multilevel Three-Dimensional Framework. Journal of Construction Engineering and Management, 150(11), 04024151.

Nissilä, J., Heikkilä, R., Romo, I., Malaska, M., & Aho, T. (2014). BIM-based schedule control for the precast concrete supply chain. *In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction (Vol. 31, p. 1). IAARC Publications.*

Ocheoha, I. A., & Moselhi, O. (2018). A BIM-based supply chain integration for prefabrication and modularisation. *Modular and Offsite Construction (MOC) Summit Proceedings.*

Peltokorpi, A., Uusitalo P., Siltanen S. & Alhava O. (2023). Toimitusketjujen hallinta. *Building 2030 osahankkeen loppuraportti, Aalto University. Available at: https://www.aalto.fi/fi/building-2030 /building-2030-teemoihin-liittyvia-tutkimusraportteja [visited 15.5.2024]*

Rakennustieto. (2024). Rakennustieto. Available: https://www.rakennustieto.Ai/en. Accessed 14.8.2024.
Sacks R, Brilakis I, Pikas E, Xie HS, Girolami M. (2020). Construction with digital twin information systems. Data-Centric Engineering.;1:e14. doi:10.1017/dce.2020.16
Valtiokonttori. (2024). The State Treasury is the Finnish Peppol authority. *Available at: https://www.valtiokonttori.fi/en/service/the-state-treasury-is-the-finnish-peppol-authority/#peppol-in-brief [visited 15.5.2024]*
Van Steen, M., & Tanenbaum, A. S. (2016). A brief introduction to distributed systems. *Computing, 98, 967-1009.*
Vom Brocke, J., Hevner, A., & Maedche, A. (2020). Introduction to design science research. *Design science research. Cases, 1-13.*
Wang, Z., Hu, H., Gong, J., Ma, X., & Xiong, W. (2019). Precast supply chain management in off-site construction: A critical literature review. *Journal of Cleaner Production, 232, 1204-1217.*