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Exploring the implications of technical interoperability in low-volume manufacturing

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Abstract

Purpose – The purpose of this study is to examine the technical interoperability of a current product data infrastructure for an engineer-to-order (ETO) process and explore the implications of technical interoperability on design manufacturing integration in low-volume manufacturing companies.

Design/methodology/approach – The results originate from a longitudinal case study of an ETO process within a large rolling stock manufacturing company.

Findings – The research identified theoretical and practical implications of low technical interoperability. The findings suggest that a lack of technical interoperability can negatively impact the efficiency of an ETO process. This lack of efficiency presents itself via an increase in manual administration and the risk of miscommunication, resulting in delayed lead times. This study also indicates that lacking technical interoperability can act as a barrier to innovation and the further implementation of advanced technologies.

Research limitations/implications – This case study was limited to a single company, which in turn limits the generalizability of the findings. Future research should therefore focus on additional low-volume manufacturing companies.

Originality/value – The results from this study provide important insights for managing ETO processes within a low-volume manufacturing sector. The findings stress the importance of the technical interoperability of product data infrastructures for design manufacturing integration and, thus, the efficiency of ETO processes. Being aware of these implications can aid management in their decision-making process and support them in circumventing the negative effects of low technical interoperability.

Keywords Technical interoperability, Design manufacturing integration, Engineer-to-Order, Production development

Paper type Research paper

Quick value overview

Interesting because – Low-volume manufacturing companies face increasingly competitive market environments, which incentivizes companies to quickly engineer and deliver products to the market, putting increased pressure on the engineer-to-order (ETO) process. The ETO process is complex and requires a robust product data infrastructure, along with a significant amount of information exchange between design and manufacturing systems. Technical interoperability, defined as the ability of systems to use and exchange information, is a necessary enabler for

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design-manufacturing integration. Prior studies on technical interoperability within manufacturing have focused on its implementation and challenges. However, the implications of technical interoperability on both the ETO process and design-manufacturing integration have not been explored, and this paper addresses that gap in the literature.

Theoretical value – This study highlights the importance of technical interoperability for design-manufacturing integration. A lack of technical interoperability was found to negatively impact the ETO process through increased manual administration and workload, leading to delays in lead time and increased costs. Furthermore, insufficient technical interoperability also significantly inhibits companies' ability to capitalize on emerging technologies and digitalization, acting as a barrier to innovation.

Practical value – Technical interoperability can have significant implications on both the ETO process and design-manufacturing integration. Low-volume manufacturing companies should be aware of said implications and, as such, need to assess and monitor the level of technical interoperability within their existing product data infrastructure. Managers should prioritize establishing a comprehensive data management strategy in order to increase overall levels of technical interoperability.

1. Introduction

Today's low-volume manufacturing market continues to face growing competition, requiring companies to produce highly complex products at the lowest possible cost and with a shortened time to market without making any compromises in product quality. These strict customer demands have led to a significant acceleration of the product development cycle for these companies (Javadi and Chirumalla, 2023). Those companies able to introduce their products to the market at a quicker rate than their competitors experience the benefits of increased market share (Araújo *et al.*, 2017). This is especially relevant for low-volume manufacturing companies, which are often characterized by higher degrees of flexibility, and more complex products, wherein a shorter time to market is considered a fundamental aspect of competitiveness (Løkkegaard *et al.*, 2023; Strandhagen *et al.*, 2019). These market pressures present these companies with great incentives to quickly engineer, produce and deliver products to customers, making the engineer-to-order (ETO) process a priority. An important factor for an efficient ETO process is good integration between design and manufacturing (Groche *et al.*, 2012; Marzi *et al.*, 2020). Such integrations have been shown to play a critical role in reducing lead times and improving product quality, thereby increasing competitiveness by overcoming barriers to integrating knowledge from manufacturing operations back to the design phase (Ahlskog *et al.*, 2017; El Souri *et al.*, 2019; Larsson and Romero, 2017; Swink and Calantone, 2004).

Successful integration between the design and manufacturing functions requires the exchange of a significant amount of data and is facilitated by the implementation of more advanced technology and its infrastructure (Swink and Nair, 2007). However, to ensure successful integration between design and manufacturing for a more efficient ETO process, one of the requirements is the existence of a robust data infrastructure for the product and production data (Genest and Gamache, 2020; Pacchini *et al.*, 2019). Within this article, the term product data infrastructure refers to the underlying structure of technology and systems that support the collection, management, storage, and dissemination of any product and production-related data across the product lifecycle. Not only does a product data infrastructure need to be present, but the systems within said infrastructure need to be able to efficiently communicate with one another, allowing for the smooth flow of data. This seamless exchange of data between systems of product-related information requires integration and has introduced an unprecedented challenge of interoperability (Zeid *et al.*, 2019). The ability of systems to effectively exchange and use information in a satisfactory way is referred to as technical interoperability (Rezaei *et al.*, 2014). Problems with interoperability can have drastic impacts of businesses' performance, resulting in communication failures,

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increased operational costs and the delay of products to the market (Cabral and Grilo, 2018; Vujasinović *et al*., 2021).

The interoperability of product data infrastructures to support design manufacturing integration has received some, albeit limited, attention within existing research, despite having been identified as a relevant strategic area for competitive manufacturing (Winter *et al*., 2022). Zeid *et al*. (2019) explore the concept of interoperability within manufacturing, identifying challenges regarding the implementation of interoperability, such as the misinterpretation of terminology used for the exchange of information, and the transfer of data between systems, which might differ in versions or be commercially different. The authors further identify the research challenges of interoperability, including legacy systems' lack of modularity and manufacturing capabilities' lack of horizontal integration. Coito *et al*. (2020) look at improving the interoperability of product data infrastructures by bridging the gap among various systems utilizing a self-developed middleware capable of transferring data among said systems, allowing for a better decision support system. Figay *et al*. (2012) present an interoperability framework for technical enterprise applications, specifically with the intention of improving interoperability among said applications, to produce a more competitive product development process. However, what has been lacking is the emphasis on the technical interoperability of product data infrastructures, specifically within the context of ETO processes, as well as the implications of inadequate interoperability.

Therefore, the purpose of this article is to examine the technical interoperability of a product data infrastructure within an ETO process and analyse its implications for design manufacturing integration. By utilizing the Levels of Information Systems Interoperability (LISI) framework (C4ISR, 1998), this study assesses the current level of technical interoperability and its implications on the ETO process and innovation. The findings provide both practical insights for the case company and theoretical contributions regarding the effects of low technical interoperability on design manufacturing integration. This study presents results from a longitudinal case study of a low-volume rolling stock manufacturer in the transportation solutions industry. By adopting an interoperability perspective in regards to a product data infrastructure and analysing its implications, it expands on existing research by highlighting how low technical interoperability affects the efficiency of ETO processes and the broader integration of design and manufacturing.

2. Theoretical background

2.1 Engineer-to-order in low-volume manufacturing

The ETO process plays an important role as an interface between design and manufacturing, and is particularly prominent within the low-volume manufacturing sector. This process includes activities from both product and production development, which are necessary to transition a conceptual design into a physical prototype ready for series production (Addo-Tenkorang and Eyob, 2012; Bellgran and Säfsten, 2010; Fortes *et al*., 2023). In low-volume manufacturing, where companies produce highly complex products with significant variety, the ETO process becomes even more important (Willner *et al*., 2016). This sector is commonly characterized by long lead times, complex designs and multifaceted information flow requiring extensive interaction among multiple stakeholders (Løkkegaard *et al*., 2023; Strandhagen *et al*., 2018; Wlazlak and Johansson, 2014). Although the ETO process is time and resource intensive, the effective management of which can enable companies to capitalize on the opportunity to quickly deliver products to the market (Wang *et al*., 2021). However, challenges regarding the effective management of data and engineering changes can negatively affect the ETO process through increased uncertainty and prolonged lead times (Koufteros *et al*., 2005; Wlazlak *et al*., 2019).

Design manufacturing integration has been shown to positively impact the product development process during both the development and commercialization phases (Adler, 1995; Brettel *et al*., 2011). This integration has been associated with the fundamentals of

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concurrent engineering (Koufteros *et al.*, 2001), focusing on parallel consideration of design and manufacturing processes, allowing for the identification of potential manufacturing issues during the design phase, thereby minimizing costly revisions later in the process and improving product quality (Song *et al.*, 2017). Another aspect of design manufacturing integration is the role of knowledge integration in enhancing product quality and innovation, wherein effective integration of manufacturing knowledge back to design is essential for achieving a competitive advantage within the ETO process (Ahlskog *et al.*, 2017). This is particularly relevant in low-volume manufacturing, where the integration of manufacturing knowledge with the design process can lead to substantial improvements in quality and efficiency (El Souri *et al.*, 2019).

Thus, ETO presents a complex environment involving a significant overlap of design and manufacturing activities, which require a continuous flow of data and information (Javadi and Chirumalla, 2023). Consequently, interoperability can play a critical role in addressing some of the challenges of low-volume manufacturing–design integration by enabling seamless data flows across enterprise applications, supply chains, and supporting technologies within manufacturing (Weichhart *et al.*, 2021). Enhancing the flow of information and data can lead to the better coordination of the design and manufacturing functions while also contributing toward horizontal and vertical integration (Mourad *et al.*, 2020; Zeid *et al.*, 2019).

2.2 Interoperability and digitalization

Interoperability is defined by IEEE as "the ability of two or more systems or components to exchange and use information". Different types of interoperability include technical, semantic, organizational and syntactic interoperability (Rezaei *et al.*, 2014; Van der Veer and Wiles, 2008). The current study focuses on technical interoperability, which is considered when electronic systems, services, or items can exchange and use information with one another in such a way as to satisfy the requirements of both the systems and their users (Rezaei *et al.*, 2014).

A recent trend in manufacturing is the push towards the increased use of data science and analytical models within the manufacturing setting, utilizing machines, systems, and their processes as sources of data for further analysis (Xu *et al.*, 2018). To realize this ambition, one of the main prerequisites is achieving interoperability across a wide range of technologies and devices, acquiring and processing large amounts of production data which can be further used to improve operations, resulting in more informed decisions and efficient production systems (Choi *et al.*, 2018; Oks *et al.*, 2022). This marks as a new era in manufacturing and is characterized by the implementation of various digital technologies such as Cyber-Physical Systems (CPS), Internet of Things (IoT), Cloud Manufacturing, Digital Twins and other systems that allow for the capture and generation of data (Dalenogare *et al.*, 2018; Hawaou *et al.*, 2024; Schlemitz and Mezhuyev, 2024). But as more advanced digital technologies become increasingly prominent within manufacturing, so too does interoperability. For instance, interoperability is often noted as a key enabler for CPS (Panetto *et al.*, 2019). This is further supported by Wassick and Perez (2024), who note that interoperability is one of the few key enablers of digitalized supply chains and holistic CPS. Furthermore, the increased connectivity enabled by IoT devices is further enabled by interoperability, as noted by Åkerman *et al.* (2018), who underlined the importance of technical interoperability in achieving better machine connectivity within production floors to enable IoT and Cloud manufacturing.

Interoperability has also been viewed as the end goal of digitalization, wherein certain digital tools are integrated with the specific intention to achieve interoperability, for instance through the use of digital twins. O'Connell *et al.* (2023) examined how digital twins could enable interoperability within a smart manufacturing network, where the objective was to create a translator able to interpret data from both the physical and virtual worlds. Vinci-Carlavan *et al.* (2024) examined digital twins for operations management in manufacturing

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ETO environments, where a digital twin was developed specifically to bridge the gap between planning and operations management by allowing for a bidirectional flow of data between both departments. Interoperability also plays a critical role in terms of the data exchange between various engineering modules such as computer-aided design (CAD), enterprise resource planning (ERP) and product lifecycle management (PLM) systems, specifically in environments prone to high degrees of product variation such as engineer-to-order, where increased integration between said systems can aid in the mitigation of excess production costs and reduce manual errors (Kadam *et al*., 2022). Additionally, it can also play a critical role in bridging the gap between older monolithic legacy systems, a common challenge within large, established organizations (Hooshmand *et al*., 2022).

From a collaborative perspective, interoperability has become a prerequisite that is important to satisfy as the ability of systems to exchange and use information with one another is critical; if not addressed, it can become problematic (Guédria *et al*., 2015). Indeed, interoperability-related problems can have drastic effects on both the performance and outcomes of businesses and their processes (da Silva Serapião Leal *et al*., 2019). Low technical interoperability can present issues such as integration challenges, wherein low interoperability may present companies with difficulties in terms of integrating the different systems to support heterogeneous workflows, resulting in inefficiencies regarding data exchange and communication (Fernandes *et al*., 2022; Malm-Nicolaisen *et al*., 2023). This can lead to increased costs due to companies investing in workarounds and the maintenance of separate systems, resulting in reduced efficiency (Das, 2012). Furthermore, limitations in technical interoperability have been found to present significant barriers to innovation, wherein companies do not fully leverage the potential of emerging technologies (Pu and Lam, 2021). To avoid such problems, Panetto *et al*. (2012) recommend that companies conduct an interoperability assessment in order to define their strengths and weaknesses regarding the topic. Such an assessment can identify potential problems and solutions, allowing for a mapping of the current state and providing a roadmap to the future state. Put simply, it enables companies to plan an individualized transformation strategy geared towards the improved future state (da Silva Serapião Leal *et al*., 2019).

More recently, with the advent of the Industry 4.0 paradigm, a more standardized interface and reference architecture, RAMI 4.0, was proposed as a standalone standard meant to facilitate smart manufacturing (Winter *et al*., 2022). This standalone reference architecture is a three-dimensional model that describes Industry 4.0, providing a multilayered view of the architectural aspects while combining lifecycle and value stream information with hierarchical layers of equipment (Weber *et al*., 2017). However, this holistic scope of RAMI 4.0 has led to some limitations and a lack of clarity for users (Resman *et al*., 2019), which is one of the reasons it was excluded from the scope of this article.

3. Methodology

3.1 Case study

This longitudinal case study was conducted at a production development site at a low-volume rolling stock manufacturing company located in Sweden. The main role of this site includes the design, development and production of traction systems, with annual volumes ranging from 10–30 units. The company's ETO process centres around ensuring that designs of prototypes are feasible in terms of safety, performance and manufacturability. This necessitates a thorough review of requirements, followed by design, assembly, testing and production before delivery. Previously, the expected delivery timeline for new designs ranged from 18 to 24 months, but market pressures have compressed this expectation to 12 months, prompting the need for a significant reduction in lead time to maintain competitiveness. This requirement underlines the importance of efficient data sharing across the various systems that comprise the product data infrastructure, as any disturbances can lead to delivery delays measured in weeks.

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This environment presented the necessary pre-conditions that positioned the ETO process to be a suitable candidate to explore via a case study, based on the following criteria. The process revolved around the design and production of products within a low-volume sector. The ETO process itself was well defined and facing long-standing problems, including delays and long lead times, with the development site having expressed a desire to further integrate the design and manufacturing functions in search for improvements. Furthermore, a robust product data infrastructure was present, with multiple systems interacting and communicating, therefore allowing for an evaluation of technical interoperability and its implications for design manufacturing integration. Finally, the ability to monitor ETO activities in real-time enabled the collection of diverse data streams, enriching the analysis of data flows among systems (Yin, 2018).

The use of case studies was deemed an appropriate method for this task as they allow for a deep understanding of complex phenomena (Yin, 2018). The objective of the case study was to examine the product data infrastructure of an ETO process from a technical interoperability perspective and then evaluate its implications for the integration of design and manufacturing. As such, the unit of analysis for this case study was the ETO process, with an embedded unit of analysis being the product data infrastructure and its technical interoperability, making this an embedded case study (Yin, 2018). The role of the researcher was to investigate ways in which the technical interoperability within the product data infrastructure impacted the performance of the ETO process. Being a participant in the ETO process allowed for an extensive gathering of information through official documentation and open access to staff, allowing for the integration of said knowledge with insights from the research community. This method aligns with the concept of an insider role in collaborative research (Coghlan and Coughlan, 2010).

3.2 Data collection

The data collection for this longitudinal case study spanned approximately two years. The opportunity to be embedded in the organization allowed for the collection of a wide range of data via internal documents, observations during various department meetings, and conversations with relevant experts on the topic. In addition, semi-structured interviews and workshops were utilized for collecting data. In total, two rounds of semi-structured interviews were conducted. The main objective of the first round was to establish a baseline understanding of the entirety of the ETO process as well as to identify any underlying challenges and why they are present. The second round of semi-structured interviews revolved around accurately mapping the product data infrastructure currently being utilized during the ETO process. The use of semi-structured interviews was considered an appropriate method for data collection, as it allows for follow-up questions in the event of any lack of clarity (Säfsten and Gustavsson, 2020). A total of 30 semi-structured interviews were conducted, each lasting between 45 and 74 minutes. A wide range of respondents were included, with the choice criteria for participation being based on their prior experience, involvement with the process, and overall knowledge of the product data infrastructure. A list of respondent roles and their respective departments is outlined in Table 1. Note three respondents were interviewed in both rounds of interviews. All interviews were recorded and subsequently transcribed; these transcripts then served as the basis for the data analysis.

A subsequent phase of data collection included document reviews and workshops. This phase was critical, with a heavy emphasis on mapping and understanding the interoperability of the product data infrastructure using the LISI model. This served as a triangulation method for the initial round of data collection, ensuring that a common understanding of the product data infrastructure, its components, and the flow of data and information was accurately depicted and represented (Yin, 2018). During the workshops, participants were asked to evaluate the level of technological interoperability between the various artefacts and components of the ETO process. The evaluation of interoperability of the product data infrastructure involved categorizing each interaction into five distinct categories based on the

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Table 1. List of respondent roles

ETO phase	Respondent title
Tender	Bid manager
Engineering	Head of Electrical Systems
	Head of Design
	Design Engineers (2)
	Lifecycle Manager
	Process Manager
	Product Managers (2)
	Requirements Manager
	Systems Engineers (2)
Operations	Head of Operation Processes
	Industrialization Engineer
	Manufacturing Engineers (4)
	Lead Industrialization Manager
Logistics	Head of Business Solutions
	Production and Logistics Developer
Testing	Testing Manager
	Test Engineer
Production and Assembly	Production Operator
	Production Manager
IT	Concept Design Engineer
	IT Systems Engineer

Source(s): Authors' own work

LISI model (C4ISR, 1998). The LISI model was considered appropriate due to its flexibility of use and its recognition as a standard framework for evaluating the technical interoperability of information systems, enabling a more seamless flow of data (Guédria *et al.*, 2008; Panetto, 2007; Vida *et al.*, 2012). The levels of interoperability used for the categorization are outlined in Table 2.

Within each level, four additional factors that influence interoperability can be identified: procedures, applications, infrastructure, and data (PAID) (C4ISR, 1998). Within this study, the focus was placed on determining the technical interoperability of the infrastructure aspect of

Table 2. LISI categorization

Degree interoperability	Status	Characteristic
Level 0 (L0)	Isolated	Interoperability at this level is limited to manual extraction and integration of data from various systems
Level 1 (L1)	Connected	Interoperability exists in a peer-to-peer form, with the simple exchange of electronic data such as text, email, graphics, and other homogenous data types
Level 2 (L2)	Functional	Local area networks enable data exchanges from systems that reside on the network. Logical data models are shared across systems. Data containing heterogeneous information are fused together (images with annotations)
Level 3 (L3)	Domain	Extensive networks connect different systems. Information exchange among different applications occurs via shared domain-based data models, thereby allowing for business rules and database-to-database interactions
Level 4 (L4)	Enterprise	Systems have the capabilities to use global information spanning multiple domains. Data and applications are fully shared and distributed. Advanced collaboration is possible

Source(s): C4ISR, A. W. G. (1998). *Levels of Information Systems Interoperability (LISI)*

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the PAID factors. Technical interoperability was graded using the LISI scale, with each workshop respondent providing justification for their assigned grade. Following a brief discussion among the respondents, a consensus was reached to determine the final grade for each system. This process was then repeated for the following interaction on the product data infrastructure map until all interactions had been evaluated.

Finally, the last phase of data collection included a workshop wherein stakeholders of the research project from within the company, including innovation managers, operations managers, and manufacturing engineers, were presented with the current map of the product data infrastructure as well as its interoperability assessment. The various implications of the overall level of interoperability of the map were discussed, and key insights and takeaways were gathered. Each workshop was recorded and transcribed for subsequent analysis. The data collection process is outlined in Table 3.

3.3 Data analysis

The data analysis followed the process of Miles and Huberman (1994) whose stages of qualitative data analysis are divided into data reduction, data display and conclusion drawing. This process was utilized in order to create a better understanding of the product data infrastructure and how it supported the ETO process. The data display stage utilized the LISI categorization to provide a comprehensive overview of the entire product data infrastructure and the overall levels of technical interoperability among its systems. Conclusion drawing consisted of a thematic analysis as outlined by Braun and Clarke (2006), focusing on the implications of the levels of technical interoperability for the ETO process. This stage was also utilized as an opportunity to triangulate the findings from the first round of data collection to improve the validity of the findings as per the recommendations of Yin (2018). During this stage, all transcribed interviews were coded to mark any notions of the implications. Subsequently, more aggregate themes related to the implications of technical interoperability

Table 3. Data collection phases

Method	No. of participants	Main objective
Semi-structured Interviews	21	Interviews were carried out with relevant stakeholders from a diverse range of roles with the intention of creating a baseline understanding of the new product development process, its efficiency and its inherent challenges
Semi-structured Interviews	9	Accurately map the product data infrastructure currently supporting ETO processes and the flow of data throughout said infrastructure
Workshop	4	Conduct the interoperability assessment of the product data infrastructure and its components for the ETO process. Also used as a triangulation method to ensure that product data infrastructure was accurately depicted on the map
Workshop	5	Triangulate findings from the interoperability assessment and discuss and analyse the main implications from said findings
Document Reviews and Informal Conversations	Full Access	Review any documents regarding the ETO process or the product data infrastructure within the case company to create understanding of the product data infrastructure and its data flow
Informal Meetings	Daily	Meet with engineers, managers and testers regarding the relevant challenges and their effects on the ETO process as well as the correct flow of data through the infrastructure and its components

Source(s): Authors' own work

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were identified and reviewed. Finally, conclusions were drawn regarding the thematic implications of low technical interoperability.

4. Empirical findings

4.1 Engineer-to-order process – current state

Based on the collected data, a map of the product data infrastructure was derived (see Figure 1). The figure illustrates the main software tools and systems of the product data infrastructure while putting into perspective where each system is located relative to the phases of the ETO process. The phases of the ETO process are illustrated on the left-hand side of Figure 1. Within each phase, the main system or tools used are illustrated, with arrows pointing to the systems with which they exchange information and data. These systems are categorized into either software systems/tools or databases, with a single instance of manual assembly being used for

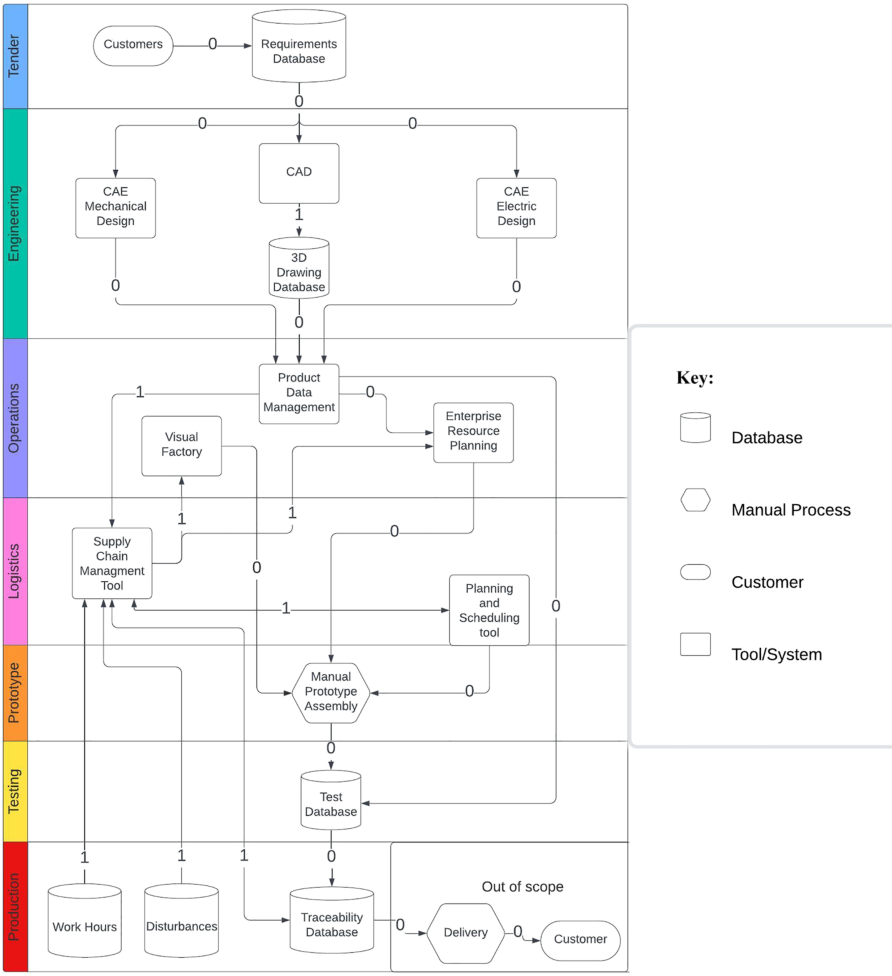

Figure 1. Current state of product data infrastructure and its relation to the phases of the new product development process (left-hand side). **Source(s):** (Authors own work)

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simplification. Each arrow between the systems represents the direction of data exchange, and the number of each arrow denotes the level of interoperability between the systems.

The subsequent sections of this chapter are organized as follows. Each phase of the ETO process is briefly described in terms of its function and objectives. The systems of each phase are outlined along with their data flow and the levels of technical interoperability of their respective data exchange. This is denoted in L0 or L1 as per Table 1. Note that the delivery of the product to the customer is beyond the scope of this article.

4.1.1 Tender phase. The initial phase of the process was the tendering phase, during which potential customers specify their requirements for a specific transport solution. Following this, the tenders team prepares a sales proposal based on preliminary estimations of the time required to design and manufacture products that meet the customer’s expectations. Key factors considered in this bidding process include anticipated costs, the current product portfolio, and the estimated number of operator hours needed.

Within this phase, a singular system exists within the product data infrastructure—namely, a database designated for the storage of diverse customer requirements. The primary tools employed during this phase consist of written communication that includes various legal clauses and PDF documents detailing product specifications. The flow of information in this phase is predominantly manual, requiring key users and database administrators to manually input these documents and extract information. Consequently, this database operates as a completely isolated system within the product data infrastructure.

4.1.2 Engineering phase. Upon receiving the notice to proceed, engineering and design are responsible for translating the customer’s requirements into a fully developed product. This process includes several iterations of design, comprised of three stages: conceptual, preliminary and detailed design. A stage gate is implemented between each of these stages to ensure that all necessary procedures and design targets have been adequately met. Throughout these stages, a variety of performance calculations are conducted to ensure compliance with customer expectations as well as meet performance standards. Both electrical and mechanical components are designed, and the software application for the product is developed.

During this phase, various CAD and computer-aided engineering (CAE) systems are utilized. CAD drawings are stored in a database prior to their submission to the product data management (PDM) system. Conversely, the flow from CAE tools bypasses the 3D drawing database and directly enters the PDM system. The PDM system functions as a repository for designs, along with other associated documents and information. Each of the CAD and CAE systems specializes in its own design area (e.g. mechanical design or electrical design). Generally, the CAE, CAD and PDM systems are isolated from one another, so product designers and engineers are required to complete their designs before manually storing them in PDM with their corresponding product information. An exception to this isolation is in the form of the single L1 = Connected link, which connects the 3D CAD system and its corresponding 3D model database, where a one-to-one link exists, allowing for information to be stored without the need for manual extraction and integration. This link allows for one-to-one correspondence, facilitating information storage without manual extraction and integration.

4.1.3 Operations phase. The handover to operations occurs almost simultaneously with the initiation of the requirements analysis and engineering design phases. This process, known as design for manufacturing, requires some concurrent activities alongside the engineering function. The primary objective in this phase is to ensure that the design is feasible from a production perspective, taking into account operator activities such as cabling, crimping and assembly tasks with emphasis on ergonomic consideration. Furthermore, an emphasis is placed on ensuring that the production process operates smoothly and conforms to quality standards while achieving efficiency targets in terms of time and costs.

In this phase, the process of integrating the various CAD and CAE models into the PDM is essential. Once the data are incorporated into the PDM system, the data must be distributed to

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three destinations: the Supply Chain Management Tool (SCMT), ERP, and the testing database. The ERP system and testing database are isolated from the PDM, with the information flow towards the SCMT classified as L1 = Connected. The SCMT also provides relevant information to Visual Factory, a system utilized to create and spread manual instructions. Subsequently, data from the Visual Factory and the ERP system are manually transferred to the prototype assembly phase. Throughout this phase, all data flows are categorized as L0 = Isolated, except those originating from the SCMT, which are classified as L1 = Connected.

4.1.4 Logistics phase. Although logistics are an important part of the ETO process, they typically operate outside of the immediate timeframe of the process, supporting multiple projects simultaneously. The map depicted above primarily focuses primarily on a single project perspective. Regardless, the relationship between logistics and the ETO process is predominantly through the SCMT and the Planning Support Tool (PST). The PST largely serves as an extension of the SCMT and extracts information related to manufacturing, inventory levels and deadlines, which is subsequently used for prototype assembly.

Within the logistics phase, two systems function concurrently, with the SCMT showcasing the highest level of interoperability among the systems within the product data infrastructure. All information flows associated with the SCMT are assessed as L1 = Connected. This level of connectivity is logical, given that one of its primary purposes is to serve as a business intelligence platform for the overall process. Conversely, the PST remains isolated from other components of the infrastructure, with the exception of its connection to the SCMT.

4.1.5 Prototype phase. A pilot prototype of the product is required before any testing. Data and information related to the product are transmitted from the ERP, Visual Factory, and PST systems to the manual assembly, where operators utilize the information received to work on the physical product. This prototype subsequently undergoes quality inspection by other operators before moving on to the testing phase. As this phase is manual, no systems are used.

4.1.6 Testing phase. Testing involves two distinct sets of assessments. The first set comprises manual tests in which standard performance metrics are subjected to stress testing to verify that the product meets established standards. The second assessment evaluates the EOS software application to ensure that the logical model embedded within the management system of the power converter performs as expected when subjected to various voltage and environmental simulations.

The primary system within the product data infrastructure for this phase is a single database. The test results from both types of assessments are manually uploaded to the test database server, where they largely remain unaltered. Certain elements of the test results are manually forwarded to a production database to establish traceability for the approved components in the process. It is noteworthy that this database is entirely L0 = Isolated, with all subsequent data flows occurring manually.

4.1.7 Production phase. Within the production phase, if all of the test results indicate that the prototype fulfils the required standards, the pre-series phase is then ramped up for full-series production. The handover from pre-series to series production may occur within the same production development unit. However, it predominantly takes place between the development site and other series production facilities located abroad.

In this phase, three distinct databases operate in isolation from one another. The first database collects data concerning the number of hours a product is sold as well as the number of operator hours required to assemble the product. The second database is primarily focused on maintaining traceability and associated maintenance activities. The third and final database is dedicated to tracking work disturbances and is used exclusively for tracking any production floor errors for KPI measurements. Although these three databases are not interconnected to one another, they do relay information back to the SCMT via an L1 = Connected information flow. Of the four information flows originating from within the production function, three have L1 = Connected, with the last manual flow marking information for the delivery with L0 = Isolated.

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5. Analysis and discussion

The empirical data showed a surprising number of isolated systems within the product data infrastructure related to the design and manufacturing interface. A prominent finding is that none of the data exchanges within the product data infrastructure achieved a higher score than L1 = Connected on the LISI scale, indicating a low degree of interoperability among the various systems. This lack of technical interoperability, not only reflects potential inefficiencies within the ETO process, but also potential barriers to the integration of design and manufacturing, that in turn might hinder innovation and competitiveness. However, it is important to note that achieving higher LISI values across the board should not necessarily be the main objective of companies. Rather, the objective should be to understand the product data infrastructure and to identify where technical interoperability should be elevated, all the while understanding the potential trade-offs it might bring, such as increased levels of complexity as the number of interconnected systems and components rise (Zeid *et al.*, 2019). The results from the interoperability assessment are illustrated in Figure 2, the analysis of which offers some key implications that are further elaborated on in the following sections and should be considered by the case company.

5.1 Impact on ETO process

The first implication from the analysis, which was derived from the significant number of zeroes from the interoperability assessment, is the potential risk for key users' increased workload. The number of non-interoperable isolated systems requires key users to remain up to date across multiple systems; if any change occurs, such as in the PDM system, these users need to ensure that the corresponding data are manually adjusted in both the ERP system and the testing database. "*There is a mismatch between the different systems, which results in the repetition of work*" (Chief of Traction Design). This points towards the increase in manual workload and compensatory administration required to offset the overall lack of interoperability. Indeed, another respondent stated, "*In PDM we store everything, it's our configuration tool. But there are no direct links [. . .] you are working with a baseline which needs to be manually exported into excel or PDF, and only then you can take and save it into the PDM system*" (Systems Engineer). This data administration being largely manual and time consuming is significant, since its effects are compounded when put into the perspective of the low-volume manufacturing environment, where time-to-market is a crucial order winner (Strandhagen *et al.*, 2019). Furthermore, the lack of technical interoperability resulted in an increased reliance on the communicational roles within the process, which can in turn risk miscommunication. As one respondent noted, "*We have too many manual processes where we rely heavily on people being correct the first time around. Our information is not monitored by a system, but by people*" (Production and Logistics Developer). The overreliance on manual information sharing and the risk of miscommunication are significant from the perspective of the ETO process, as accurate and relevant information exchange is especially relevant within

	Requirments	CAD	CAE Electric.	CAE Mech.	3D Drawing DB	PDM	ERP	VF	SCMT	PST	Testing	Work h	Disturbance	Traceability
CAD	0													
CAE Electric Design	0													
CAE Mechanical Design	0													
3D Drawing Database		1												
Product Data Management			0	0	0									
Enterprise Resource Planning						0			1					
Visual Factory									1					
Manual Prototype Assembly							0	1		0				
Supply Chain Management Tool						1				1		1	1	1
Planning and Scheduling Tool									1					
Testing Database						0								
Work Hours Database														
Disturbances Database														
Traceability Database									1		0			

Figure 2. A summarizing table that illustrates the LISI values between the different systems in the product data infrastructure. **Source(s):** (Authors own work)

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the interaction between design and manufacturing (Javadi and Chirumalla, 2023), where any misinterpretation of the product-related specifications by the employees or operators results in unclear or insufficient information regarding the product and can be detrimental to the overall efficiency of the process (Surbier *et al.*, 2014). The practical implications of such misinterpretation can have harsh effects on the overall lead time of the ETO process. For instance, a single revision or a request to change specifications may cause the lead time to increase by up to 2–3 months.

However, lead-time increase is not the sole implication of the lack of interoperability; cost is another implication. The findings indicate a large number of isolated systems within the product data infrastructure; as such, manual intervention and exchange of data are required, meaning additional communicational roles. This implication is further illustrated by the following statement from workshop 2: *"due to the number of zeroes, we are certainly creating communicative roles to compensate for this lack of interoperability"* (Lead Manufacturing Engineer). Thus, the costs associated with such roles may be mitigated through increased interoperability. Such improvements are particularly important for low-volume companies, as they frequently encounter high development costs during product development, often stemming from inefficient data transfer and communication (Fortes *et al.*, 2023). Therefore, it is sensible to evaluate the potential savings of improved interoperability against the costs and efforts required for its implementation (Kadam *et al.*, 2022). Notably, improving technical interoperability among systems that lack this capability can demand significant time and resources, thereby incurring extra costs (Givehchi *et al.*, 2017).

The implications of low technical interoperability on the ETO process, in regards to the increased manual administration and workload, lead-time delay and increased costs are in line with previous findings. Fernandes *et al.* (2022) note that where technical interoperability is low, communication and cooperation suffer. Moreover, Das (2012) highlights that one of the significant risks of lacking interoperability is the increased costs due to additional administrative duties as well as the development of technological workarounds. Addressing such issues through increasing technical interoperability would mitigate risks associated with overreliance on manual communication and decrease the administrative burden placed on key personnel. The enhancement of data transfer is particularly relevant within the context of the ETO process, as due to its inherent complexity regarding information flows and stakeholder collaboration (Wlazlak and Johansson, 2014).

5.2 Barriers to innovation

Furthermore, the outcome from the analysis showed an overall lack of technical interoperability of the various systems within the product data infrastructure. *"Our systems are simply too old fashioned. They don't talk to one another, [and] they are not integrated"* (Production and Logistics Developer). This is a clear indication of the lack of interoperability of the product data infrastructure, requiring the manual intervention of personnel for successful data exchange and inhibiting further vertical integration. This is in line with the findings of Tabim *et al.* (2024), who note that interoperability is one of the key technological factors required to enable increased vertical integration of manufacturing systems. The relative immaturity of interoperability is concerning and should be considered by the case company, especially in light of the previously mentioned ambitions of acting as an innovation hub for the remainder of the organization. The lack of interoperability also acts as a significant barrier for the company to capitalize on emerging advanced technologies associated with the digital manufacturing era. As such, technologies akin to CPS, IoT or Cloud manufacturing become significantly more difficult to integrate without a solid foundation systems interoperability (Åkerman *et al.*, 2018; Dalenogare *et al.*, 2018; Hawaou *et al.*, 2024).

The findings also indicated a lack of strategy for further utilization of the data already being stored within the product data infrastructure. This was evident form the number of isolated databases that were gradually accumulating data, yet lacking subsequent analysis for the

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purpose of process improvement. "*At the moment we store testing data and test results in our designated database. There are no connections to other systems*" (Senior Test Engineer). This data congestion, which inhibits the data being used elsewhere, coupled with the lack of strategic vision, further hinders efforts to foster emerging technologies that rely on data exchange to create insights for process improvements (Mustafa *et al*., 2023). This inability to further utilize the currently existing data exemplifies the negative impact that technical interoperability can have on innovation, supporting the findings of (Pu and Lam, 2021), who stress the importance of interoperability as an enabler for companies to fully leverage emerging and more advanced technologies. The related long-term implication is the inability to move from intuition-based decision-making to informed decision-making, as supported by Choi *et al*. (2018), who underlines the important role of interoperability in achieving data-driven decision-making.

Finally, the findings show a distinct lack of data flow from the production phase to the design phase, as outlined in Figure 1. Instead, the ETO process follows a more linear path. This highlights that an important factor of the design manufacturing integration is missing and that production requirements are largely not considered during design. During a discussion about whether production requirements are considered during the bidding phase, a Senior Bid Engineer stated "*that is not really something that is discussed, but rather we expect it to be solved later down the line*". Such statements are strong indicators of functional silos not cooperating to them to their fullest potential. The prevalent practise of "throwing designs over the wall" to manufacturing, without confirming their producibility, represents a key issue that should be addressed to ensure a more efficient ETO process (Anderson, 2020). Furthermore, the same Senior Bid Engineer went on to state that "*it would be much better to have more information during this stage regarding how the customer requirements effect the production.*" This statement further indicates the lack of understanding how specific design changes driven by customer requirements can impact the production.

6. Conclusions and implications

6.1 Conclusions

The purpose of this study was to analyse the current state of a product data infrastructure supporting an ETO process, with a focus on understanding the impact of technical interoperability on design manufacturing integration. To achieve this, a longitudinal case study was conducted within a low-volume rolling stock manufacturer, utilizing semi-structure interviews, workshops, internal document reviews and informal meetings. An interoperability assessment was performed using the LISI categorization to evaluate system interoperability and data exchange capabilities. The findings indicate that the ETO process relies on a significant number of isolated systems that lack the capability to exchange data due to insufficient technical interoperability. This limitation negatively impacts process efficiency by increasing workload for key system users, increasing dependency on communicational roles, and inhibiting data utilization and vertical integration. Additionally, lacking technical interoperability highlighted a lack of integration between design and manufacturing, further inhibiting innovation and process improvements.

Further research on this topic is required to build upon these findings. A logical next step would include identifying specific systems that contribute most significantly to the negative implications due to insufficient technical interoperability. Additionally, future research should explore available methods and tools currently used within other industries to increase technical interoperability. Given that this study was based on a single case study, its generalizability can be somewhat strengthened. Conducting a multiple case study across various low-volume manufacturing companies would enhance the applicability of these findings to a broader context. Finally, this study primarily focused on evaluating the implications of technical interoperability, excluding other forms such as semantic and organizational interoperability.

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As such, future research should investigate the role of these additional dimensions of interoperability in facilitating design manufacturing integration.

6.2 Theoretical and practical implications

Prior literature has argued for increased integration of design and manufacturing to achieve a more effective product development process (Brettel *et al.*, 2011), a topic particularly relevant to the low-volume manufacturing industry. The literature has also asserted the importance of interoperability and its role regarding collaboration (Åkerman *et al.*, 2018; Zeid *et al.*, 2019). This study further expands on these two areas by examining how the technical interoperability of a product data infrastructure impacts the efficiency of product development within an ETO process, thereby contributing to existing knowledge on design manufacturing integration from a low-volume perspective. The primary theoretical contribution of this study is its expansion of research on design manufacturing integration by specifically addressing a research gap regarding the implications of technical interoperability within the ETO process in a low-volume manufacturing context.

Practical contributions from this paper include a detailed account of how to assess the current product data infrastructure of an ETO process, offering a baseline for improvement and measurable progress towards increased technical interoperability and design manufacturing integration. By contextualizing the impact of limited technical interoperability on the ETO process, this study highlights several operational challenges, including increased manual administrative efforts, associated costs, and lead time delays. These insights serve as a foundation for identifying and prioritizing systems that would benefit most from enhanced technical interoperability (Cox and Schleier, 2010). These practical insights can be extended to other companies operating within the low-volume industry relying on complex production processes and may be experiencing similar issues within their ETO process. The methodology of this study may be repeated and iterated upon to establish a baseline understanding of product data infrastructures while also identifying the detrimental implications due to said lack of technical interoperability. Just as the findings from this case study revealed numerous detrimental implications, similar results may be observed at other companies. This may aid them in circumventing said implications and leveraging advanced digital technologies (Fernandes *et al.*, 2022; Pu and Lam, 2021).

Furthermore, the findings showed a substantial number of isolated databases in which data are stored but not effectively utilized, indicating a lack of data management strategy. An issue that is prevalent across sectors and hinders innovation and the adoption of advanced technologies such as CPS, IoT and cloud manufacturing (Mustafa *et al.*, 2023). Thus, the development of a comprehensive data management strategy is recommended, not only for operational efficiency but also to facilitate a structured roadmap for future technological advancements (da Silva Serapião Leal *et al.*, 2019).

Finally, the analysis indicated that limited integration exists between design and manufacturing phases, despite the case company's ambitions to integrate the two. To mitigate this issue, a bidirectional exchange of data between design and manufacturing is required. One such way to effectively integrate knowledge from manufacturing in design is through product configurators, which can assist key users in defining custom products by presenting them with design specifications while restricting how the various components can be produced and assembled (Haug *et al.*, 2011). Product configurators serve as a mediator of data exchange between manufacturing and design as they have been shown to aid with combining knowledge from both domains in prior research within product development (Zhang *et al.*, 2013). Moreover, they also provide beneficial features commonly associated with product platform approaches (Zárate *et al.*, 2024).

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