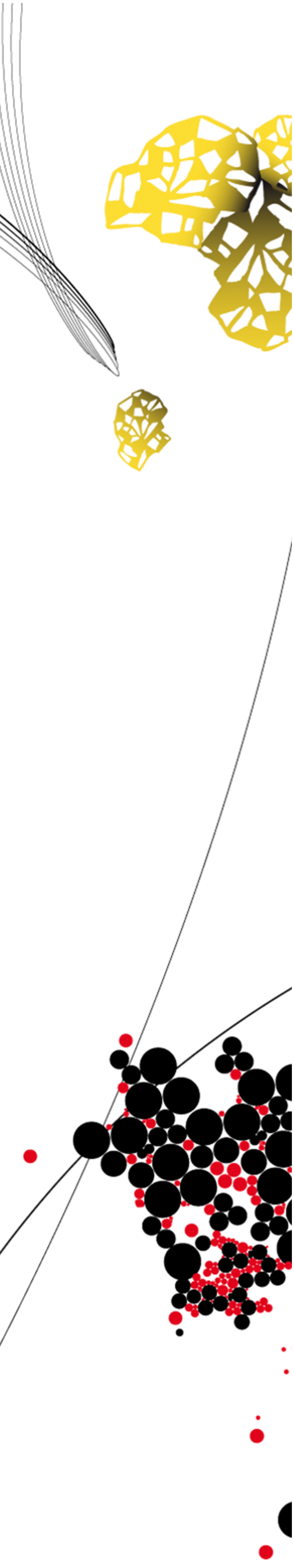

UNIVERSITY OF TWENTE.

Faculty of Electrical Engineering,
Mathematics & Computer Science

From Component to Product
Digital capabilities for the Digital Product Passport in the Production Sector

Malina Lara Wiesner

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Supervisors:
Dr. João Luiz Rebelo Moreira
Faculty of Electrical Engineering,
Mathematics and Computer Science,
Section Semantics,
Cybersecurity and Services

Dr. Renata Guizzardi - Silva Souza
Faculty of Behavioural Management
and Social Sciences
Section Industrial Engineering
and Business Information Systems

University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Preface

I am deeply appreciative of the support and guidance provided by my two supervisors, Dr. João Luiz Rebelo Moreira and Dr. Renata Guizzardi - Silva Souza, during the course of my master's thesis. Their dedication to helping me navigate the complexities of my research, their insightful feedback, and their willingness to engage in meaningful discussions have been instrumental in shaping this work.

Additionally, I want to express my heartfelt gratitude to my friends and family for their unwavering support throughout this challenging journey. Their encouragement, patience, and understanding have been my constant source of motivation. Whether it was lending a sympathetic ear during late-night brainstorming sessions or offering words of encouragement when I faced setbacks, their presence has been an important aspect throughout the entire process.

Summary

Resource-intensive manufacturing supply chains have a significant impact on sustainability and provide one of the biggest levers to achieve sustainability objectives. However, supply chains are riddled with complexity aspects because they are geographically dispersed and often include multiple tiers. As a result, data, systems, processes and stakeholders do not interact in a way that supports sustainability today. At the same time, requirements for supply chain transparency are intensifying and digital product passports as policy instruments are required in the near future.

This thesis looks at the following research question: How to address and develop the digital capabilities necessary for the digital product passport in the manufacturing domain?

In this context, the relationship between digital transformation, interoperability and sustainability is reviewed in terms of current and future challenges and opportunities.

This research evaluates the status quo of digital transformation in manufacturing and explores technology trends for supply chain transparency and sustainability. It offers guidance to researchers and practitioners, helping them prepare for future sustainability reporting needs. In particular, concepts such as industrial digital twins and data spaces are researched in their relevancy for Digital Product Passport (DPP) implementation. By focusing on manufacturers internal digital competencies today, this thesis bridges the gap between research and practice, presenting realistic next steps to build up the capabilities for inducing sustainability. Through a proof of concept this thesis shows how a digital product passport could look like for manufacturers and what digital capabilities they need to be built up today to streamline their data and systems for use cases like the digital product passport and sustainability.

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List of acronyms

EWM	Enterprise Warehouse Management
ERP	Enterprise Resource Planning
MES	Manufacturing Execution System
IoT	Internet of Things
IIoT	Industrial Internet of Things
PLC	Programmable Logic Controller
OPC UA	Open Platform Communications Unified Architecture
SIS	Secure Integration Server
BoM	Bills of Materials
CAD	Computer-Aided Design
DPP	Digital Product Passport
ESPR	Ecodesign for Sustainable Product Regulation
EC	European Commission
APO	Advanced Planning and Optimisation
AAS	Asset Administration Shell
AI	Artificial Intelligence
DT	Digital Twin
LCA	Life Cycle Analysis
PLM	Product Lifecycle Management
OEM	Original Equipment Manufacturer

DTDL	Digital Twin Definition Language
I4.0	Industry 4.0
I5.0	Industry 5.0
SC 4.0	Supply Chain 4.0
SCM	Supply Chain Management
EDI	Electronic Data Exchange
SC	Supply Chain
IDS	International Data Space
IDSA	International Data Spaces Association

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Chapter 1

Introduction

1.1 Motivation

The single biggest contributor to the EU economy is Industry [4, p.5]. With regulations such as the Supply Chain Due Diligence Act and mandatory digital product passports well underway, firms are under increasing pressure to report on their global supply chain operations and become sustainable. As a consequence, sustainability is no longer just an option for manufacturing companies and their supply chains. In addition, disruptive events such as the COVID-19 pandemic have demonstrated the lack of resilience supply chains have today and adds a financial incentive for Industries. Major drivers for sustainability including consumer demands, regulation and efficiency and cost continue to increase pressure on manufacturers to become sustainable.

The majority of emissions are caused by operations in the supply chain [5, p.9]. This means supply chains are among the biggest levers for the European Industries to become sustainable in the long run. The geographical dispersion of global supply chains adds an element of complexity to systems, processes and stakeholders involved in supply chain operations of resource-intensive industries. This means that an end-to-end perspective is necessary to address the current barriers of manufacturers to improve their sustainability.

Industry 4.0 and Industry 5.0 technologies can be seen as enablers for sustainable manufacturing particular addressing information transparency in the context of supply chains. However, the status quo of digital transformation in manufacturing and supply chain operations indicates a landscape of scattered implementations of emerging technologies and traditional methods of data sharing between supply chain partners with little focus on sustainability-related purposes. Digital product passports (DPP)s both as a policy instrument and a vehicle to manage product data across the entire product lifecycle, have gained increased attention in recent years. DPPs provide a use case for addressing supply chain transparency and sustainability and have the potential to facilitate the streamlining of data and systems infrastructure in manufacturing.

The focus of this research is on what is needed to build a foundation for resource-intensive manufacturing and supply chains today to address complexity and become sustainable. This research attempts to bridge the gap between Industry 5.0 incentives (interoperability and sustainability) and the status quo (complexity and isolated Industry 4.0 solutions) by looking into the current challenges and applicability of solutions to address sustainability for resource-intensive manufacturing.

The intrinsic focus of this research lies on interoperability in the context of digital capabilities for harnessing the data needed for the DPP. Advanced cooperation and collaboration are needed for companies to become agile and able to manage complexity - particularly in regards to sustainability reporting requirements. This research argues that interoperability is the foundation for integration and interconnectivity and consequently also for the use case of the DPP.

1.2 Research objectives

To address the problem of sustainability reporting and DPP implementation in resource-intensive manufacturing from a digital transformation perspective, the following research question is defined:
How to address and develop the digital capabilities necessary for the digital product passports in the manufacturing domain?

For this question to be answered comprehensively, the research question has been further divided into three sub-questions, called knowledge questions (KQ);

KQ 1 What are the challenges and opportunities in achieving sustainability in manufacturing and supply chains?

KQ 2 What are the implications of digital transformation in manufacturing and supply chains and how can they promote sustainability?

KQ 3 What is the concept of the DPP and how can it be implemented in the manufacturing domain?

By answering the above questions, this report aims to contribute to existing literature on digital transformation, interoperability and sustainability in the context of resource-intensive manufacturing supply chains. In particular, both theoretical and practical implications are reviewed to draw a complete picture of the status quo today and of the future potential of transformational technologies within the problem context for DPP implementation. By reviewing both the challenges in manufacturing supply chains and technology solutions emerging to address them, this research provides an outline of the key technology trends that suggest promising implications for the cause of sustainability and specifically for the implementation of DPPs.

1.3 Research methodology

This thesis uses a combination of exploratory literature review and design science research methodology for the development of a target architecture and proof of concept for the DPP.

An exploratory literature review is conducted to explore the research field of sustainability and digital transformation in manufacturing. The methodology was used to provide a holistic perspective on the current state of research and practice in manufacturing. By including a wide range of sources, including grey literature, this research was able to identify key trends, patterns, and gaps in the existing literature, as well as to highlight areas where further research is needed.

Design Science Research (DSR) methodology was used for the development of a target architecture and proof of concept for a DPP in them manufacturing domain. The methodology is an iterative and problem-solving approach used in information systems research, particularly for designing and evaluating artifacts to address complex problems [6]. In the context of implementing a Digital Product Passport, DSR involves several distinct phases. The first phase, ”Awareness of Problem,” involves recognizing the need for a Digital Product Passport. This phase is supported by the exploratory literature review. The ”Suggestion” phase follows, proposing a design solution for the DPP, considering elements like data structure, user interfaces, and functionalities. The subsequent ”Development” phase focuses on building and implementing the DPP based on the proposed design. Finally, the ”Evaluation” phase assesses the effectiveness of the artifact, gathering feedback from stakeholders to refine and improve the design, thus completing the iterative cycle of DSR in the context of a Digital Product Passport.

1.4 Report organisation

The thesis is structured into eight chapters. Chapters 2, 3, 4, and 5 constitute the theoretical and exploratory literature review, presenting the central problem context of sustainability in manufacturing. Chapter 6 and 7 propose a solution outlining the digital capabilities for manufacturers in the context of the DPP.

Chapter 2 initiates by examining sustainability in manufacturing, providing an overview of the current political and regulatory landscape, including the evolution towards a circular economy and the use of DPPs as a policy instrument to promote sustainability in this context.

In Chapter 3, the thesis examines the theoretical implications of digital transformation within the framework of Industry 4.0 and Industry 5.0 for manufacturers and their supply chains. Specifically, the relationship between sustainability and interoperability is explored concerning data quality and legacy infrastructure.

Chapter 4 situates the theoretical implications of digital transformation within the practical context, offering a comprehensive analysis of the current state of manufacturing and supply chains. This chapter identifies the key gaps between research and practical application and presents arguments for the potential of DPPs to serve as a bridge for achieving sustainability goals.

Subsequently, Chapter 5 conducts a detailed examination of DPPs, discussing the digital capabilities required by manufacturers to meet upcoming regulatory obligations.

Chapter 6 introduces the proposed solution design for manufacturers, providing a comprehensive assessment of the digital capabilities existing within European manufacturing by means of an example manufacturer representative for discrete manufacturing processes. This chapter outlines a proposed target architecture for a DPP in manufacturing, considering the current state of processes, systems, and data.

Chapter 7 presents a proof of concept for the defined target architecture, illustrating how data can be streamlined to enhance the accessibility of product data for the specific use case of DPPs.

The thesis concludes with Chapter 8, which offers a discussion of the major findings, limitations, and potential directions for future research.

Chapter 2

Sustainability in Manufacturing and supply chains

This chapter discusses the problem context for this research. Specifically, the complexity of supply chains in the context of resource-intensive manufacturing supply chains is discussed. The chapter discusses answers to the first knowledge question;
KQ 1: What are the challenges and opportunities in achieving sustainability in manufacturing and supply chains?
For this purpose the chapter is divided into three sections, beginning with an introduction to the complexity of manufacturing supply chains in the context of sustainability. The chapter outlines the main concepts to assess sustainability in manufacturing and sketches a picture of the political and regulatory environment manufacturers in Europe operate in today.

2.1 Complexity and sustainability

Supply Chain Management (SCM) can be defined as the ”planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities”. The main goal is to synchronise supply and demand through through Information- and coordination mechanisms [7, p.27] . Popular frameworks for SCM include Supply chain and operation management (SCOM), Supply chain operations reference (SCOR) and Global supply chain forum (GSCF), which each suggest a breakdown of supply chain activities. The SCOR Model for instance breaks the supply chain into the five categories of planning, acquisition, make, delivery and return [8]. The complexity of manufacturing supply chains depends on product and production characteristics such as product volume and variations [9, p.308]. The product variety is influenced by consumer demands and can put manufacturers under additional pressure. Smaller batch sizes come with masscustomisation of products and manufacturers need to shorten their development cycles to fulfil these volatile customer requirements. Shorting product development cycles in turn can result in increasing dependency towards suppliers [7, pp. 28-29]. These aspects in combination with economic globalisation and outsourcing have resulted in highly complex, geographically dispersed and decentralised supply chain networks spanning across the globe [10, pp.1-2], [11, p.68]. There are three basic flows within a supply chain, namely the product and materials associated, funds and information [12, p.17]. S. Chopra, 2019, specifies six supply chain drivers that define the performance of a Supply chain in terms of efficiency and responsiveness. Facility-, inventory-, and transportation management influence the logistics of supply chains directly, while information, sourcing and price influence all areas of the supply chain [12, p.59]. The global dispersion of supply chain networks results in multi-tiered supply chains that often hinder information flow and transparency [11, 68]. Previous research on the topic of Supply chain transparency underlines the importance of efficient information exchange and data sharing. Recent disrupting events such as the COVID-19 pandemic have showcased the lack of end-to-end supply chain visibility and transparency. The resilience of supply chains in such situations depends on quick and efficient information communication [13, p.2]. Already a study in 2004 by the National Institute of Standards and Technology (NIST) estimated the cost of inefficient interorganisational data exchange at around 5 billion dollars for the sectors automotive and electronics alone [10, p.2]. Inefficient information exchange is largely attributed to the lack of interoperability across supply chains [13, p.2]. Enablers for effective supply chain governance on the other hand include effective communication and collaboration among supply chain stakeholders [14, p.49]. In this context, the complexity aspect of supply chains itself can be seen as a major barrier to supply chain performance [9, p.316].

The complexity of supply chains is matched by the large environmental impact supply chain operations are associated with. Supply chains have significant environmental impact attributed, with eight key sectors responsible for over 50 percent of annual greenhouse gas emissions worldwide: food, construction, fashion, fast-moving consumer goods, electronics, automotive, professional services, and freight [5]. Greenhouse gas emissions are categorised into three scopes by the Greenhouse Gas Protocol according to the sources of emissions in their relation to the company's operations: Scope 1 specifies direct company emissions, Scope 2 specifies the company facility electricity usage, and Scope 3 bundles all other indirect emissions, including from the supply chain [15]. The GHG Protocol lists examples for scope 3 emissions, such as emissions from the extraction and production of raw materials as well as the transportation of purchased fuels, but also the use of sold products and services [15, p.25].

In addition to the GHG Protocol, there are general concepts that define sustainability objectives in manufacturing.
Sustainability in manufacturing can be defined through the concept of triple bottom line (TBL). TBL frames the social, environmental, and economic concerns of operations, and focuses on balancing them [16, p.41389]. Each of the TBL dimensions includes a set of indicators. Social indicators include measures such as employee satisfaction, diversity and inclusion and human rights and labour practices. The environmental pillar of the TBL framework deals with greenhouse gas emissions, as well as energy and water consumption and waste generation amongst other indicators. Finally, the economic dimension looks into the traditional financial performance of a firm and its surroundings, including the economic impact on the environment it operates in [17]. The United Nations (UN) has defined 17 Sustainable Development Goals (SDGs), several of them link to the idea of sustainable SCM [18]. Within the environmental dimension of TBL, SDGs 8 (decent work and economic growth), 9 (Industry Innovation and infrastructure) and 12 (responsible consumption and production) are specifically relevant in the context of manufacturing supply chains. Similarly, for the social dimension, SDGs such as 1 (no poverty), 3 (good health and well-being) and 5 (Gender equality) also extend into manufacturing supply chains. The SDGs overlap and extend to the economic dimension of the TBL concept as well.

The OECD specifies environmental indicators for sustainable manufacturing in three aspects of inputs (e.g., non-renewable material intensity), operations (e.g., water, energy, greenhouse gas intensity), and products (e.g., recyclability) [19]. The OECD indicators point to the underlying data necessary for their calculation. While the concepts of TBL, the SDGs and the environmental sustainability indicators defined by OECD form by no means a comprehensive list of sustainability indicators for manufacturers, they give an idea about the information necessary to eventually calculate relevant sustainability KPIs. A comprehensive review of sustainability frameworks and KPIs goes beyond the scope of this research. Because of the relevancy of scopes 1,2 and 3 defined by the GHG Protocol for manufacturing supply chains, this article therefore largely relies on the definitions used in said protocol. It is worth mentioning however, that supply chain sustainability is often mentioned as a dedicated sustainability KPI, but that the accurate measurement remains tricky for obvious reasons as also discussed in the this section.

2.2 Assessing sustainability

Section 2.1 provides the introduction to this section discussing how manufacturers can assess their sustainability given the complexity of their operations and supply chains.

Sustainable SCM can be defined as the ”management of raw materials and services from suppliers to the manufacturer to customer and back, with the improvement of the social and environmental impacts explicitly considered” [9, p.308]. Enablers include lean manufacturing principles and the six R practices: reduce, reuse, recycle, re-manufacture, re-design, and recover [20], [21]. In this context, sustainable product design encompasses considerations for manufacturing, material reuse, recycling, functionality, and eco-friendly packaging [22, p.51]. In terms of circularity, the development of a product can have a significant influence on manufacturers' ability to actually disassemble and circulate parts of the product afterwards.

Next to green product design and green manufacturing practices, green material purchasing is defined as one of the key strategic processes in achieving sustainable supply chains. This includes the purchase of raw materials, parts and components but also all other supplies that contribute to the manufacturing of the final product. Green distribution (using sustainable means of transportation) and reverse logistics (managing the return of the product from customers to manufacturers) are also activities associated with the supply chain that play a significant role in the ability of manufacturers to become sustainable. [22, pp.51-54]. From an organisational perspective, top management commitment, flatter hierarchies, employee empowerment such as through lean manufacturing practices and feedback loops from shopfloors foster sustainability in manufacturing [21]. Finally, information and communication technology (ICT) are mentioned as a key enabler specifically concerning supply chain activities as they facilitate competencies like real-time monitoring and transparency across the supply chain and its stakeholders [20].

The discussed drivers show how manufacturers can improve to become more sustainable. To determine a starting point, it's essential to have information about the current sustainability status. For a comprehensive overview of methods to assess sustainability, this article refers to the works of Ande et al from the Karlsruhe Institute for Technology [23]. The main methods to assess the environmental and social footprint of products and associated manufacturing processes are a mix of traditional methods such as value stream analysis and input-output analysis, and comprehensive methods such as life cycle assessment and the extended life cycle sustainability assessment.

To perform a Life Cycle Assessment (LCA), it is necessary to collect data on the environmental effects of a product or service during its entire life cycle, from the extraction of raw materials to its disposal. This means information about the use of resources and raw materials extraction, energy consumption, CO2 emissions, and waste production as well as product and part composition is necessary as part of the LCA.. To carry out a Life Cycle Sustainability Assessment (LCSA), additional information for example about the social impact of the product throughout its life cycle must be available. This includes information about social aspects such as working conditions, human rights, and the impact on local communities by the manufacturer and its suppliers [24]–[27]. The described information needs for LCA and LCSA underline the complexity of comprehensive sustainability assessment. Life cycle assessment stretches beyond the operations within one manufacturing company, as it includes the entire life cycle of a product from raw material to its end of life, consequently extending into the supply chain. In addition, traditional engineering tools in manufacturing include Product Lifecycle management (PLM), often based on ERP systems or dedicated PLM software, which help manage the information about the product in organisations today [28].

While sustainability metrics can help companies to understand the effect of their product design and manufacturing and supply chain operations on sustainability, current and previous research underlines the lack of formal models and standardisation especially around product life cycle information [25]. Accurate measurement of sustainability, despite the metrics and tools to measure available, is yet substantially hindered. Part of the reason is the deficient information infrastructure, that fails to serve all phases of the product life cycle. As a result, information exchange at the interfaces between domains (i.e. between product design, engineering and manufacturing functions) and across company borders (i.e. concerning all supply chain partners in a network) fails to overcome data silos and the information necessary to properly assess sustainability is therefore often missing or incomplete [29].
The described data quality issues resonate with the GHG protocol, which has published technical guidance for calculating scope 3 emissions. This guidance considers the difficulty of assessing CO2 emissions accurately throughout the entire value chain and suggests using a combination of different calculation methods depending on the company's abilities and the information available. The pragmatic approach suggests the use of more accurate calculation methods for those activities with the highest emissions within scope 3 and less specific methods for those activities that have the lowest emissions within scope 3 [30, p.13]. The guidance also advises companies to assess the quality of data used for the calculations, acknowledging the problem of limited availability of data, especially from suppliers, and advising the prioritisation of data quality improvements (including availability) for those activities within scope 3, that generate high emissions but have low levels of data quality

hindering the accurate calculation [30, p.18-19]. For example for the category of purchased goods and services, the guidance suggests four different methods of assessing the emissions. One of the key questions determining the suitability of each method concerns the information availability from suppliers on their scope 1 and 2 emissions, which contribute to the scope 3 emissions of the manufacturer. Based on this availability or limited availability of information, a spend-based method (based on the economic value of the goods and services purchased) or an average-based method (using average emissions per unit based on the mass of goods or services purchased) [30, pp. 20-23]. The same system of applying different calculation methods depending on data quality is suggested by the guidance for the other categories of scope 3 emissions [30]. To summarise, the level of sustainability achieved is directly related to the quality of the information utilised [29].

The following contradiction should be pointed out based on the above introduction to manufacturing supply chains and sustainability;

- The GHG Protocol states that the reporting of scope 3 emissions is optional as of 2011 [31] and only by 2024 will the reporting of scope 3 emissions become mandatory in Europe [32] - this points to the currently limited institutional pressure exercised onto manufacturing companies in the EU to report on their scope 3 emissions. As institutional pressure is a major driver for sustainability efforts [33], the assumption can be made that this likely results in only marginal efforts by manufacturers to build up capabilities for more sustainability in their Supply Chain at present.

- The capability of companies to actually assess and measure emissions properly is likely limited at present, due to the lack of information transparency in the supply chain [10], [34].

- The report by the World Economic Forum and Boston Consulting Group showcases the disparity between scope 1,2 and 3 emissions, indicating that with 70 to 90 percent of emissions occurring in scope 3 across industries (specifically in upstream supply chain activities), these emissions far exceed those generated by company operations in scope 1 and 2 [5, p.9].

In a nutshell, we have supply chains that significantly impact the environment, but only little ability to measure this impact accurately across the globally dispersed supply chains. The paradox here lies in the fact that supply chain operations generate some of the highest global emissions among all company activities, yet there is comparatively little pressure to measure and report these emissions.

The next section examines the political and regulatory environment manufacturers operate in closer.

2.3 Political and regulatory environment

There are several standards and regulations, either already in place or in different stages of review that apply to manufacturing companies (Europe and/ or globally) that highlight a trend towards circular economy and sustainable objectives [35], [36]. This section focuses on the current developments within the European Union. In their paper on the Digital Product Passport, Götz et al. (2022) illustrate the evolution of policies in the EU that focus on sustainability and circular economy [35, p.14]. The European Green Deal introduced by the European Commission in 2019 is a strategy aimed to pave the way for a climate-neutral European Union in 2050 and includes different sets of policy initiatives addressing the different domains and industries respectively. The Green Deal can be seen as an accelerator for further policies that will become relevant for manufacturers in Europe in the next decade [37].

The new circular economy action plan introduced by the EC in 2020, sets out a new framework to support the goals of the European Green Deal in terms of circular economy and sustainability. The action plan addresses those industries in the EU that are resource-intensive and have a high potential for achieving circularity, including the sectors of electronics, vehicles, packaging, plastics, construction and buildings. The action plan introduces several legislative measures relevant for manufacturers in Europe. The Deal reviews for instance the current legislation on the restriction and use of hazardous substances in products placed on the EU market, as well as introducing an electronic product passport that should contain information about the product material composition, repair and dismantling options [38].

Under the wing of the European Green Deal, the carbon border adjustment mechanism (CBAM) introduced in 2021, addresses carbon-intensive goods imported into the EU. The measures of CBAM target the risk of carbon leakage, which can occur when organisations outsource the production of goods to countries outside the EU, where emissions may be less controlled thereby risking an actual increase in emissions by the outsourcing activity. The EC attributes the risk of carbon leakage especially to certain emission-intensive industries and therefore targets imported goods such as cement, electricity, iron, steel and aluminium, which are associated with high levels of GHG emissions. The financial obligations of the CBAM will be phased in starting 2023, with mandatory CBAM certificates by 2026. Effectively, the mechanism will require EU-based companies to pay for indirect emissions by purchasing CBAM certificates. This means that, unless a corresponding price for the carbon was paid in the country of production, the importing organisation will have to pay the difference to match the carbon price in the EU [39], [40].

In 2022, the European Commission has further laid out regulations that will in the future hold companies responsible for their actions along the whole of their value chains. The directive on corporate sustainability due diligence aims to mitigate adverse impacts on the environment and societies, and with the extended scope on the whole of the value chain also looks to tighten the responsibilities of companies towards the actions of their suppliers, both inside and outside of the EU. While the directive is currently under review, once in place EU member states have two years to respond with the translation of the directive into national law. After that, organisations need to be ready to adhere to the new regulations. The capabilities needed to conform with the upcoming directive likely include a higher level of collaboration within supply chains as companies require more insights on their suppliers' operations [35], [41], [42].

In the context of circularity, the EC also published the eco-design for sustainable products regulations (ESPR) in 2022, introducing a framework for requirements to make products more eco-friendly and suitable for circularity. The ESPR is supposed to create a foundation for future policies and legal obligations to eco-friendly products and defines information requirements that will translate into future obligations to disclose information about products including for example their durability, reliability, re-usability, environmental impact footprints [35, p.15]. In addition to the growing pressure to report on supply chain activities, the ESPR indicates requirements for organisations to firstly introduce aspects of eco-design into their products and secondly to build the ability to measure and report those features accurately. We can see a general trend in the public environment to call for applying the capabilities of technologies associated with Industry 4.0 and 5.0 for circular economy and sustainability-related purposes. In particular, the European Commission promotes strategies such as the so-called twin transition, which seeks to utilize digital transformation for the creation of climate neural and sustainable European economy [35, p.10]

In line with policies such as the ESPR, the EC introduced Digital Product Passports as a policy instrument and tool for inducing circular economy into the European economy [43, p.242]. In addition to the ESPR, there are several policy instruments and projects that are related to the concept of Digital Product Passports, including the Circular Economy roadmap for Germany for instance, the Product Circularity data-sheet in Luxembourg and the cradle-to-cradle product passport introduced in the Netherlands [36, pp. 15-24]. The European Commission (EC) defines a 'product passport' as a product-specific data set, which can be electronically accessed through a data carrier to "electronically register, process and share product-related information amongst supply chain businesses, authorities and consumers" [44]. Consequently, The DPP would provide information on the origin, composition, repair and disassembly possibilities of a product, including how the various components can be recycled or disposed of at the end of life. This information can enable the upscaling of circular economy strategies such as predictive maintenance, repair, remanufacturing and recycling. It also informs consumers and other stakeholders of the sustainability characteristics of products and materials [35, p.9] The battery passport will be the first to become mandatory in the next few years [43, p.242].

A comprehensive discussion of current and future regulations would go beyond the scope of this thesis. However, especially the current developments surrounding new and upcoming regulatory incentives in the EU point to the trend of increasing institutional pressure towards manufacturers and their supply chains. In particular relevant to SCM is the draft of the directive on corporate due diligence, which will require companies to become more transparent in terms of their social and environmental impacts along their entire value chain, including direct and indirect suppliers. An additional economic incentive will be brought forward through the carbon border adjustment mechanism, which is likely going to make sole compensation through sustainability certificates more expensive through the taxation of indirect carbon emissions.

On the bottom line, the discussed regulations indicate that in the future, sustainability for manufacturing supply chains will become (to a certain extent) more mandatory and also expensive to those who are slower in their response to the new policies. This current political and regulatory environment creates urgency for manufacturers in the EU to increase their capability of measuring indirect emissions and their impact on sustainability accurately and consequently forms part of the motivation for this research on the topic of increasing supply chain transparency.

To answer **KQ 1: What are the challenges and opportunities in achieving sustainability in manufacturing and supply chains?**, information transparency is both a challenge and opportunity for manufacturers to improve in their operations and supply chains. In a nutshell, the current political and regulatory play-ground for manufacturers incentives to increase transparency across the entire lifecycle of the product. At the same time, the complexity of supply chains and resulting information quality issues hamper transparency at present.

The next section of this thesis examines the topic of digital transformation in manufacturing, investigating technologies that can help with transparency in manufacturing operations and supply chains.

Chapter 3

Digital transformation in manufacturing supply chains

This chapter, together with the following chapter 4 of the thesis examines the second knowledge question of **KQ 2: What are the implications of digital transformation in manufacturing and supply chains and how can they promote sustainability?**. Specifically, this section introduces the concepts of Industry 4.0 (I4.0), Industry 5.0 (I5.0) and Supply Chain 4.0 (SC 4.0) and discusses the *theoretical* implications of digital transformation for sustainability.

3.1 Industry 4.0 definition and maturity index

The industrial revolutions up to I4.0 are sufficiently described in academic literature [45]–[47]. For this research, the definition by Schuh et al., 2020 as "[...] real-time, high data volume, multilateral communication and interconnectedness between cyber-physical systems and people" is used to define [47, p.11]. This definition highlights the objective to streamline corporate decision-making and adaptability processes, for organisations to become into agile and able to navigate complexity [47, p.11-13]. The I4.0 maturity index by the German Academy of Science and Engineering, Acatech, offers an effective framework for comprehending the developmental stages necessary to achieve this desired outcome and for evaluating the status quo in manufacturing industries.

The index describes six different stages in the I4.0 development path, with each stage representing a corresponding level of maturity in the context of I4.0 application [47], [48]. Interoperability is a key factor in the maturity index, assuming increasing levels of interoperability as an organisation moves up through the different stages. Stage one focuses on digitising analogue information and isolated IT use. By stage two, organisations should exhibit some operational technology interoperability. From stage 3 onward, interoperability between information technology and operational technology becoManufacturing Execution System (MES) a fundamental principle. Stage three introduces ”visibility,” which involves data collection and integrating Enterprise Resource Planning (ERP) , MES, and Product Lifecycle Management (PLM). In the subsequent stage, ”transparency” emerges as the ability to understand causality. This stage assuMES companies capable of analysing heterogeneous sets of data and performing root cause analysis. Stages 5 and 6 involve predictive capabilities and automated decision-making, respectively. Each of the six stages relates to four structural areas: resources, information systems, culture, and organizational structure, each defined by specific capabilities necessary for progression [47, p.23-24]. For a detailed definition and explanation of each stage this thesis refers to the works of Schuh et al, 2020 [47, p.17-37].

The maturity index outlines key capabilities for manufacturing firms to achieve optimal agility. It should align with a company’s individual strategy and goals, as not all companies need to or want to reach stage 6 on the index. Effective performance in complex environments, especially stages 3 and beyond, relies on integrating heterogeneous data sources and information systems integration is a crucial capability in this context. The index also sheds light on technology adoption based on a company’s stage. Stage 3 introduces the concept of a ”digital shadow,” requiring for instance ERP and MES integration. Later stages necessitate data analytics, predictive capabilities, and automation, with cloud and collaborative platforms as part of the IT infrastructure. The index envisions seamless, automated information flows across the organisation and supply chain, promoting agility and expediting decision-making in complex environments [47, pp. 23-30].
The maturity index was first introduced in 2017 [47] and applied in case studies throughout the past few years to assess I4.0 maturity of industrial companies [46]. Chapter 4 discusses the insights from hose cases in detail.

3.2 Supply Chain 4.0

I4.0 maturity frameworks such as the Maturity Index by Acatec discussed in the previous section, usually draw the system boundary at the organisational level, including company internal processes and systems, but leaving out the wider supply chain. However, I4.0 key technologies are viewed as enablers for transparency also in the supply chain. Recent literature looks into I4.0 impact and applicability on the supply chain as a whole, coining the term SC 4.0 [49]–[51].

SC 4.0 is a transformative approach that utilises disruptive technologies from I4.0 to optimise supply chain operations, interactions, and partnerships. This generates strategic benefits for all supply chain stakeholders. Research suggests that by fully embracing SC 4.0 concepts, companies could potentially save up to 30 percent of their costs and reduce inventories by up to 75 percent. This highlights a central capability derived from I4.0 and extending to SC 4.0: managing and harnessing information across the entire supply chain [8].

Leveraging I4.0 technologies in supply chain holds significant promise. In theory, potential benefits encompass enhanced flexibility, productivity, and higher quality standards achieved through end-to-end supply chain integration and resulting in increased transparency. Prior research and industry experts concur that addressing interconnectivity and integration in supply chains could reduce waste, lower costs, and boost efficiency with information transparency facilitating improved orchestration of inventory, logistics, and production activities [8], [52]–[55]. The key argument within SC 4.0 is that the disruptive I4.0 technologies such as IoT, AI, Cloud and Blockchain, can enhance the streamlining of supply chain processes, activities, and relationships. The most significant I4.0 technologies in this context are;

- IoT, can be implemented into production systems and distribution networks to improve process effectiveness and decision-making assertiveness, in the case of implementation within supply chain operations it could facilitate the real-time tracking and monitoring of parts and products by using RFID technology, for instance, [56], [11, p.75]. IoT facilitates the generation of data from numerous devices within the manufacturing domain and could therefore benefit supply chain operations [55, p.279]

- Big data technologies can facilitate data-driven decision-making by providing supply chain actors with the capabilities to analyse large volumes of data from a variety of sources. In the context of supply chain operations, insights could be generated through Big data analytics capabilities related to forecasting, risk management as well as general planning and orchestration activities within the Supply chain [55, p.278]

- Cloud infrastructure can be used to store, process harness and integrate large amounts of data generated by supply chain operations in a scalable and cost-effective manner, which in turn facilitates big data analytics which can help to identify patterns and aid in data-driven decision-making to improve supply chain collaboration and process performance [55], [57].

- Blockchain technology can be used to create secure, transparent, and tamper-proof records of supply chain transactions, improving traceability and accountability [7], [57]. Benefits for supply chain actors could include data security and traceability, supported by Blockchain's decentralisation aspects [55, p.278].

- Augmented reality (AR) such as wearable devices and cameras could aid with the efficiency and quality of operations such as order picking and delivery, ultimately leading to better customer service [55, p.277]
- Digital twin technologies can be used to create virtual representations of physical assets, processes, or systems in the supply chain, allowing for advanced life cycle analysis, real-time monitoring, and simulation [58].

While not explicitly mentioned as one of I4.0 key technologies, semantic technologies are likewise discussed in their theoretical implications for supply chains. Research suggests that semantic technologies can enable the integration of data and information across the supply chain and therefore facilitate communication between supply chain actors, especially given the heterogeneity of data sources [55, p.280] In general, research suggests that while IoT and cloud technologies are relatively widely applied, Blockchain and digital twin technologies can be assumed to be still in their infancy shoes, as most research and applications are currently in a case study phase, rather than at a widespread implementation level [59]. Similarly, technologies like Blockchain and Digital twins are discussed controversially both in academia and industry and while the above statements may hold in theory, the practical implications are hampered by the technological maturity of these concepts today [55].

Smart green supply chains involve the integration of environmental factors into supply chain management, aiming to minimise the environmental impact of supply chain operations while concurrently sustaining or improving economic performance. Existing research widely acknowledges the pivotal role that I4.0 technologies can play in empowering smart green supply chains by furnishing the essential tools and capabilities required for their effective implementation [49], [51], [60], [61]. Furthermore, there seems to be a tendency to combine I4.0 key technologies for their capability of improving information flows in supply chains [60]. Also, previous research indicates a direct relation between the digital transformation of supply chains (i.e. smart supply chains or SC 4.0 and improved sustainability in the supply chain [51]. This hints at the dual use of I4.0 technologies in the supply chain for economic optimization and sustainability, for instance in achieving common goals of resource efficiency [60]. The value lies in the enabling relationships and combined application of the technologies which contributes to the optimisation of supply chains by facilitating evidence-based decision support [62].

3.3 Industry 5.0 and sustainability objectives

In recent years, the term I5.0 has been coined in the context of Europe's strategies to achieve the defined goals for 2030 and beyond. The focus of I4.0 has primarily been a techno-economic one, seeking to optimise the efficiency and flexibility of production through digitalisation and AI-driven technologies. The key argument brought forward by the European Commission to usher in a new industrial revolution highlights that I4.0 lacks the comprehensive perspective to look at the role and impact of technology on society [4, p.5- 8]. With the Covid-19 pandemic acting as a catalyst for industries to address existing weaknesses (the disruptive events followed the outbreak of the pandemic certainly highlighted systemic vulnerabilities), the European Commission suggests that this renewed urgency for industries could be ”[..] a window of opportunity [..] to shape and renew the role of industry in society” [4, p.6]. I5.0 is rooted in the concepts of I4.0 in terms of the technologies and high-tech strategies for Europe. However, the concept of I5.0 aims to integrate digital transformation with social and environmental priorities in Europe [4, p.5-10]. The European Commission states three core elements of I 5.0, namely human-centricity, sustainability and resilience [4, p.13]. The human-centric approach seeks to use technology as a tool to create an inclusive environment, where technology serves people first. One example is the use of AR and visual assistance solutions to provide guidance and training to the workers on the production floor [4, p.14], [55, p.277]. The sustainability component of I 5.0 seeks to advance the role of technology for resource efficiency and minimisation of waste, allowing for economic growth within the limits of the planet's resources. Resilience, as the third focal point, seeks to increase the ability of industries to face disruptions (such as the COVID-19 pandemic) and counterbalance the phenomenon of increased efficiency at the cost of lowered resilience. Such disruptions show how value chains, while cost-efficient under stable conditions, may also be vulnerable, with the potential for single points of failure and cascading impacts on the entire system [4, p.14,23]. The holistic perspective on the transformational effects of technology on society is not entirely new, with the concepts of Society 5.0 already introduced in Japan in 2016 as a reaction to the European Initiatives of I4.0. Society 5.0 is a comprehensive approach to technology and society, promoted by the Japanese Government as part of a national transformational strategy beyond the industrial application of technology. The two concepts of Society 5.0 and I 5.0 are, while temporally offset by a few years, related in their holistic focus [4, p.9].

The introduction of a new paradigm is supported through recent academic research [4, p.40] and also reflected in related projects on an EU-wide level [4, p.13,30]. Recent literature points to challenges such as an increased need for efficient data processing that have resulted from the implementation of I4.0 technologies [63, p.2]. Research specifies I 5.0 enabling technologies into Industrial Cyber-physical systems (ICPS), Industrial IoT, novel computing paradigms such as edge computing) distributed ledger technologies such as blockchain, digital twins and augmented or mixed technologies [64, p.2]. The concepts of I4.0 and I 5.0 are intrinsically related in their overlap and application of technologies, and the positive impact of technologies to promote aspects such as sustainability has already been recognised within the concepts of I4.0 [65, p.p.4-6]. However, the need for industries to apply technologies with the purpose of environmental preservation and support the collaboration between humans and AI requires the need for a paradigm shift according to include a more holistic perspective [63]–[65]. The European Commission has identified six categories of technologies especially relevant for the new paradigm, that reflect the holistic perspective of technology on society and environment; Individualised human-machine-interaction, bio-inspired technologies and smart materials, digital twins and simulation, data transmission, storage and analysis technologies, artificial intelligence, and technologies for energy efficiency, renewables, storage and autonomy [4, p.7].

On a side note, it is desirable to look at digital transformation and sustainability from two perspectives. On the one hand, the EC promotes the use of digital technologies as enablers for sustainability. On the other hand, the impact of technology should also be considered to avoid adverse effects (such as disproportionate energy consumption through data storage) and instead create meaningful and sustainable digital solutions [1] [35], [59]. The incentives brought forward by I 5.0 strengthen the research objectives of this thesis and underline the need for digital transformation for sustainability and resilience within the entire value chain.

3.4 Relationship between interoperability & sustainability

The discussion thus far highlights that I4.0 technologies can enable sustainability in supply chains (section 3.1 3.3, 3.2), but the lack of necessary IT infrastructure hinders sustainability assessments (section 2). Supply chain sustainability is complex due to global dispersion, amplifying environmental and social impacts, while managing information across domains and among actors becomes more challenging. The

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[1] Acatech (2021) differentiates between the terms digital sustainability (i.e. the utilization and impact of digital solutions on sustainability) and sustainable digitalisation (the sustainability impact and footprint of the digital solution itself) [59]

I4.0 maturity index by Acatec underscores interoperability as an underlying design principle across various I4.0 development stages [46], [47], [66] and the implications on supply chain sustainability are outlined in theory above.

According to ISO 16100, manufacturing software interoperability is defined as the ability to share and exchange information using common syntax and semantics. It is important to distinguish between interoperability, integration, and compatibility. Integration involves a degree of functional dependence and less flexibility, while compatibility is when systems do not interfere with each other's functioning but cannot exchange services. Interoperability lies in the middle of an 'Integration Continuum' between compatibility and full integration. Distinguishing between these concepts is crucial for meaningful discussions on how to achieve them [67].

Interoperability and sustainability are linked as both concepts have something to do with the distribution of activities and processes in the context of manufacturing and supply chains. Sustainable manufacturing and supply chain operations require certain levels of interoperability of the processes [67]. This would fall under organisational or process interoperability more broadly speaking. Digital interoperability as the capability to achieve quick, seamless, secure, and reliable information exchange between entities plays a significant role in logistics and supply chain operations because those domains are particularly dependent on cross-organisational and cross-functional collaboration for strategic planning and operation management [13]. Information and communication technology are mentioned explicitly as organisational enablers for sustainable manufacturing [20]. Interoperability, therefore, can be seen as the baseline, with digital interoperability in particular relevant for (1) supplier's information sharing, (2) logistics service provider's operational information availability and (3) end-to-end supply chain mapping and monitoring [13].

Previous research underlines the benefits of proper interoperability in the wider manufacturing system, including the reduction of costs and higher productivity, which directly links to the economic aspect of sustainability. Interoperability also functions as the digital foundation for capabilities of virtualisation, decentralisation and real-time data collection and analysis, all of which can support supply chain operations [66]. Extending these capabilities onto sustainable manufacturing and supply chain practices, we can for instance use real-time capabilities to track logistic efforts and support reverse logistics, or identify opportunities to optimise resources and the reduction of residual waste in the production environment [68]. The link between interoperability and sustainability becomes all the more clear if we take a look at the incentives brought forward by I4.0 and I4.0; namely horizontal integration across the entire value creation network, end-to-end engineering across the entire product life cycle and vertical integration of manufacturing systems. All of these are necessary for true and comprehensive sustainability in manufacturing supply chains, and all three incentives have interoperability, either of the systems in place (digital, technological interoperability) or the processes involved (organisational, process interoperability) as a necessary foundation [69]. The lack of transparency is one of the main barriers to sustainability in manufacturing and supply chains, and technical issues associated with that problem are the insufficient data quality and scalability as well as the lack of techniques and standards to share and integrate data, In turn, data quality issues for instance are caused by disparate and incompatible systems utilised throughout the life cycle of a product. Consequently, adequate sustainability and product lifecycle assessment won't be possible because of the lack of interoperability of the systems used [10].

Life cycle sustainability assessment is a data-driven process, and therefore relies on resilient data infrastructure and sharing mechanisms [27, p.45]. Pedrazzoli et al. (2022) identify several challenges that need to be addressed to successfully deploy a manufacturing ecosystem that supports circular value chains, most of them are directly related to the issue of data availability and heterogeneity of interfaces between data sources. The authors highlight, that while information silos are only relieved partially up until today, addressing them remains a burdensome process due to overlapping communication and data-sharing standards and a variety of vendor-specific platforms used by supply chain stakeholders. Furthermore, IoT-enabled data streams are often not used up to their potential and the general lack of data exchange and management leaves stakeholders often with no reliable data sources for life cycle analysis, which is a critical ability to introduce circularity into value chains [70, p.2-7].

Based on previous research on interoperability in supply chains in the context of I4.0 technologies, this thesis identifies digital solutions in three main categories [13]:

- **Digital Platforms:** These are online (cloud-based) platforms comprising information systems and interfaces for users to collect, exchange and search information from. These solutions as part of data ecosystem developments, and can (or especially) assist in interoperability among different companies. Issues with multi-stakeholder collaboration platforms include privacy preservation, data format and integration. Such platforms are often Ontology-based which aids with semantic interoperability.

  Distributed ledger technologies and Blockchain can be a part or component of such platforms and are said to mitigate or ease some of the concerns digital platforms for supply chain collaboration usually have, including traceability and privacy conservation of the data.

- **Data-driven solution design, planning, modelling and control:** These capabilities are usually facilitated by (IoT) data collection, cloud and edge computing and depend on sufficient digital interoperability for data collection and analysis while creating interoperability through its own solution space.
- **Digital Twin and cyber-physical systems:** Industrial Internet of Things (IIoT) and virtual components need to achieve digital interoperability between physical objects and digital objects to create a digital twin. Therefore, the creation of a working digital twin solution creates such interoperability itself.

The intermediate findings from the above descriptions demonstrates that I4.0 and 5.0 applications for the goal of increased transparency are not mutually exclusive, but rather interact and enable each other to different extends. For all these solution spaces, digital interoperability is a key enabler for company-to-company, network-to-network, or system-to-system communication and data sharing which can be seen as a core requirement for sustainability in manufacturing [13].

Chapter 4

Status quo in manufacturing and supply chains

After discussing the theoretical implications of digital transformation in manufacturing and supply chains in chapter 3, this chapter of the report examines the *practical* implications of the question **KQ 2: What are the implications of digital transformation in manufacturing and supply chains and how can they promote sustainability?**, reviewing the status quo of digital transformation and how technologies support sustainability objectives today.

4.1 Industry 4.0 maturity of manufacturing companies

Between the years of 2017 and 2020, the I4.0 Maturity Center in Aachen has undertaken over seventy maturity assessments of industrial companies, providing valuable insights into the status quo of manufacturers' capabilities today [46, p. 10]. This report utilises the findings from these case studies to define the status quo and problem context of manufacturers in their journey of digital transformation.

According to the study by Schuh et al., 2020, most manufacturers are currently in stages 2 (Connectivity) and 3 (Visibility), with digitisation efforts and implementations scattered throughout different stages. 45 percent of the companies included in the assessments have not yet achieved full horizontal and vertical integration of their in-house systems. A lack of bidirectional exchange of data, data quality and data availability are identified among the most pressing matters to meet the defined I4.0 goals. While interdepartmental collaboration is stated as essential for many digital transformation projects, the hierarchical structures characteristic of the traditional manufacturing domain and lack of change management hamper efforts for

cooperation and collaboration across domains. In the context of supply chain collaboration, some efforts have been made, including dedicated third-party platform solutions such as the Gaia-X initiative. The main incentive, namely the improvement of administrative processes, which specifically includes full supplier integration throughElectronic Data Exchange (EDI) remains to be addressed comprehensively. The main finding relevant to this report is that a holistic viewpoint of I4.0 has remained largely neglected, resulting in isolated I4.0 solutions and data silos [46, pp.9-14].
The findings by Acatech I4.0 maturity assessments align with recent academic literature beyond the Aachener I4.0 hub in Germany [64], [70]–[74]. In the context of integration across domain and company borders, the status quo can be summarised scattered implementations including middleware solutions between different actors in the manufacturing value chain, with little standardisation terms of communication and data exchange especially across different organisations [75, pp. 1256-1257].

A second study by Acatech coined the term 'digitainability' (a blend of sustainability and digitalisation) and explores digital solution groups within I4.0 for environmental sustainability. The study focuses on eight leading industry sectors in Germany, including manufacturing [59]. The findings are viewed as representative for the current state of digital solutions in sustainable manufacturing supply chains for this thesis. Among I4.0 technologies, cloud and edge computing, IoT, CPS, VR and AR, and data analytics are the most widely used in manufacturing, while distributed ledger technologies are less commonly implemented [59, pp. 30, 37].
The examination of digital solution groups' impact on environmental indicators in the German economy by Acatech reveals a two-fold pattern. On one hand, there are digital solutions that offer limited improvements in specific environmental aspects, including "green" ERP systems, virtualised applications such as for product design, machinery control, data-based optimisation, and vehicle electrification. On the other hand, there are digital technologies like data ecosystems, data analysis tools, digital product passports, digital twins, and sustainable procurement, which have the potential to significantly and positively influence all environmental indicators included in the examination to a greater extent. Acatech also highlights a notable disparity in the adoption of these solution groups across the eight industry sectors. While technologies like digital twins and data optimisation are generally more widely employed according to the study, other solution groups like sustainable procurement and digital product passports are not widely applied yet [59, pp.38-39].

The study by Acatech concludes that for the production sector, the following groups of digital solutions crystallise as two key trends that could influence on sustainability incentives in the future [59, p. 30];

- Data ecosystems, tools for system modelling and data analytics capabilities: Within the manufacturing, but especially also within the related domain of transport and logistics applications of data ecosystems and data analytics support insights and data-driven decision making concerning raw material consumption and greenhouse gas emissions [59, p. 25].
- Digital Twin (DT) technologies and digital product passport applications: These solutions count among the key enablers for circular economy because they can provide transparency of relevant data and information along a products value chain [59, p. 13]

Recent literature also highlights controversies tied to I4.0/I5.0 technologies, revealing challenges and issues resulting from their application. For instance, cloud computing and IoT technologies in supply chains raise concerns about data security and privacy. These concerns may lead supply chain actors to restrict data availability and usage, exacerbating information gaps. For instance, cloud computing and IoT technologies may raise concerns for data security and privacy, which can cause supply chain actors to restrict data availability. In essence, two critical success factors for I4.0/I5.0 technologies in supply chains emerge from these debates: the need for the requisite skill-set and knowledge, and the necessary technical infrastructure for effective implementation [55], [74].

Next to the above two trends, the activity of sustainable procurement is mentioned to have a high potential for inducing sustainable practices in all sectors. Not a digital solution itself, sustainable procurement can be enabled through for example digital product passport applications or other applications with the objective to induce transparency into supply chain operations [59, p. 13].

4.2 Data sharing in manufacturing supply chains today

This section discusses how data is shared across supply chain participants today and highlights two ends of a spectrum, with industry maturity to one side and research implications on the other.

Existing data-sharing technologies in Supply Chain (SC)s include the standards of EDI and XML. Legacy systems such as as ERP and dedicated platforms are likewise used to support data sharing within supply chain operations [10], [76]. The World

Manufacturing Foundation gives details on the status quo of the mode of communication between supply chain partners, stating in their report from 2022 that communication is seldom digital or system-based, but often dependent on direct personal contact via email, and phone calls. This seems to be the case even for the more advanced aerospace and automotive industries, with email and Excel spreadsheets the rule rather than the exception [76]. This opens the door to potential disruption during crises because information about lower-tier supply chain levels depends on personal contacts, and official systems may not accurately reflect reality, leading to data integrity and quality problems.Moving down the value chain, information gaps between supply chain actors tend to widen [77, 2-3].

In addition to existing legacy systems and dedicated supply chain platforms, the World Manufacturing foundation recognises third-party broker systems like the International Data Space (IDS) standard and Gaia-X as digital infrastructure opportunities for data exchange among supply chain stakeholders [76, pp.36-40]. IDS is a federated architecture ensuring secure data exchange while preserving data sovereignty. Data is exclusively exchanged between participants, eliminating the need for central data storage [78]–[80]. Initiated by Fraunhofer in 2015, IDS is now managed by the International Data Spaces Association (IDSA) since 2016. IDS offers a comprehensive approach to cross-border data sharing, providing technical components and organizational roles and responsibilities [78].

IDS infrastructures are implemented through several applications through partnerships between research institutions such as Fraunhofer institutes and the Netherlands Organisation for Applied Scientific Research (TNO) and industrial companies, and exist in various states of maturity today [81]. The TNO Smart Connected Supplier Network initiative is among the most mature of these implementations, with 300 manufacturing companies currently connected to the initiative. The ecosystem is based on the reference architecture of IDS and offers integration with a collection of standard ERP systems as well. The main benefits for participants include that in contrast to traditional EDI solutions, the ecosystem addresses not only the semantics of the data being exchanged but also the technical and legal aspects between partners in the ecosystem [82]. Similar solutions include the Supply chain manager, an IDS-based initiative by Fraunhofer ISST, Volkswagen and thyssenkrupp [81].
Project GAIA-X, a European project that provides a digital ecosystem aiming to ensure data sovereignty and trust while facilitating data exchange among industry partners is another example of such a platform, in this case, the information exchange is regulated by an external party [10]. Further initiatives in this context include Catena-X a data space for the automotive industry, a data ecosystem for Horizontal Supply

Chain Collaboration supported by track and trace system services offered by SICK and ONCITE, a hybrid cloud solution for industrial edge computing in Germany to mention a few relevant for the context of supply chain and data sharing [81]. While the mentioned initiatives show the potential of data ecosystems and federated infrastructures for data sharing to overcome the technical and organisational barriers of data sharing across organisations, most of the initiatives are still in different stages of development, with only a few ecosystems already operating live [81], [83].

Barriers to adoption and participation include a general lack of understanding of the value of data sharing, which is partly rooted in the missing recognition of data as a valuable resource. Also, doubts about the legal aspects, data privacy and security aspects remain, paired with concerns about the quality of data shared by other potential participants. Next to IDS use cases, there are a couple of dedicated platforms functioning as data marketplaces, some of which are driven by specific companies such as the BMW Cardata platform to share vehicle data specific to BMW models, others provided by third parties such as the Caruso data place [62].
In the category of third-party platforms to share data, we can find commercial platforms dedicated to supply chain transparency next to those data marketplaces initiated by specific industries or companies. One of the most mature platforms currently available on the market is offered by the technology company Circulor [84, 26]. The company offers platform solutions based on several technology components, including Blockchain technology, to provide participants with the ability to track and trace the origins and movements of materials through supply chains. Clients such as Volvo use Circulor to trace the sourcing of their cobalt [85], [86]. Similarly, the technology company Circularise offers a platform for supply chain traceability and transparency, which is used by Porsche to obtain more detailed information from its suppliers about the components and materials used in their vehicles [87]. Circularise offers solutions for sectors including construction, automotive, electronics and metals and covers a variety of use cases including LCA, carbon footprint and compliance-related topics in the supply chain [88], [89]. Both Circular and Circularise make use of the Blockchain Platform provided by Oracle.

Distributed Ledger technologies such as Blockchain, remain a controversial topic, both in academic and industry circles. DLT and blockchain technologies are scarcely implemented in the sectors of manufacturing, transport and logistics as of today [59, pp. 25,30] and the implementation faces technical challenges due to a relatively low maturity of the technology itself [55, p. 278]. DTL is associated with several barriers of entry, including high costs and infrastructure requirements, which in practice have limited the extent to which the potential for sustainability-related purposes has been tapped as more cost-effective solutions are used instead [59, p.38]. There are two concerns about Blockchain in particular; The first relates to the energy consumption of Blockchain technologies, and the second to the ambiguity of the mechanism towards the GDPR and related legal frameworks. Blockchain technologies require significant amounts of energy consumption necessary to perform transactions, an issue that not only makes the solution cost-intensive but also not sustainable in terms of their resource-efficiency [7], [59], [89], [90]. Secondly, Blockchain mechanisms are ambiguous to the GDPR. While GDPR grants the right to be forgotten, Blockchain promises the irreversibility and immutability of data records as part of the value proposition. Likewise, while GDPR requires data protection by design, Blockchain offers transparent and tamper-proof records to all participants in the Blockchain [91]. In the supply chain context, this second issue may be bypassed through the application of private Blockchain and authentication and access control for participants [7, p.24]. Thirdly, GDPR requires a kind of central entity of Data controller, while Blockchain in contrast works as a decentralised system. The details of the ambiguities of Blockchain with the GDPR are discussed in detail by Tatar et al. (2021), and point to open questions and concerns that underline the maturity of Blockchain in the wider context [91]. The discussed aspects make Blockchain technology not (yet) attractive for the wider industry. However, the trust and storage characteristics of Blockchain and DLT could make the technology of particular interest for circular business models, if the unanswered questions concerning energy consumption and wider legal aspects are answered in the future [59, 38].

4.3 Digital Twins for sustainability in manufacturing

When examining platform solutions such as Circulor and Circularise, DT technologies are applied next to components like Blockchain. In the context of DTs and for the following sections, the following terminology is briefly distinguished;

- **Digital shadow:** Digital shadows are tailored data structures that represent a specific system [92] and require automated data streams between the state of the physical entity and the digital one [93, p.1051].
- **Digital twin:** Definition of DT varies in each area of application and domain [94, p.143]. This report utilises the definition provided by Acatech; ”A Digital Twin is a virtual representation of a physical asset which allows it to be simulated, controlled and improved. ” [59, p. 18] A DT requires bidirectional automated data exchange between the physical and the virtual entity [93, p.1051].

- **Digital product passport:** " a data record which summarises a product's components, materials and chemical substances or indeed information on repairability, spare parts or proper disposal." [59, p. 18]

In the manufacturing context, DTs employ simulation, mathematical models, sensed and real-time data, to represent physical entities and optimise production processes [95, p.2533]. They are utilised for monitoring, planning, and controlling manufacturing operations, either in the pre-production phase (e.g., during product and process design) or throughout the product's lifecycle [94], [96]. Production optimisation is the focus point in this context [97], [94, 144].

As demonstrated by providers such as Circulor and Circularise, the DT components enable transparency and traceability of products and materials through the product value chain by creating the digital representation and necessary data connections. Thus, product lifecycle and circularity assessments as well as the operationalisation of circular business models could be supported by their implementation [59], [98]. Key technologies that act as enablers for DTare IoT and sensor technologies, virtual modelling technologies, as well as data processing, integration and data transmission [99]. Interoperability is supported by the standardised digital representation of real world-objects a DT implementation could provide [100, p. 61]. Consequently, a DT could be used as a precursor to successful supply chain collaboration, as such a standardised platform could build a foundation for overcoming the data and information gaps along value chains [77], [101], see also section 3.4.

The adoption and complexity of digital twin technologies vary across different sectors. The potential for sustainability gains through digital twin implementation is said to be significant according to Acatech. However, it's important to note that while digital twins are being utilisedeffectively in certain manufacturing processes such as for product design and simulation, their adoption is not universal across the entire sector, especially for targeted implementation for sustainability use cases [59].

Huang et al. (2021) conducted an extensive survey of AI-driven DTs, categorising use cases into factory/shop floor, machinery/equipment, and process/material levels. These cases encompass production planning, quality control, condition monitoring, and intelligent sensing. The integration of AI techniques provides DTs with tools to create models based on observed patterns and historical data, which can enhance data analysis and prediction capabilities for the mentioned use cases such as quality control [102].

In contrast, Hu et al. (2021) note that most currently applied DT models have one-way data flow from the physical to the virtual entity. In general, DTs find application in four product lifecycle phases: product design, manufacturing, operation/maintenance, and recycling. The authors recognise the role of computer-aided design

(CAD) systems for Product lifecycle management (e.g. product design phases) but point out that these systems do not provide a blending of the virtual and physical entities by themselves. The design of a DT model depends on the specific use case, comprising physical entity, virtual representation, and a connection between the two. Physical entities serve as data sources, requiring various sensing and measurement technologies, such as IoT sensors, RFID, image recognition, and particle sensing [99]. Because of the different stages of the product lifecycle with multiple stakeholders and intricate information parameters, DT implementation can be complex [100, p.65]. There is a sound body of academic literature dedicated to the application of DTs in the manufacturing domain that provides further explanations on DTs [93], [96], [97], [102]–[105].
In the context of interoperability, the concept of the Asset Administration Shell (AAS)) is relevant DT architectures [106]. AAS serves as an information framework for I4.0, describing the technological features of an asset and was introduced in 2016 as part of the Reference Architectural Model for I4.0 (RAMI 4.0). According to RAMI 4.0, an Industry 4.0 component consists of an asset (could be the physical asset of a machine or product), its corresponding AAS and a connection between the two. This outlines the role of the AAS standard as a concept for DT and its potential in interoperability and standardisation within manufacturing systems [95, p.2533]. Academic literature explores DT architectures based on the AAS standard [95], [107]–[109]. However, there is ongoing debate on the terminology and distinction between AAS and DTs. Either they are considered synonymous in the context of DT implementation for I4.0, while others distinguish between the two, with AAS serving as a blueprint for DT implementations [95, pp.2533-2535]. AAS's potential in facilitating interoperability due to its standardised digital asset representation is acknowledged, but questions remain about its full implementation, particularly regarding bi-directional data exchange and simulation [95, p.2536].
Notable DT architectures based on AAS include FA^{3}ST (Fraunhofer Advanced AAS Tools for DTs), an extensive toolbox for creating and managing AAS-compliant DTs, enabling connections with various data sources, including legacy systems. FA^{3}ST offers key features such as data integration, asset representation and interoperability via the underlying AAS metamodel [93, pp.1052-1053].

The AAS specifications result from collaborative efforts involving the Industrial DT Association (IDTA), the Zvei network (German Electrical and Electronic Manufacturers' Association), and Industry 4.0 platform participants. These specifications encompass the AAS meta-model for I4.0 assets, including a UML model and data model serializations in XML, JSON, OPC UA, RDF, and AutomationML formats. These data formats are compliant with data from Industry 4.0 applications (for instance OPC UA information models are compliant with the OPC UA protocol commonly used by production machines today).The standard also specifies how the data exchange with the AAS should work through the AASX exchange format for the data packaging file format. Data security is addressed through attribute-based access control as part of the AAS specification [106]. The AAS specification outlines the virtual-to-physical asset connection, including the meta-model based on the IEC 63278 AAS standard. The AAS standard is part of the IEC series of industrial standards, and it is also taken into consideration by AAS implementations within the DT Consortium, along with the ISA-95 / IEC 62264 ontology standard [110], [111]. Ontologies like ISA-95 / IEC 62264 enhance the representation of real-world phenomena in machine-readable information models [63, p.3].

Semantic technologies and ontologies address the challenges of sharing diverse information in supply chains, promoting semantic interoperability for data exchange among machines, systems, and stakeholders in the supply chain [55, p.280]. In manufacturing, relevant ontologies and standards, such as SAREF [1] and SAREF4INMA [2] by ETSI, model relationships among products, materials, and manufacturers. Additional domain-specific ontologies, like the Building Product Ontology (BPO), cater to specific industry use cases [113]–[115], [115], [116].

The AAS specification exemplifies how ontologies can serve as the underlying meta-model for DT implementations, fostering interoperability and compatibility with other information models. In the Microsoft Azure world, this is for example solved by the Digital Twin Definition Language (DTDL) [117]. This language can be used to replicate existing ontologies such as the those of the AAS standard into a data model compatible with Azure services such as the Azure IoT hub [92, p.2]. While languages like DTDL support standardiseddata formats such as JSON [117], it is worth mentioning that proliferation of diverse standards and ontologies today can actually hinder interoperability as different DT implementations may employ incompatible underlying standards, potentially impacting scalability of the solutions as well [55], [70], [92].

DTarchitectures based on the AAS standard have received attention in recent years [95], [107], including for sustainability objectives [108], [109]. However, Hu et al. (2021) emphasize the existing gap in considering environmental aspects within cur-

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[1] The SAREF ontology, or Smart Applications REFerence ontology, is designed to facilitate interoperability between different solutions from different providers and across various sectors using the Internet of Things (IoT) [112]

[2] SAREF4INMA is an extension of SAREF for the smart industry and manufacturing domain [113], [114]

rent DTs [99]. Davila et al. (2023) discuss DT in the context of manufacturing sustainability, showcasing applications like energy efficiency assessment. The authors also suggest that for circularity objectives, data sharing in supply chains is both a necessary pre-requisite and one of the main barriers to DTs for sustainability [94, pp.143-144].

Contemporary research underlines the potential of DT in manufacturing for sustainability and circularity based on the associated capabilities to capture the product life-cycle [58], [94], [101], [118]–[120]. Specifically, DTs are recognised for their capability to enhance product and material tracking and tracing. Key components of DTs in supply chains are IoT, cyber-physical systems, AI, modeling and simulation, and Blockchain technologies [101, pp.5-7]. Specifically AI-driven DTs can offer valuable insights that contribute to sustainability goals, such as optimisedresource and energy utilisation [101], [102].

Today, projects are also exploring the integration of DT with IDS components, such as the RI-OTANA initiative by Fraunhofer ISST and IAIS and the previously mentioned Smart Connected Supplier Network by TNO and IDSA. These initiatives support both the AAS and IDS concepts for interoperability and data exchange [93, pp.1052-1057].

In the realm of DTs for circular economy and sustainability, academic and public entities advocate for the Digital Product Passport (DPP) concept and its associated infrastructure, referred to as the DPP system [35], [43]. Although the DT and DPP concepts are distinct (see terminology definitions in section 4.3), the potential of DTs, including those based on the AAS standard, for sustainability supports the idea of DT based DPP systems. Because DT technologies can address and comprehensively capture the product life cycle, managing data infrastructure heterogeneity through standardised digital representations, and facilitating data integration, thus serving sustainability and circularity use cases.

4.4 Intermediate findings

This chapter, along with chapters chapter 2 and 3, scrutinises the problem context, culminating in the formulation of the main research question. Chapter 2 underscores the importance of enhancing product lifecycle transparency, influenced by the evolution of regulations and the emergence of DPP as a policy tool. Between 2017 and 2020, over seventy maturity assessments conducted by the I4.0 Maturity Center in Aachen, revealed how most manufacturers are in stages 2 (Connectivity) and 3 (Visibility) of digital transformation, yet suffering from challenges including the lack of full

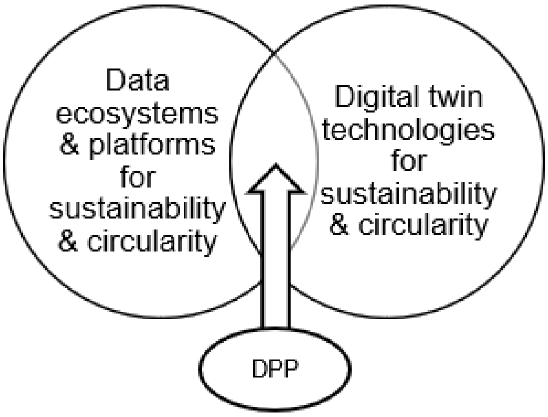


Figure 4.1: Placing the DPP into the main solution groups for transparency and sustainability, own representation

integration of in-house systems and deficient data exchange and quality. Although initiatives such as IDS and Gaia-X offer promise for improved cross-organisational data exchange, many manufacturers still rely on conventional methods like EDI, XML, emails, and phone calls.

Acatech's findings further indicate a sector-wise disparity in adopting digital sustainability solutions. This thesis identifies two primary trends in manufacturing and supply chain transparency and sustainability: (1) data ecosystems, system modeling, and data analytics tools, and (2) Digital Twin (DT) technologies and digital product passport applications. Notably, the automotive industry, with companies like Volvo, Porsche, and BMW, is pioneering in developing and participating in data ecosystems, raising questions about the broader applicability of such platforms in the production industry and the viability of components like Distributed Ledger Technology (DLT). The contrast between manufacturers' digital transformation maturity and their capabilities for data sharing versus the current state of the art is stark. On the other hand, DT technologies crystallise as both more widely applied in manufacturing industries and for their capability and potential to address sustainability and circularity objectives.

Figure 4.1 illustrates the two main trends, situating the DPP at the intersection of both. The DPP acts as a vehicle for product information, facilitating exchange between supply chain entities, while also being supported by DT technologies as part of its foundational system to capture product information. To address the question **KQ 2: What are the implications of digital transformation in manufacturing and supply chains and how can they promote sustainability?**, it's evident that the practical impact of digital transformation on sustainability is constrained by the current maturity levels of manufacturers and the development stage of relevant technological solutions. The gap between research advancements and manufacturing realities limits the accessibility of innovative data sharing and collaboration platforms for manufacturers. The Digital Product Passport (DPP) could act as a nexus between supply chain and product data, aggregating information in compliance with European Commission requirements. Developing digital competencies for the DPP necessitates an understanding of the entire product lifecycle, both internally and in the context of supply chain collaboration. Given manufacturers' current digital maturity, the focus should initially be on internal data infrastructure improvements to facilitate future supply chain collaboration. Therefore, this thesis formulates the main research question as **How to address and develop the digital capabilities necessary for the digital product passports in the manufacturing domain?** justified by considering the prevailing maturity of manufacturers and the identified technology trends that underscore the DPP's relevance for transparency and sustainability.

In essence, manufacturers need to start by resolving their own internal issues, laying a solid foundation for improved collaboration with partners in the value chain. The remainder of the thesis looks into the digital capabilities necessary for manufacturers to facilitate the requirements of the digital product passport given the current state of maturity.

Chapter 5

DPP for manufacturing supply chains

The preceding sections emphasize that transparency of product information, including quality, materials, functionality, plays a crucial role in enabling circularity and sustainability [35, p.10], [77, p.2]. Digital Product Passports can serve as information repositories which can promote circular economy practices through increased transparency about products [43, p.244], [77, p.3]. This chapter focuses on exploring the concept of DPPs and addresses the question of **KQ 3: What is the concept of the DPPand how can it be implemented in the manufacturing domain?**.
The core benefits attributed toDPPs include the collection and integration of product and sustainability data, potentially supporting communication in supply chains through improved accessibility to relevant information [35, pp.12-18]. Notably, the European Commission is moving towards making DPPs a policy instrument to drive circular economy practices (see section 2.3), starting with the mandatory battery passport in the upcoming years [43, p.242]. This development underlines the significance for manufacturers to build up the necessary capabilities and warrants a closer examination of practical implications, including information requirements, infrastructure, and existing DPP implementations, which this chapter provides respectively.

5.1 Information requirements

This thesis draws from a collection of sources to delineate the content of DPPs. Sources encompass EU legislative instruments, which outline varying degrees of specificity regarding future reporting requirements. Additionally, valuable insights into information requirements are derived from the ongoing work of the CIRPASS project and consortium. CIRPASS, funded by the European Commission as part of the Digital Europe Programme, plays a pivotal role in laying the groundwork for DPPs, aligned with relevant standards and the proposed Ecodesign for Sustainable Product Regulation (ESPR). CIRPASS collects industry feedback on initial DPP information sets as part of a benchmarking. In addition, recent scientific publications, like [35] and [120], shed light on European legislative instruments linked to DPP initiatives. The ESPR already articulates high-level information requirements for DPPs, including:

- Durability
- Reliability
- Re-usability
- Upgradability
- Repairability
- Possibility of maintenance and refurbishment
- Presence of substances of concern
- Energy use or resource efficiency
- Recycled content
- Possibility of re-manufacturing and recycling
- Environmental impacts, including carbon and environmental footprint
- Expected generation of waste materials

The ESPR also offers guidance on emissions calculation and gives a first indication of what might be expected from a DPP dataset [35].

At present, the CIRPASS project primarily targets the electronics, batteries, and textile sectors, but it also gathers broader industry feedback on information specifications. The benchmark outlines eight clusters of information and provides specific details for each. For instance, the ”product identification” category includes unique product ID, date, global trade identification numbers, and potentially IDs from original equipment manufacturers (OEMs) for product parts. Other CIRPASS categories cover user manuals, instructions, product design and service information related to disassembly and safe usage, and repair data, including dates and indicators for replaced or repaired parts [3]

Contemporary literature, including works by Jansen et al. (2023) [43], Gotz (2022) [35], and Berger (2023) [77] and Stratman et al (2023) [121], discuss information requirements similar to those outlined by the CIRPASS project. Jansen et al. (2023) identified seven relevant data clusters for DPPs, validated through interviews with OEMs: usage and maintenance, product identification, products and materials, guidelines and manuals, supply chain and reverse logistics, environmental data, and compliance. Their mapping of these clusters to other literature reveals a ”[..] a dispersed overview of the data and information required for a DPP [..]” [43, p.252], with a prevalence of information about product identification, hazardous substances, environmental impact, and material composition, suggesting a potential bias towards DPPs as static platforms primarily capturing data during upstream activities [43, pp.242-252]. Stratman et al. (2023) categorize product data for DPPs in the manufacturing industry into four main classes: product, utilisation, value chain, and sustainability information, distinguishing between static and dynamic data. Static data encompasses master data, material data, and design information (e.g., bill of materials), while utilisation information is expected to be dynamic, depending on maintenance services, and sustainability information relates to end-of-life considerations [121, pp.452-454]. The mentioned research sheds light on the essential information and potential categories that could be incorporated into DPPs. However, these debates also underline that the precise information requirements have not been comprehensively established as of yet. At present, CIRPASS provides insights from sectors like electronics, textiles, and batteries, thus offering an initial set of information requirements based on direct industry feedback [1], [2]. Given the overlap with information requirements discussed in related research, the following information could be part of a DPPs [3];

Table 5.1: Information requirements for the DPP based on [3]

Information category	**KPI / Product paramter / Reporting requirement**
Product identification	Unique product ID
	Global trade identification number
	Product tracebility (such as date, location, operator,..)
Company information	Manufacturer ID
	Company ID
	Unique facility identifier
	Registered trade name
	Adress
Functional and technical specifications	Product information sheet on energy consumption and performance
	Technical documentation on enegry consumption (EEL)
Material and composition information	CE marking
	Disposal, return and collection scheme
	Information on different materials and location of dangerous substances and mixtures (WEEE)
	Substances of concern; name, location within the product, concentration at the level of the product, main components and spare parts concerned
	Hazardous substances (according to REACH, POP, CLP, Ecodesign, WEEE)
	Individual material declaration
	Full material composition
	Recycled content
	Recycling orentated information
Product design and service	Use, repair information (such as information on maintenance, spare parts, updates, disassembly instructions and component map)
	user manuals, instructions, warnings, safety information, instructions for safe use

Continued on next page

Table 5.1: Information requirements for the DPP based on [3] (Continued)

	Resale options, end of life options, service availability for waste handling
Usage and repair history	Repair data (date, part and images), other statistical data on usage
Environmental indicators and certification	Circularity indicators, social impact indicators, supply chain indicators demonstrating responsibility, CO2 footprint

The last three points in table 5.1 are less specified throughout the literature as of today and need further investigation. This list illustrates that for the deployment of DPPs, organizations must develop the relevant capabilities to effectively gather the required information. The following section provides an examination of the necessary capabilities and infrastructure for DPPs.

5.2 Required capabilities, key components, and infrastructure

Given the discussed information requirements, a DPP implementation serves as a vessel for relevant product information. It should not operate in isolation but rather integrate with external information sources without creating its own content. Complex products with numerous parts and materials require DPPs to handle intricacy effectively. A DPP system and supporting infrastructure should provide organisations with the capability to link different sets of existing information about a product from a variety of heterogeneous sources. Consequently, DPPs must also strike a balance between transparency (providing product lifecycle data) and confidentiality (protecting sensitive and proprietary information) [35, pp.20-21]. The GS1, a network of non-profit organisations, highlights the importance of a decentralised approach for DPPs, avoiding central points of failure. The GS1 also underlines the relevancy of open standards for the development of DPPs, providing a set of standards such as ISO/IEC standards for barcodes (15417, 15420) and GS1 digital link and W3C linked data standard [122]. Implementing DPPs involves addressing infrastructure choices, such as centralisation or decentralisation, integration with legacy systems like ERP, and confidentiality requirements.

Next to their survey on information requirements for a DPP, the CIRPASS project also published a recent benchmarking of existing DPP-oriented reference architectures, and presents the main components ofDPPs according to a mapping of existing initiatives as follows [98];

- **Product Identification ID:** The identification of a (physical) product in the form Bar-code, QR-code, Bluetooth tag or RFID tag that is often put onto the packaging or otherwise attached to the item. In addition, some codes such as the OEM identifiers for part or multiple parts may be etched onto the product. In terms of product complexity, this could mean that a product has an identifier as well as several OEM codes for its different parts [98, p.19]
- **Product data carrier:** The product data carrier is referred to as two things, firstly the way the product ID (such as bar-code) is attached to the physical product, and secondly, how this identification is made machine-readable to enable automatic identification [98, p.20]
- **Digital connector:** The digital connector refers to how the connection between the physical product and the digital place of information on the product is resolved, and therefore includes the subject of ID issuing and data storage [98, p.21].
  - The benchmarking by CIRPASS shows that there is more than one way to build this connection and that both approaches of either linking the ID directly to information or using an intermediate resolver are present in the reviewed initiatives.
  - When it comes to the issuing of product IDs, approaches vary between centralised or decentralised and also depend on questions concerning the interoperability of identification schemes depending on the number of participants involved in the identification (i.e. standardisation entities and commercial companies).
  - Data storage is likewise a controversial topic, with approaches varying between centralisation and decentralisation. CIRPASS underlines the significance of data storage for the business models of DPPs. The simplicity and clarity of a central storage platform of allDPPinformation stand in contrast to the scalability of decentralized solutions that could handle complexity well.
- **IT architecture** pillar is divided into the following four categories: (i) the data transport, (ii) the access control, (iii) the data use, and (iv) the data management features.
  - **IT architecture data transport:** The category of data transport is further divided into data packaging (such as API-based data packaging) and

openness level of the data transport (in terms of standardised, proprietary or even more confidential). The use cases of stakeholders involved are relevant to the choice of data transfer, and the data streams should be bi-directional [98, p.91].

- **IT architecture access control:** Advanced access control could be role-based or attribute-based in its set-up [98, p.93].

- **IT architecture data use:** The data usage category ties together with the data use limitation rooted in the area of Digital Rights Management area. CIRPASS differentiates between two streams of rights labelling and rights management enforcement. The benchmarking also allowed other answers however to include novel concepts as well [98, pp.24,92].

- **IT architecture data management features:** Data management features aspects of traceability (related to the component of data carrier and identification options such as QR code, NFC or RFID), data protection (considers data protection measures such as anonymisation, encryption, privacy enhancing technologies, authentication or access control), convenience (features determining the ease of access and use through mechanisms such as wallets of data ports), and evidence (mechanisms for validation such as verifiable credentials but also blockchains) [98, p.93]

The categories within IT infrastructure components are not mutually exclusive. The CIRPASS project provides a reference classification framework for mapping DPP-related initiatives, indicating trends in DPP design aspects. Survey results show a preference for API-based data transport, role-based advanced access control, QR codes, NFC, and RFID for product traceability, anonymisation for data protection, and verifiable credentials for evidence [98]. Regarding data storage and management, there is no clear preference for a centralised or decentralised approach among surveyed initiatives in CIRPASS. Hybrid solutions like federated platforms are also considered [1], [98]. Contemporary research acknowledges the potential of federated data ecosystems like IDS, Gaia-X, and Catena-X for DPP systems but emphasises the need to assess their maturity in the manufacturing domain [35], [36], [43]. This corresponds also to the main findings from section 4 of this thesis. Next to the technical complexity ofDPPsystems, research suggests that DPP architectures should also include thorough investigations on the implicationsDPP on organisations [43], [98], which is in line with the research objectives of this thesis.

5.3 Relevant existing applications

This section closes with a review of existingDPParchitectures and solutions to provide a picture of the status quo today.

Jansen et al. (2022) compiled a list of 76 current DPP initiatives, encompassing public, private, and EU research projects. CIRPASS conducted benchmarking on 62 European-level initiatives, with 32 undergoing the detailed assessment as part of the benchmarking. CIRPASS assessed the maturity of these initiatives using Technology Readiness Levels (TRLs). About 40 percent of the surveyed initiatives reported being in the application phase, while the rest were in various stages of development and prototyping. Similarly, Jansen et al. (2023) found that almost 45 percent of reviewed initiatives were integrated into the market or undergoing testing, with the remainder in development or concept phases.

are not identical but complement each other. Jansen et al. (2023) included initiatives like Gaia-X and governmental projects, while CIRPASS focused on commercially available solutions from private firms and public-private collaborations. For instance, CIRPASS reviewed platforms like the previously mentioned Circularise and Circulor service providers [43], [123]. These findings collectively offer insights into the maturity and diversity of DPP initiatives across different sectors and levels of development.

In the following paragraphs, a few selected DPPinitiatives with high levels of maturity and significant relevancy for supply chain sustainability and transparency are presented;

- **Circulor** Circulor specialises in supply chain traceability and sustainability using a platform that combines blockchain, AI, and advanced technologies. Their solution is considered one of the most comprehensive and mature in the market at present. Circulor utilises blockchain technology to collect primary data from the upstream value chain for traceability and the platform covers various supply chain use cases, extending beyond the typical scope of a DPP system. Their primary focus for DPP development is on battery passports, and they collaborate with organisations like Catena-X, GBA, and the German Battery Pass project. The company also works on digital twin technologies as part of its platform solutions to support track and trace functionalities [84], [85].

- **Circularise** Circularise is a SaaS company with a similar focus on supply chain transparency and traceability as Circulor. Their solution uses blockchain and cryptography technology to allow communication on the data that is being shared and spans use cases such as LCA and carbon footprint analysis, next to their focus onDPPs including the battery passport. Like Circular, the firm is collaborating with initiatives such as Catena-X as well [89], [124], [125].

- **atma.io** atma.io provides track and trace solutions to the textile industry, stating that 6 out of the 20 biggest fashion brands trace around 28 billion items. The solution is also offered to other sectors including food, pharmaceuticals, beauty, packaging, logistics and automotive. The product cloud platform is a microservices-based architecture with loosely coupled services and RESTful APIs for data exchange with external systems and applications. The APIs are GS1 EPCIS compatible and the firm also states to be able to integrate with Blockchain and Distributed Ledger technologies [84], [126]

The three mentioned solution providers are just a few examples of those offering DPPs integrated with their track-and-trace solutions. Others include ToxNot, specializing in chemical substance transparency compliance like REACH, and EasyBat, which leverages the Energy Web Decentralized Operating System (EW-DOS) for connecting stakeholders in the energy sector [98]. Other DPP like solutions include ROCKWOOL's Rockcycle platform supporting stone wool insulation recycling, demonstrating interoperability with BIM and EPD standards as well as Niaga's DPP platform that offers QR code access with different levels for stakeholders as well as Hydro Circal, an aluminum producer, using blockchain for a DPP pilot on green aluminum certificates [35, pp.22-24]. For a comprehensive overview of current initiatives, this thesis refers to the existing literature published by the CIRPASS project [84], [98].

In summary, the examination of existing DPP initiatives reveals a growing body of research, increasing attention from public entities, and the emergence of various SaaS platforms that offer DPPs alongside track-and-trace solutions. These sources provide valuable insights into the capabilities and information that DPP systems should encompass. Key research questions for future DPP studies include the ongoing debate over infrastructure implications, such as the choice between centralised and decentralised approaches, as well as the level of granularity that DPPs should possess to cater to different use cases and product complexities. However, despite the evolving nature of DPP concepts, common themes, such as achieving interoperability in alignment with Industry 5.0 strategies and fulfilling sustainability objectives in the European Union, are evident in current initiatives and developing instruments alike [35], [36].

5.4 Relevant standards for digital representation of the product

In the context of interoperability research on the DPP underlines the need for standardised classification systems and data models to facilitate the implementation of

DPPs in the manufacturing industry [121]. Therefore, this section briefly reviews standards and research concerning the representation of the product for the DPP use case.

The AAS standard is gaining prominence in academic literature, both in the domain of DTs and specifically for DPPs. Recent research points to the potential of the AAS to become the standard for DPPs, encompassing digital product representation and data sharing [108], [109], [84, p.84]. The AAS metamodel defines the structure and behaviour of digital twins for physical assets, comprising assets, submodels, properties, and asset relationships. Assets represent physical or virtual objects that can be managed and monitored, each associated with descriptive properties like name, type, and location. Submodels group assets based on common traits and can be organised hierarchically. Properties define asset attributes, accommodating textual descriptions, numerical values, and references to other assets. Asset relationships are established through references, representing dependencies or associations between assets, facilitating the representation of complex relationships within the digital twin. The AAS metamodel also encompasses events, operations, and views, allowing information to be either static or dynamic, depending on whether they remain constant or change over time [95], [106]. In the Industry 4.0 circles of the EU, we can find a few novel publications onDPParchitectures and prototypes that combine concepts such as the Asset administration shell and international data space components into aDPPsystem [123]. This indicates thatDPPsystems can potentially overcome similar issues that are addressed by platforms and ecosystems such as IDS and Gaia-X [108], [109] [84, p.84]. The application of the AAS standard as part of DPP systems highlights how a standardised digital representation of the product fosters both data integration and interoperability with stakeholders [106], see also section 4.3 in chapter 4.

In addition to the AAS, notable data models in the context of digital product passports include the Product Lifecycle Management (PLM) data model, and ISO 29002 series. The Product Lifecycle Management (PLM) data model manages product information across its entire lifecycle, including design, development, manufacturing, and disposal. It organises data entities, attributes, and relationships for effective management, ensuring consistency and interoperability in PLM systems. PLM data model is widely used in industries such as automotive, aerospace, and consumer electronics and implemented in PLM software [127]–[129].

In conclusion, this chapter has provided a comprehensive discussion of Digital Product Passports by addressing the concept, information requirements, and necessary digital capabilities. To answer the question of **KQ 3: What is the concept ofDPPand how can it be implemented in the manufacturing domain?**, the DPP is essentially an extensive digital record that encompasses a product's entire lifecycle, including details such as specifications, components, materials, and maintenance history. DPPs serve as datasets that connect and integrate product data from various sources and rely on digital capabilities for efficient data management throughout the product lifecycle. The implementation of DPPs entails making critical infrastructure decisions, including centralisation or decentralisation, integration with legacy systems, and addressing confidentiality requirements. In the manufacturing domain, successful DPP implementation revolves around the utilisation of standardised data models and classification systems to consistently represent product data. This chapter has also discussed relevant standards, with a particular emphasis on the Asset Administration Shell standard, underlining the significance of data standardisation and interoperability in the context of DPPs.

CIRPASS highlights open questions concerning the DPP implementation, including the granularity of product information. Given the maturity of manufacturers in their digital transformation journey discussed in the previous sections of this thesis, the question arises if and to what extend manufacturers are able to harness the necessary information from their systems depending on the required level of granularity. This chapter outlined the potential information requirements that need to be fulfilled under the apprehension of standardised representation, which raised the question how internal information structures given the historically grown legacy infrastructure of manufacturers can support them. To fill this gap, this thesis has formulated the main research question **How to address and develop the digital capabilities necessary for the digital product passport in the manufacturing domain?**. The remainder of this thesis focuses on the internal digital transformation capabilities needed by manufacturers. Specifically, there is a need to explore whether manufacturers have the ability to effectively leverage their existing information structures and, if so, to what degree, in order to harness meaningful information for DPP implementation and data sharing, thereby bridging the gap between technology adoption and internal readiness.

Chapter 6

Solution Design

This chapter focuses on the main research question of **How to address and develop the digital capabilities necessary for the digital product passport in the manufacturing domain?**. Specifically, this thesis studies the legacy infrastructure in terms of processes, information and IT systems of a manufacturer in Europe and designs a target architecture outlining the required internal digital capabilities for the DPP.

The chapter is structured into four sections. Section 6.1 presents the current status analysis of the manufacturing company, primarily focusing on material flow processes and IT infrastructure. Section 6.2 analyses DPP system architecture requirements, considering existing digital capabilities and high-level requirements from Chapter 5. Section 6.3 identifies gaps between requirements and current capabilities, highlighting necessary additions for DPP functionality. Finally, Section 6.4 outlines the proposed target architecture for the DPP system based on specified requirements and identified capability gaps.

The target architecture proposes data collection and integration capabilities that enable manufacturers to harness the relevant information for the DPP from their existing systems as much as possible. By closely examining the status quo in manufacturing, this chapter bridges the gap between the ambitious implications of the previously discussed state of the art in terms of DTs and DPPs and the currently available competencies at manufacturing companies.

6.1 As is analysis

The as-is analysis serves as the foundation for developing the target architecture and proof of concept. The chosen manufacturer for this analysis is emblematic of manufacturing enterprises in Europe, particularly those involved in discrete manufacturing and assembly employing a high-mix, low-volume production strategy. This choice allows this thesis to encompass the intricacies and challenges associated with producing a diverse product range in smaller quantities, which can pose unique considerations and demands, especially in the context of the DPP use case, compared to high-volume production with limited product variations. The identified digital capabilities within the manufacturer align with the broader maturity landscape of Industry 4.0, as discussed in Section 4. Key findings from the analysis highlight a combination of expanding competencies in IIoT and common constraints related to data and systems integration due to legacy infrastructure.

6.1.1 Relevant business processes

This analysis focuses on two key processes in production and assembly. Firstly, the flow of material through the manufacturing plant is examined. This scrutiny is essential for the DPP as material flow represents a significant portion of the product's life cycle, comprising its constituent materials and components. Secondly, the analysis briefly touches upon change management within the manufacturer's product life cycle management. This thesis considers the change management process as an integral element of the broader product category life cycle. These two processes collectively provide insights into how product information moves through various stages of the product life cycle.

Flow of Material

The flow of materials describes the different steps material goes through until it becomes part of the final product Figure B.1 shows the main business processes at the manufacturing plant. The components and materials associated with a final product go through several stations at the plant before being assembled into the final product. Materials and components are delivered to the receiving docks and transferred to the warehouse. Most components and spare parts delivered to the plant are going through some form of incoming quality control. Deliveries can comprise raw materials or components that need to go through one or more manufacturing steps at the plant first, for instance heat treatment or different steel cutting procedures. Deliveries can also comprise components and spare parts that can directly go into the product, for instance screws, but also electronic components such as the batteries not produced by the manufacturer. This means that once stored on larger palettes in the warehouse, material can either flow in batches through different steps of machining, or be directly repacked into smaller, so called handling units that are used to transport the material to the assembly lines in the plant. Once arrived at the assembly line, the components are assembled into the final product and the final product is transferred to the warehouse until shipped further to distribution centres.

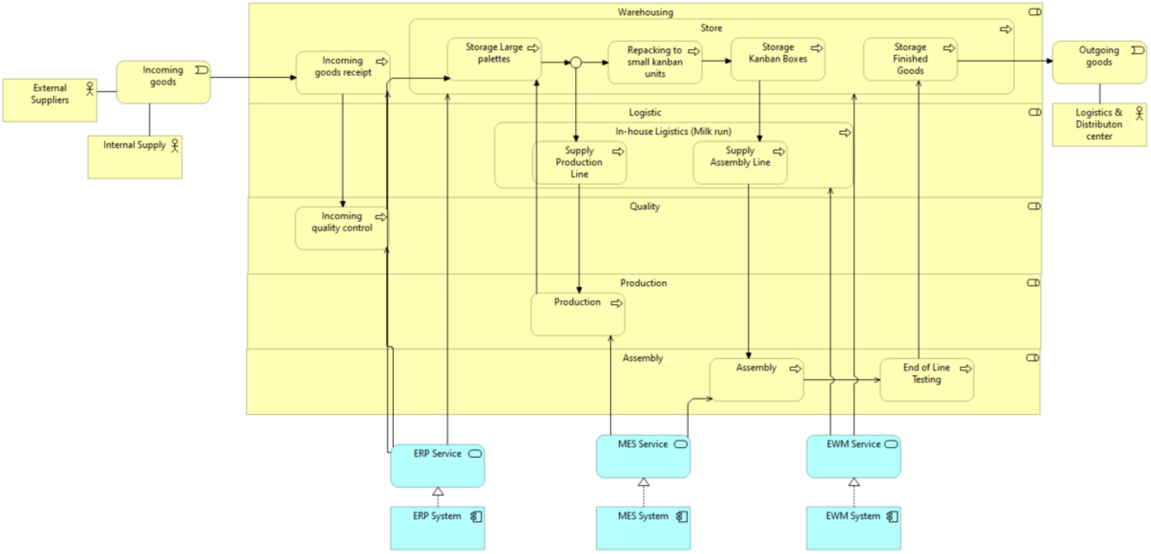


Figure 6.1: Main business processes associated with the flow of materials at the plant and the information supporting this process, own representation

The archimate model in figure B.1 shows how components move through the plant and divided into smaller batches throughout their journey, starting from batches on palettes to smaller handling units. The upper processes displayed in the figure happen at the warehouse, whereas processes displayed on the bottom of the figure are under the responsibilities of either in-house logistics, production or assembly.

Figure B.1 illustrates the primary business processes at the manufacturing plant. Components and materials for the final product undergo various stages within the plant, beginning with delivery to the receiving docks and transfer to the warehouse. These deliveries may include raw materials or components requiring different manufacturing steps, such as heat treatment or steel cutting. Alternatively, deliveries may consist of components and spare parts ready for direct use in the product, such as secondary components or parts manufactured by suppliers. Subsequently, materials are either batch-processed through different machining stages and then repacked into smaller handling units for transportation to assembly lines, or materials move directly into warehousing and repacking. Once at the assembly line, components are assembled into the final product, which is then stored in the warehouse before being shipped to distribution centres. The ArchiMate model in Figure B.1 visualises the movement of materials, highlighting their transition from larger palettes to smaller handling units. The upper processes depicted in the figure occur within the warehouse, while those at the bottom are the responsibility of in-house logistics, production, or assembly.

Figure B.1 highlights the key supporting systems and information related to the flow of materials: Enterprise Warehouse Management (EWM), ERP, and MES. The majority of data is centralised in the ERP system, with information related to both inbound quality control and production orders. The EWM system manages warehouse and in-house logistics processes such as supply to production and assembly lines, tracking batch locations and transactions. Simultaneously, the MES system supports production and assembly processes, sharing information with the ERP system. For a comprehensive process overview and role details, please refer to Appendix B.

Change management

Change management involves making alterations to a product model, potentially leading to a new version or revision level. This is crucial for the DPP as it shapes the product model and the foundational information of the actual product. Key stakeholders include internal supply chain participants like engineering, quality, procurement, and health, safety, and environmental departments. Figure 6.2 illustrates the main business processes of product model changes, initiated by various stakeholders such as plant quality and procurement, driven by quality issues or supply shortages for instance. This process highlights how new product versions emerge and showcases the complexity of product lifecycle management given the number of stakeholders involved. The ERP system, Computer-Aided Design (CAD) system and project management software support this process. Depending on the change required the CAD system is used to create new drawing of a product of component while the ERP system is used to register the change in revision

6.1.2 IT Infrastructure

The description of the two relevant overarching business processes already shows how the three core systems ERP, EWM and MES hold information about the production and assembly of the final product and its components. This section details out the supporting IT infrastructure at the manufacturer, to give an overview of the systems and integration in place.

IIoT pipeline

The DPP requires the reporting on information related to manufacturing activities of a product [35]. Figures 6.3 and 6.4 present the current IIoT pipeline at the manu-

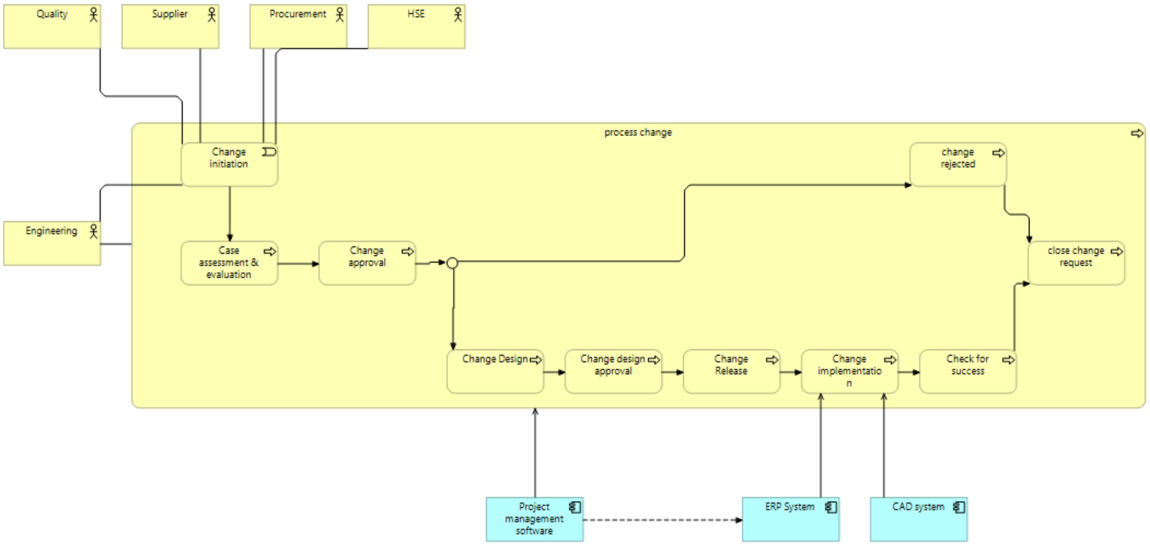


Figure 6.2: Change management process described in archimate, own representation

facturer. The figure shows how the data collected through IIoT devices at the machines in the production and assembly areas flows into the cloud and integrates with databases and applications. Figure 6.3 illustrates the on-premises part of the IIoT pipeline. For production area data, machine data is transmitted from machines to a Secure Integration Server (SIS) through Open Platform Communications Unified Architecture (OPC UA) protocols. This communication solution is provided by an industrial communication solutions provider. Depending on the machine and sensor type, data either directly reaches the SIS through OPC UA servers on the machines Programmable Logic Controller (PLC), or it passes through an OPC UA broker for translation into the OPC UA format, ensuring semantic interoperability. The data then proceeds to OPC publisher and edge device, connecting to the cloud-based IoT platform. In the case of data from assembly areas, a similar pipeline structure is employed as shown in Figure 6.3. Here, the data originates from sensors at assembly lines, and the integration path also depends on the sensor type. The edge device serves as the link to the cloud, as depicted in Figure 6.4, representing the second part of the IIoT cloud-based pipeline. The manufacturer leverages a platform for IoT asset connectivity and management. Additionally, the manufacturer employs serverless infrastructure components for event-driven triggers for data processing, transfer and integration purposes. The IoT pipeline connects to the MES system, transmitting data, including typical information like production machine status, piece counter information, and machining task cycle times, to the MES.

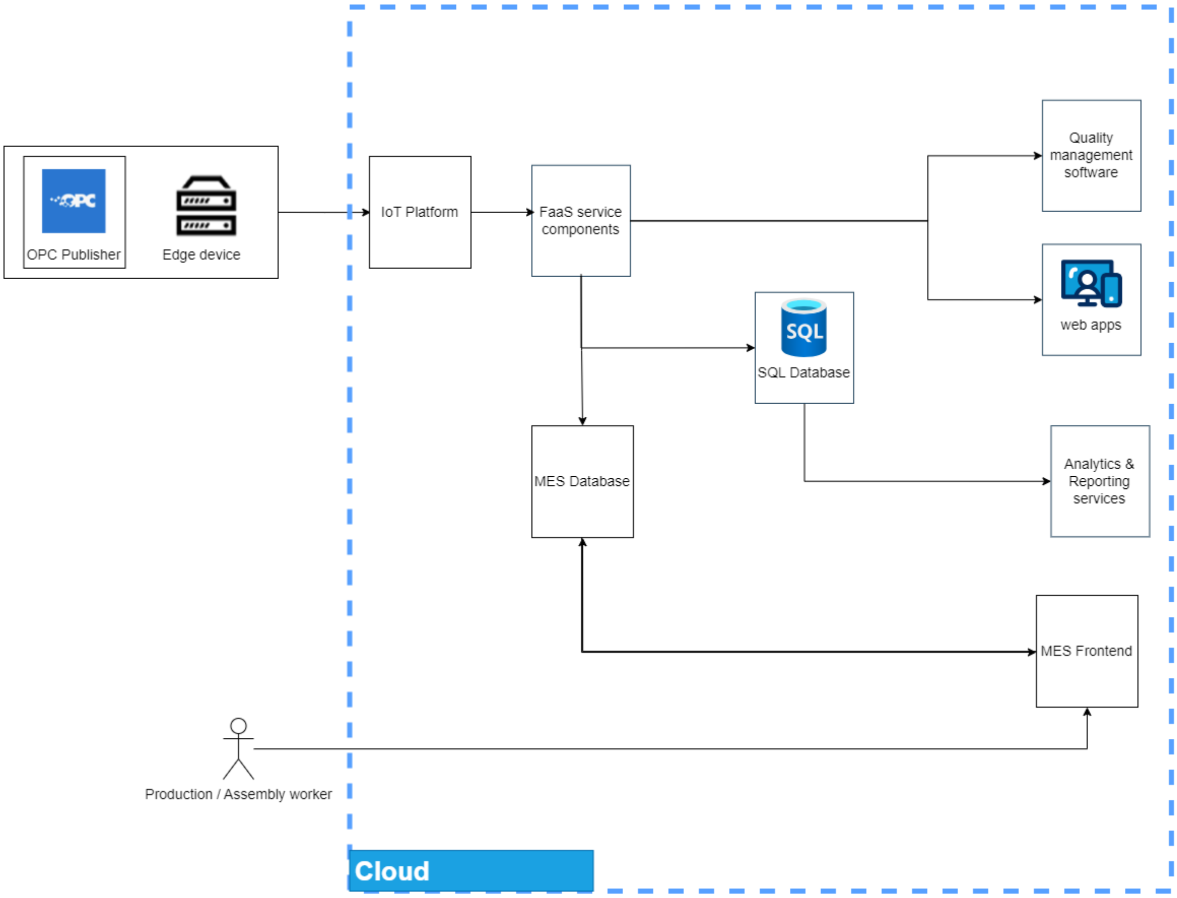


Figure 6.3: IIoT Pipeline at the manufacturing plant part one: On premise, own representation

IIoT device location	IIoT devices	Data points
Production areas	Machine sensors	cycle time, machine status, piece counter
Assembly areas	Sensors, Cameras, torks	triggers for piece counter (1 trigger = 1 assembly step / final product)

Table 6.1: Data from IIoT devices specified for production and assembly areas

Application landscape

The primary data points transmitted from the IIoT pipeline to the MES are outlined in Table 6.1, distinguishing between production and assembly areas. Production areas incorporate IIoT sensors within or at machines, resulting in the transmission of more data points compared to assembly line IIoT. Assembly lines can employ various sensors, including cameras, light sensors, and torque sensors, which trigger the registration of completed assembly tasks or count assembled products at the

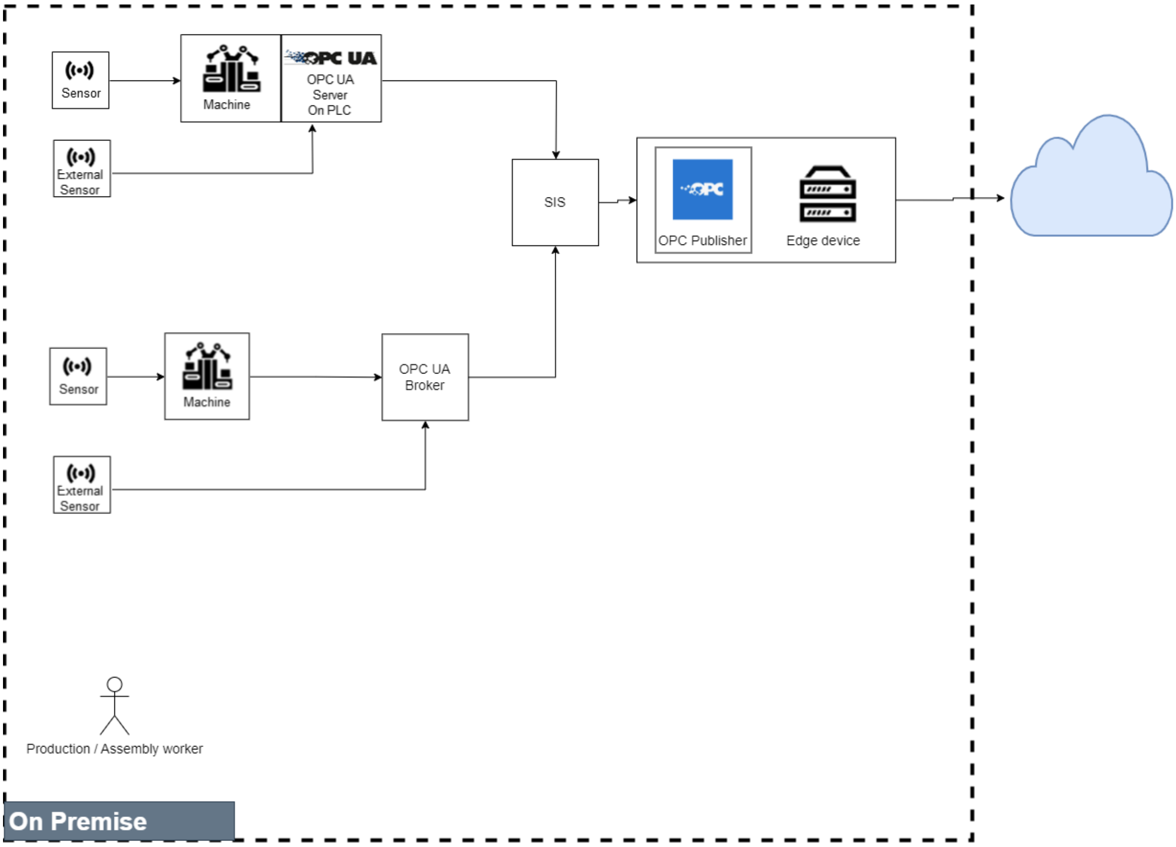


Figure 6.4: IIoT Pipeline at the manufacturing plant part two: In the cloud, own representation

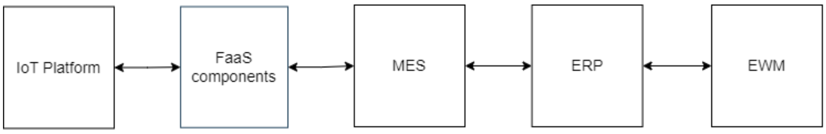


Figure 6.5: Integration between core systems and IoT pipeline components, own representation

line's end. In addition to data collected by IIoT devices on the shop floors, machine operators and assembly workers input data through the MES system's front-end, as illustrated in Figure 6.4. This manual input includes information such as the scrap rate for components or parts exhibiting quality defects in the final product. For a comprehensive view of the plant's IIoT pipeline, please refer to Figure B.3 in Appendix B.2.

The IIoT pipeline described is a common feature in manufacturing companies, facilitating data extraction from IIoT devices for various purposes [130], [131]. Data pertaining to product components and materials is only partially covered by the IoT Hub and the MES system. The majority of relevant information, such as Bills of Materials (BoM) details, is stored within the ERP and EWM systems as already outlined in section 6.1.1 of this chapter. Figure 6.6 illustrates the current IT infrastructure related to ERP, MES, and EWM systems in use. MES data and IIoT data are integrated through generic functions. A designated function receives data input from the MES system via HTTP POST requests. This function is responsible for processing data, mapping data from the IIoT side to data from the MES side, including aligning timestamps. Figure 6.5 illustrates the primary integrations between IIoT data and the three core systems: MES, ERP, and EWM. These integrations are based on standard interfaces. MES and ERP are linked, transmitting data about production orders from ERP to MES and feedback on pieces produced, including scrap rates, from MES to ERP. In contrast, ERP and EWM are seamlessly integrated, utilizing standard protocols and communication methods for data exchange between the systems. Engineering is supported by the CAD system and for planning and demand data the manufacturer uses a standard Advanced Planning and Optimisation (APO) system, with ERP system integration through the translation of planned orders into actual production orders.

In summary, there is partial integration between the IIoT pipeline and MES, similar partial integration between MES and ERP, and complete integration between ERP and EWM systems to support transactions. In the context of the change management process described in section 6.1.1, project management software is employed to track and manage issues and activities. For procurement, the manufacturer uses

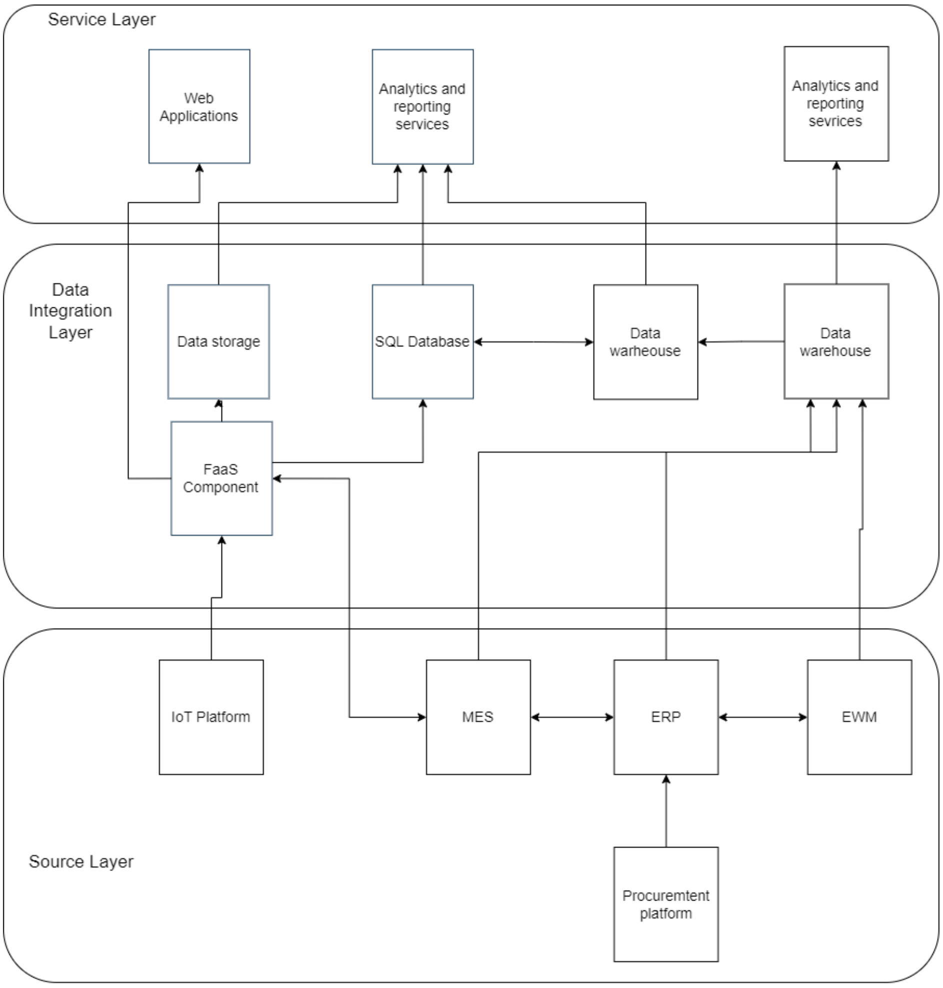


Figure 6.6: Application Landscape at the manufacturing plant supporting the flow of materials, own representation

a cloud-based procurement platform, which allows the connection and collaboration with suppliers and enables streamlining of procurement processes. It's important to note that the usage of the procurement platform varies among the manufacturer's suppliers at present based on their size and digital capabilities. Specifically for sustainability reporting, a dedicated questionnaire is sent to suppliers to gather additional necessary information. Figure 6.6 is not an exhaustive list of all software systems in use at the plant, but it represents a high level overview of the relevant applications that likely hold the information necessary for the DPP, including the core ERP system. Most importantly, it also shows where in this infrastructure the IIoT pipeline connects with the core systems , namely via the MES system and the additional function components for data transfer and integration. Table 6.1 lists the data from the IIoT devices that can be accessed from the MES system via the data integration in the described pipeline.

Manufacturers often face challenges related to vendor lock-in and the complexities of integrating external applications with their enterprise systems. In the manufacturer's case, this is also associated with high costs for new data and systems integrations. This can impact data analysis and visualisation given possible restrictions of data flows out of the systems. Common data flows out of the ERP system to data visualisation and reporting systems include manual exports via xml, automatic export and integration into SQL databases or data lake infrastructures. Depending on the software vendors involved, vendor specific data warehousing solutions also play a role.

6.1.3 Information structures

To complete the as-is analysis, the information structures are briefly examined in connection to the flow of materials at the manufacturing plant. Figure 6.7 shows the high-level information structure, and their supporting sources. Key elements are;

- Serial Number: This unique identifier for manufactured products is situated in the top left corner. It is linked to historical records commonly known as the serial number history which captures movements and status changes of the actual product throughout the later stages of the product lifecycle.
- Warehousing Information: Found on the top right, warehousing information provides the links between the final product (identified by the serial number), production environment at the manufacturer (i.e. the production order) and supply chain information such as orders from suppliers. The supporting EWM system handles both in-house logistics and shipments from the plant elsewhere.
- Handling units are pivotal for in-house logistics at the manufacturer, facilitating component and product transport within the plant, especially to assembly lines. They serve as the link to batches, including internal production and supplier delivery. This connection is vital because it defines the final step in material flow into the product, with materials and components distributed from batches onto handling units and then into the products during the assembly process. In short, it is through the handling units that the relevant systems can register which component from which batch is built into which product.
- Production Order: At the centre of the figure 6.7, the production order ties together data from production and assembly lines. It also links to the material number, representing the specific product model. This material number, in turn, connects to the bill of materials, listing all materials and parts associated with that product model.

To complete the as-is analysis, the information structures are briefly reviewed in their links to the product lifecycle and the IT infrastructure. The information model in figure 6.7 shows the high level information model. The production order is a central aspect, linking most information of the product together. On the top left of the model, the serial number is the unique ID for a manufactured product, and links information about the history of the serial number, which includes any movements or status changes registered in the respective IT system. On the top right of the information model, the warehousing information links to both the final product (represented by the serial number) and the production order). Warehouse tasks can be internal movements of products or components, but can also represent the movement of final products to the outside of the plant. The warehousing information also related to an information element called handling unit, which represents smaller holding units to transport components and products within the plant and is displayed on the bottom right of the figure 6.7. These handling units are used to supply production and assembly lines at the plant. The handling unit is also linked to the order number for raw material and components delivered by suppliers to the plant. The order number in turn relates to information about the order, including supplier information available in the respective systems. Finally, the production order, central to the information model for product related information at the plant, links to information from production and assembly lines, such as the tasks completed, as well as to the material number, which represents the product model (a product of type X, such as BX-3). The material number is linked to the bill of materials within the respective systems, which lists all materials and parts associated with one product model.

The respective source systems of the information modelled are displayed in figure 6.7. The three core systems MES, ERP and EWM are the single source of truth for the information, with MES holding information coming directly from production and assembly lines (such as the task completed), ERP holding information about the production orders, the orders and suppliers as well as information about the final product. Finally, the EWM system is the source for warehouse information, including information about the handling units.

6.1.4 Sustainability reporting

Sustainability reporting at the manufacturer relies primarily on manual data processes depending on the information granularity. Currently, supply chain data is gathered through various methods, including office applications, direct communication with suppliers, and the use of procurement platforms, which facilitate automated interactions between manufacturers and suppliers for sustainability-related data and

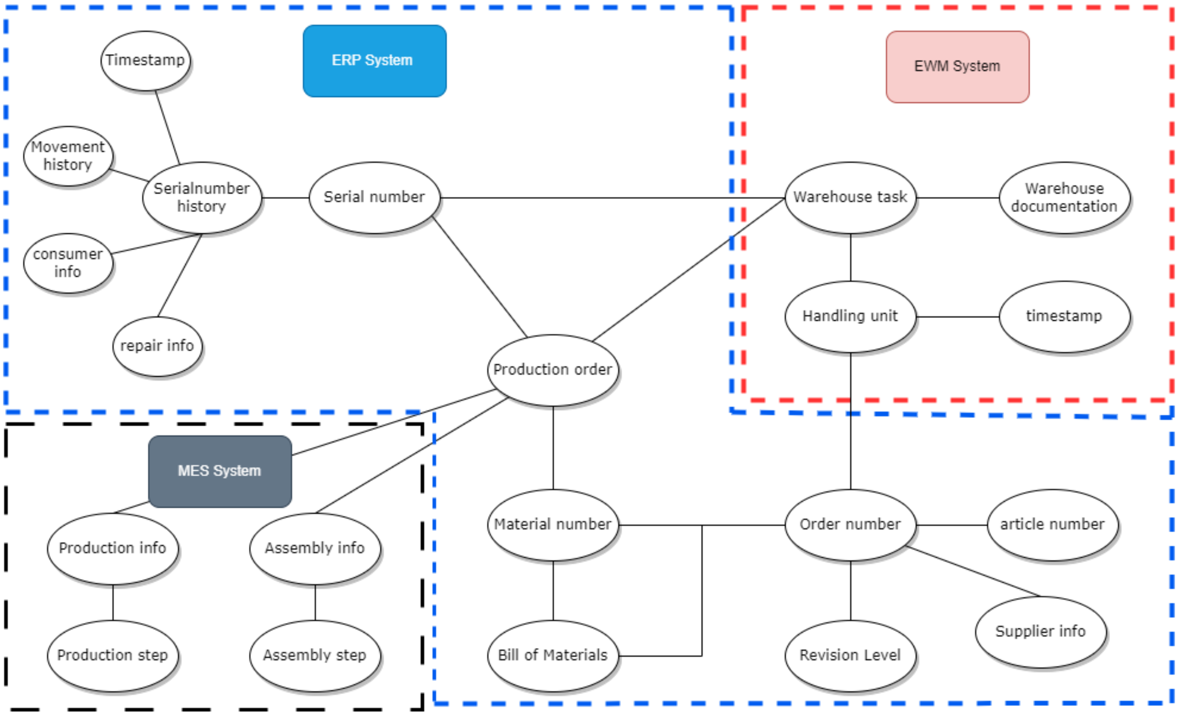


Figure 6.7: High level information structure of product related information with relation to their information source, own representation

support the sending of inquiries from the manufacturer to the suppliers. Because the reporting requirements for sustainability are still evolving, manufacturers usually do not have standardised information sets they require from their suppliers, and the information exchange is based in individual digital capabilities of the suppliers and individual demands of the manufacturer. The manufacturer also utilises environmental management systems to calculate and report sustainability KPIs, with the level of detail and accuracy depending on available data obtained via the described dataflows.

6.2 Requirements analysis

This section outlines the requirements for the DPP system and necessary digital capabilities for the manufacturer, following a top-down approach. Initially, basic KPIs and information requirements are defined based on the considerations in chapter 5. These general information requirements to the DPP defined in the previous chapter are then tailored to the manufacturer's current process and information landscape and specified at the necessary level of granularity. IT infrastructure requirements are subsequently formulated to align with the proposed data granularity. Figure 6.8 illustrates this top-shaped approach, where reporting requirements drive the process from the top-down, while IT infrastructure requirements are inferred bottom-up. Existing applications and architecture models, such as the battery passport, serve as reference points for the manufacturer's DPP implementation [2], [132].

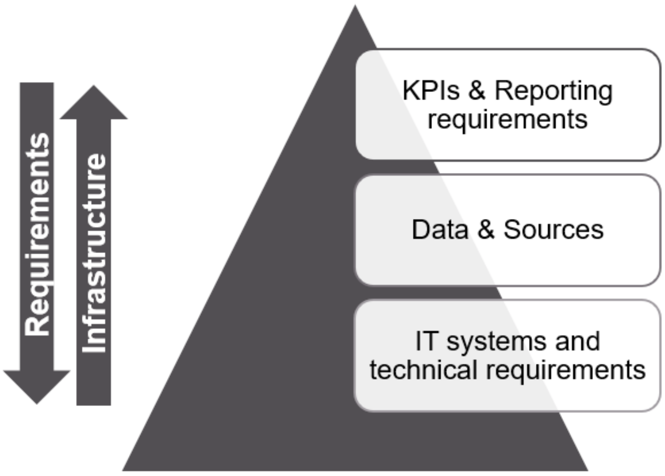


Figure 6.8: Approach to the requirements analysis, own representation

DPP granularity for products

The level of granularity for the DPP is specified by the ESPR to be either on product model (e.g.product model A), batch (e.g. product A, from plant X in year 2023) or item (e.g. product A, Serial number 12345678910). The manufacturer offers services such as repair and maintenance which means that the company already tracks a part of the movement of the end-product during their time with the customer. This demonstrates the manufacturers capability to register dynamic information related to the later stages of the product lifecycle on a product item level. Therefore, this thesis proposes a DPP granularity on product item level using the individual serial numbers the manufacturer allocates to each individual product.

Previous literature on the classification of product information highlights that a substantial portion of product data tends to be static in nature [121]. Consequently, not all data underlying a DPP for individual product serial numbers requires the same level of granularity. For instance, consider the calculation of a product's CO2 footprint, which aggregates specific scope 1, 2, and 3 emissions based on their relevance to the product. Various calculation methods, as outlined in the technical guidance for scope 3 emissions (see also Section 2.2), can impact the granularity of the product's CO2 footprint. Calculations can vary, depending on input, where the use of average energy usage in production processes would be less precise that using specific machine cycle times.

Given the high-mix low-volume strategy of the manufacturer, the low-volume per product model means that average data about that model is already relatively specific to the single item. Secondly, product models at the manufacturer have a long product category life cycle, which means changes to the model are be relatively seldom.

To enhance the utility of the DPP, this thesis introduces an additional perspective focused on quality control within the manufacturing context. It underscores the importance of maintaining a certain level of granularity to facilitate in-depth analysis of quality issues and the tracking of defective items in the market. This is exemplified through two specific quality control use cases: (1) market reclamation's of products and (2) Supplier or production issues that require the backtracking of products for instance with faulty components.

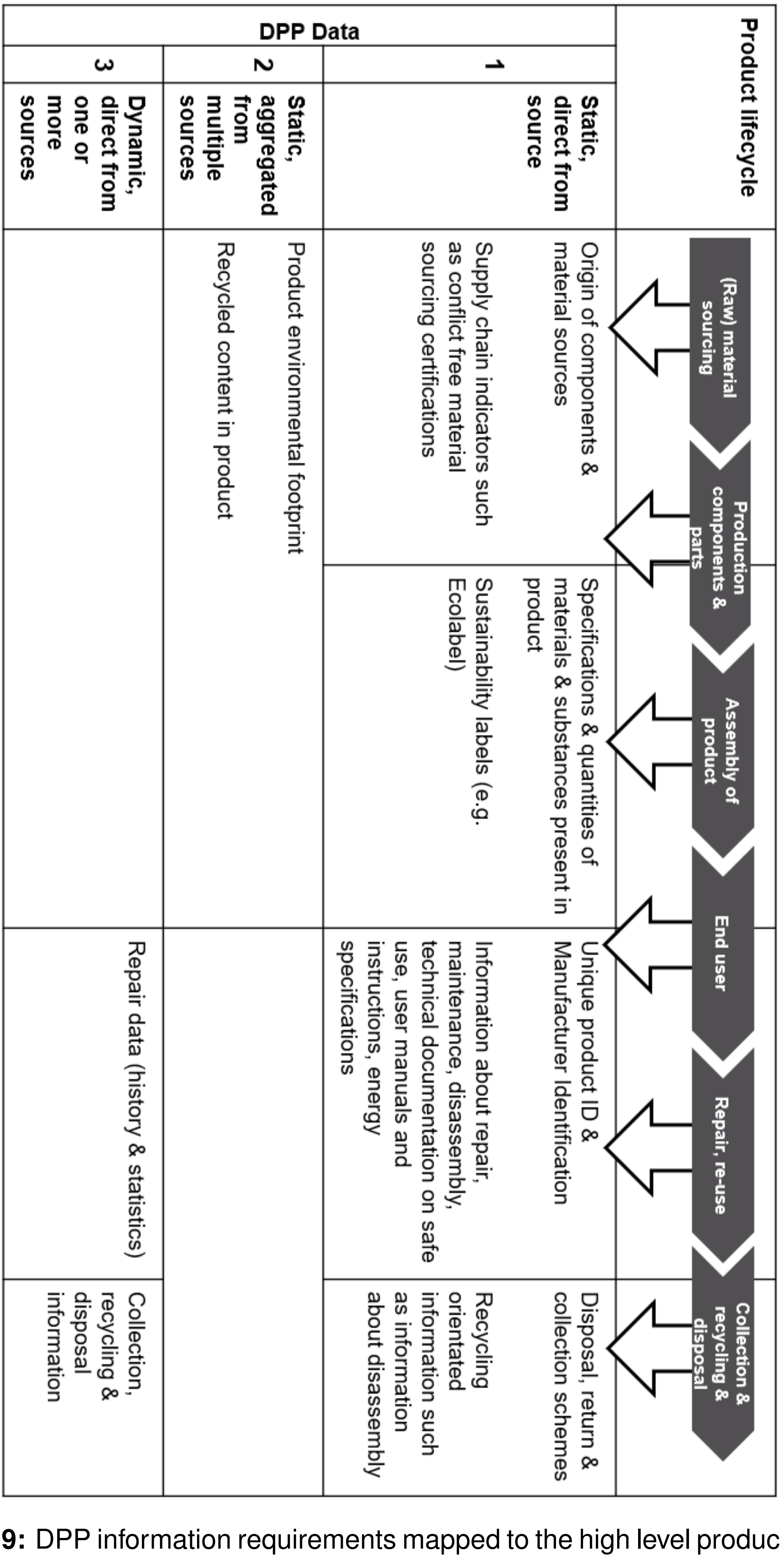
- When quality issues arise with a product or product model at the customer's end, it becomes imperative to pinpoint the component(s) responsible for the problem. Stakeholders must identify the batches and suppliers potentially contributing to the quality concerns and deviations in the final product. This necessitates the capability for conducting root cause analysis.
- In scenarios where a batch of components is identified as faulty, which could happen at different stages of the material flow including faults registered by a supplier and internal production issues, it becomes essential to trace their final destination. Stakeholders need to determine the products, complete with their serial numbers, in which these defective components were incorporated. This enables them to track all the products in the market that contain these faulty components.

Essentially, these two use cases highlight the importance of having the capability to establish connections between batches from suppliers or internal production, individual components, and the final product. In order to conduct root cause analysis and vice versa, stakeholders, particularly those involved in quality control, must be able to associate products with their respective components. If a batch of components is responsible for issues in final products, it is crucial to not only identify the problematic batch but also the specific range products in which these components were used. This underlines the benefit of traceability at batch level granularity or higher.

The use cases from quality show that a similar set of capabilities is necessary as for the DPP. Establishing links between products, components, and the different kinds of batches allows for the seamless integration of information about raw materials from suppliers to the final product, ensuring that product information is not solely reliant on master data such as the bill of materials.

Based on the above considerations, this thesis proposes that a product model granularity is generally sufficient for most of the data points required for the product passport, in line with discussions on static product information by Stratman et al (2023) [121]. However, the DPP also necessitates information about the origin of components and materials, which may change periodically based on supplier choices and sourcing. Considering potential future reporting obligations, such as dedicated supply chain regulations (see section 2.3), there is a likelihood that this information will require a finer level of granularity. Therefore, it is recommended in this thesis to adopt a batch-level granularity for data points such as raw material origin. This ensures that individual products can be linked to specific information related to the orders associated with their respective components. Based on the current flow of materials and supporting IT systems, Batch level granularity can be achieved mainly through data integration of existing systems, therefore feasible without extensive efforts required. Achieving item-level granularity for product KPIs however would likely entail a significant investment in capabilities, both internally and within the supply chain, including advanced track and trace systems and the placement of further IoT components on shop floor level. Moreover, for manufacturing companies, like the one under study, with relatively low production volumes per product model, the return on investment may not justify the effort required. The figure 6.9 shows the information requirements based on section 5.1 summarised and mapped to the high level product lifecycle. The figure further differentiates between static vs. dynamic data and direct vs. aggregated data. Three different combinations are identified:

- Static data collected directly from the source, with the source either the manufacturer's internal system or a system at one of the other participants in the value chain.
- Static data which is aggregated from multiple sources, such as the product environmental footprint, which is partly based on emissions generated in the supply chain prior to the manufacturer in the value chain, and partly based on emissions generated during the manufacturer's internal production and assembly processes.
- Dynamic data, coming from one or more sources, such as repair data during the use of the product. Service centres external to the Original Equipment Manufacturer (OEM) may also be allowed to perform certain types of repair services, which means that third parties can also generate dynamic event data about the product.



DPP Data					
1	Static, direct from source	Origin of components & material sources Supply chain indicators such as conflict free material sourcing certifications	Specifications & quantities of materials & substances present in product Sustainability labels (e.g. Ecolabel)	Unique product ID & Manufacturer Identification Information about repair, maintenance, disassembly, technical documentation on safe use, user manuals and instructions, energy specifications	Disposal, return & collection schemes Recycling orientated information such as information about disassembly
2	Static, aggregated from multiple sources	Product environmental footprint Recycled content in product			
3	Dynamic, direct from one or more sources			Repair data (history & statistics)	Collection, recycling & disposal information

Figure 6.9: DPP information requirements mapped to the high level product lifecycle of the manufacturer products, differentiated between static vs. dynamic data and direct vs. aggregated data, own representation

Static and dynamic data can be distinguished by looking at whether or not they change regularly. Static data usually does not change or changes only seldom, while dynamic data is expected to change [2].

Based on the preceding discussion, it's reasonable to anticipate that data related to the product's initial lifecycle stages remains relatively stable, categorising it as static data, as depicted in Figure 6.9. Conversely, data pertaining to usage, repairs, and processes involving product collection, recycling, and disposal are expected to exhibit dynamic behaviour.

For static data, this thesis proposes a granularity level at the product model or batch level as adequate due to the limited expected changes over time, resulting in minimal variations among batches. However, for dynamic data, this thesis suggests adopting a finer granularity at the product item level. This is because movements in and out of repair centers for instance are already tracked based on serial numbers today. Furthermore, the DPP should be designed to facilitate data exchange with third-party service providers engaged by the manufacturer for product repair and disposal in the future.

In summary, this thesis proposes a DPP on product item level using the associated product serial numbers, with data on product item level for dynamic data and product model or product batch level for static data depending on the data source

Requirements

The chosen granularity level imposes specific IT infrastructure requirements, dictating the collection, processing, and aggregation of varying data volumes from different sources to fulfill the final KPI needs for the DPP;

- For static data originating from a single source within the manufacturer, suitable interfaces are needed to feed this data into the DPP back-end system.
- Static data that is aggregated from multiple sources requires a data connection and a data processing layer within the DPP back-end to perform the necessary aggregation.
- Dynamic data in the later stages of the product lifecycle demands bidirectional data connectivity to allow stakeholders to both read and write data to the DPP system.

To ensure accessibility for external stakeholders, the DPP must provide secure and reliable data interfaces for data access and exchange. Additionally, secure data storage is vital, considering that not all DPP information can be accessed uniformly.

Therefore, implementing proper access control and authorisation features is essential.

Three business scenarios have been constructed to reflect the different requirements related to product lifecycle data for the DPP:

1. Dynamic Data Exchange: The business scenario (see Figure B.5 in Appendix B.4) outlines the need for bi-directional data exchange to support dynamic data in later product lifecycle stages, such as repair and maintenance services.
2. Supplier Collaboration: The business scenario (refer to Figure B.6 in Appendix B.4), outlines the necessity for suppliers to share pertinent DPP-related information with the manufacturer.
3. Internal Infrastructure Integration: Figure 6.10 in this section presents a business scenario focused on gathering and integrating information from the manufacturer's internal legacy infrastructure. This scenario forms the core business case for the target architecture, emphasising the data requirements for DPP based on contemporary discussions regarding DPP dataset contents [121].

As a result, the following requirements can be deducted for the DPP back-end system based on the proposed information granularity, business scenarios for the DPP and reviewed IT infrastructure implications (see chapter 5):

- **Data processing and integration capability**: Data from various stages of the product lifecycle, from various different data sources and in various different levels of granularity need to be collected, processed and integrated onto a level suitable for the DPP.
- **Interoperability**: DPP system architecture should be interoperable, standardised to ensure maximum compatibility with legacy infrastructure and applications of all stakeholders involved in sharing and accessing the DPP. Compatibility with future advancements of adjacent systems should be ensured through standardisation likewise.
- **Scalability**: DPP system should be scalable to both data and query volume to accustom the requirements for bi-directional data exchange and processing of both static and dynamic data
- **Standardised interfaces** The DPP back-end system should enable secure and reliable, bi-directional data exchange to allow a variety of systems and stakeholders to connect to the system with minimum effort involved.

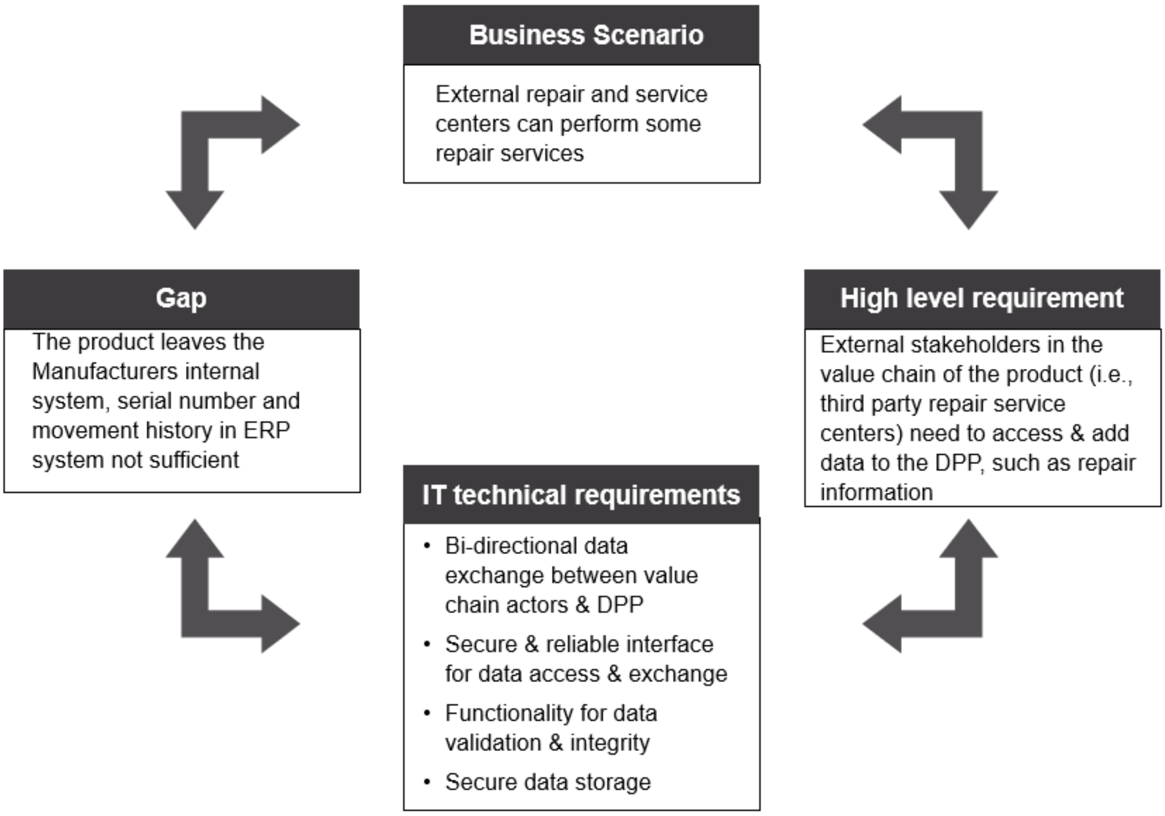


Figure 6.10: Business scenario demonstrating requirements for internal data collection at the manufacturer from sourcing, production to find a product assembly, own representation

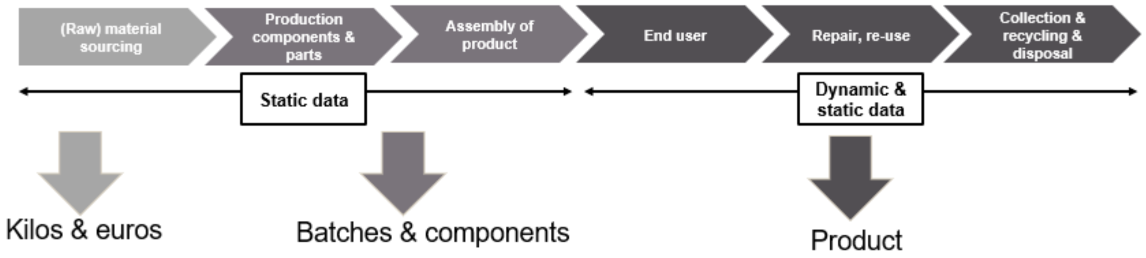


Figure 6.11: Visualisation of different information granularity across the value chain of the manufacturer products, own representation

- **Security:** Appropriate access control and authorisation measures should be put in place to facilitate both internal and external stakeholder access to information

6.3 Gap Analysis

This section examines the gaps between the high-level requirements discussed earlier and the current state of affairs at the manufacturer, regarding the processes outlined in section 6.1. The most significant gap is the absence of the DPP system itself, both its back-end and front-ends, which has yet to be implemented. Regardless of the final configuration of the DPP, OEMs must establish internal data collection infrastructure to support it. However, the existing digital capabilities within the OEM present challenges in implementing this infrastructure, primarily due to the absence of essential capabilities for collecting and processing the required information. This thesis has identified three main gaps related to the capabilities required for establishing the necessary data infrastructure for the DPP system.

Gap 1: Different data granularity across the product lifecycle

Figure 6.11 illustrates varying levels of granularity associated with different data sources and types, which aligns with the data availability issues and data sharing mechanisms discussed in section 6.1.4. Typically, data from supply chain operations is provided to the manufacturer by suppliers in aggregated form, such as X tons of steel delivered with Y kilos of CO2 emissions generated in the process. In contrast, the manufacturer possesses data at a more granular level, primarily at the production batch level, as outlined in section 6.1. Components typically move through various production and in-house logistics steps in groups, either as batches or smaller handling units. Consequently, DPP-related information is also available at the batch level. However, once the product is fully assembled and in use, data is

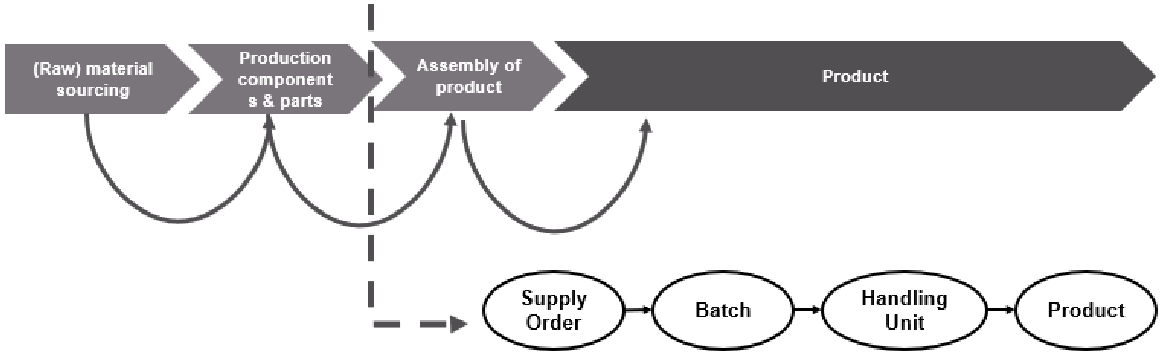


Figure 6.12: Visualisation of missing automated link between individual product and batches of a component based on the flow of materials through the manufacturing plant, own representation

generated at the individual product item level, including usage and repair information on the individual serial number.

The DPP necessitates information to be available at product level, whether it's aggregated from batch, model, or item level of that product. Information from operations earlier in the product's lifecycle, including the supply chain, production, and assembly processes, must be aggregated on product-level. For instance, if a supplier provides data on the amount of steel used, the manufacturer needs to aggregate how much of that steel is incorporated into the final product. Consequently, the target architecture must include capabilities to process and aggregate data from various sources and levels of detail to achieve this level of granularity.

Gap 2: Limited batch tracking capability

The second gap identified at the manufacturer considers the absence of batch tracking capabilities. The ability to track and trace components or batches within a manufacturing plant is not universally necessary and varies depending on the product being manufactured. In safety-critical domains products are subjected to stringent safety requirements, necessitating detailed information on the product's origins and production processes in the event of safety-related issues. In such cases, manufacturers are likely to have implemented internal batch or item tracking systems already and can leverage the data for DPPs in more detail. However, for less critical products, comprehensive tracking of components may not be cost-effective or feasible due to the complexity involved, which requires advanced digital competencies, including IoT, and the relevant hardware and software components to support in-house logistics processes.

Figure 6.12 illustrates how the absence of competencies to link a batch to the product can pose challenges for DPP data collection at the batch level, and consequently break the link to the supply chain from an information integration perspective. Currently, the mapping of batches to final products relies on manual efforts within the plant, where personnel use ERP and EWM data and timestamps to piece together the sequence of events related to production and assembly (as described in section 6.1.1). Consequently, comprehensive batch tracking through IoT devices like RFID is not implemented at the manufacturing plant in question. Instead, batches and deliveries are matched to final products through the reverse engineering of the chain of events using ERP and EWM data.

This results in the requirements to ensure information can be made available on batch level. Consequently, either the manual data mapping process needs automation or comprehensive batch tracking should be implemented using IIoT devices such as RFID technology at the manufacturing plant. The first likely results in requirements towards data warehousing to collect data from different source systems and map it.

Gap 3: Missing product data

Some data inputs are missing today according to the analysis done at the manufacturer. The information about which data is missing comes from internal interviews conducted with stakeholder responsible for sustainability reporting today. Missing data can result into several requirements depending on the data source. If the data comes from external partners in the value chain, suitable interfaces for data exchange need to be implemented. Opportunities such as data spaces and Blockchain (see section 4.2 could help with supplier collaboration in the mid to long term future. If the data input is not done properly inside the manufacturer, this likely results in requirements for process optimisation at the time of data creation. Both issues and their opportunities are beyond the scope of this thesis.

In addition to the three gaps identified in this section, table 6.2 shows the main DPP components according to CIRPASS [98] mapped to components equivalent at the manufacturer if existing. The main gap comes to no surprise as the DPP back-end system itself with all main requirements discussed in the previous section. Therefore, the remainder of this thesis focuses on the architecture for the DPP system and adjacent components that build up the digital competencies of the manufacturer in terms of data integration and batch traceability.

DPP component according to CIRPASS	Component equivalent at manufacturer	Gap yes or no?
Product identification ID	Serial number generated by ERP system	no
Product data carrier	printed bar-code or QR code on final product	no
Digital connector	the manufacturer internal capabilities exist, for DPP they have to be added to the back-end-system	partly
IT architecture	the manufacturer has internal IT infrastructure components including data warehousing and standard interfaces to legacy systems. However, the DPP system itself it not established, including all main features such as data transport, access control and data management.	yes

Table 6.2: DPP components according to CIRPASS mapped to the manufacturer's equivalent components

6.4 Target Architecture

As discussed in Chapter 5, research suggests that DT architectures and standards like the AAS hold potential to play a significant role for DPP systems. Nevertheless, the current state of digital capabilities in manufacturing, as outlined in Chapter 3, presents challenges, particularly in the context of advanced technologies such as Artificial Intelligence (AI) and industrial digital twins applications given the current data available from the established IoT pipeline and integration with core systems like MES. This digital capability gap in manufacturing is reflected in the as-is analysis of the manufacturer's current data and IT infrastructure, as discussed in Section 6.1. It implies that while DT applications are indeed already emerging gradually, fully-fledged industrial digital twins including bi-directional data exchange are unlikely to become widespread across the manufacturing sector soon.

The good news is that the first DPP requirements are not expected to become mandatory before 2026, and a lot of products are not actually included in the initial round of regulations by the European Commission (EC). This gives manufacturers time to prepare for the impending DPP requirements. However, once a manufacturer's products fall under the scope of the delegated acts associated with the DPP, the company has just two years to provide the required data. Therefore, it is crucial to ensure that the necessary infrastructure and capabilities are in place by that time to efficiently extract and process the relevant data for the entire product portfolio, minimising the need for manual efforts.

Considering the current status quo and the information requirements identified in this research, proactive and timely preparation is highly recommended. At present, it remains uncertain how closely a DPP system will align with DT architectures, as evidenced by the variety of proof of concepts and prototypes reviewed by CIRPASS (see section 5.3. Contemporary research on the one hand does indicate a trend toward developing DPP systems based on DT principles to enhance Life Cycle Analysis (LCA) capabilities- the manufacturing industry. On the other hand, prior research also suggests that the manufacturing industry, is traditionally slow to embrace change. This may lead to slower adoption of state of the art technologies, as opposed to forerunners in the automotive industry, and a tendency to meet DPP requirements with minimal effort [133]. Nonetheless, the benefits of digital twins for sustainability and quality cases alike in terms of transparency and abilities for root cause analysis show how DT implementations could serve both DPP requirements and optimisation and business continuity in the wider context at the same time. This thesis argues, that the answer in the short and mid term, including the first wide-

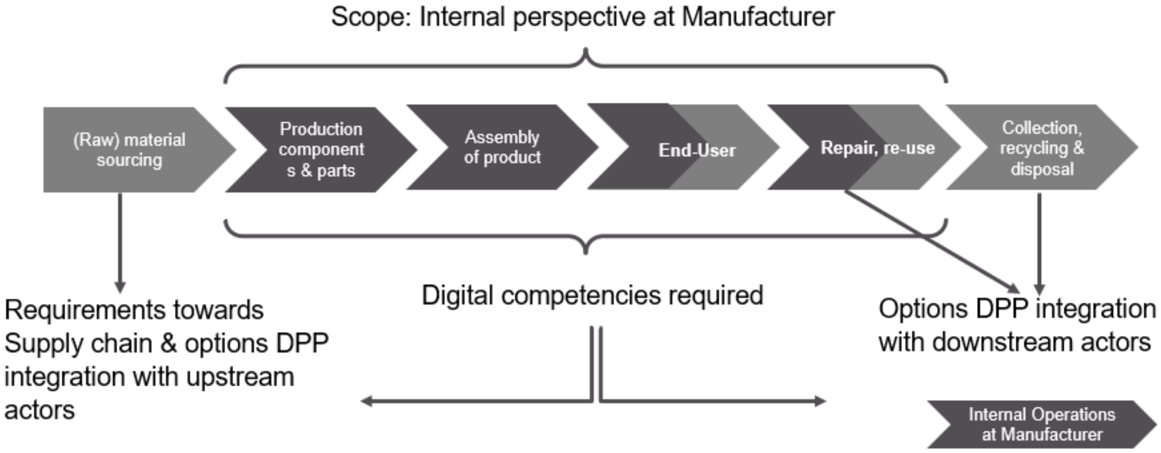


Figure 6.13: Scope and expected outcome for the target architecture, own representation

spread roll-out of DPPs lies somewhere in the middle between both spectra. In the long run, ambitions for DTs and DPPs might well harmonise naturally due to the overlap in required and offered competencies and benefits.

This research introduces a target architecture for the DPP system, aligning it with existing manufacturing infrastructure and digital capabilities. This architecture aims to meet the baseline DPP requirements, as defined by ongoing work in academia and industry, while maintaining adaptability for future developments in digital transformation (DT). Also, flexibility in operationalising the DPP system is considered so that third-party service providers like Circulor or Circularise can be considered in the future for additional benefits of supply chain transparency through material traceability. The decision regarding whether to directly adopt a DPP service from established providers is not within the scope of this research, given the still ongoing evolution of DPP requirements. Instead, the focus is on internal digital capabilities necessary for data collection and integration, which remain essential regardless of whether a third-party or OEM-owned system is eventually chosen. Therefore, the suggested target architecture can be seen as a balancing act between the current state (refer to Section 4) and future aspirations (refer to Section 3). To ensure alignment with the thesis objectives, Figure 6.13 defines the scope and expected outcomes of the target architecture within the broader product lifecycle context. It primarily focuses on the OEM's internal digital capabilities related to data extraction from production and assembly processes and supporting systems. The central question it addresses is: 'What are the digital capabilities required for the DPP at the manufacturer?' Furthermore, the target architecture highlights two potential avenues for future research: (1) gathering and mapping information from the supply chain and (2) integrating

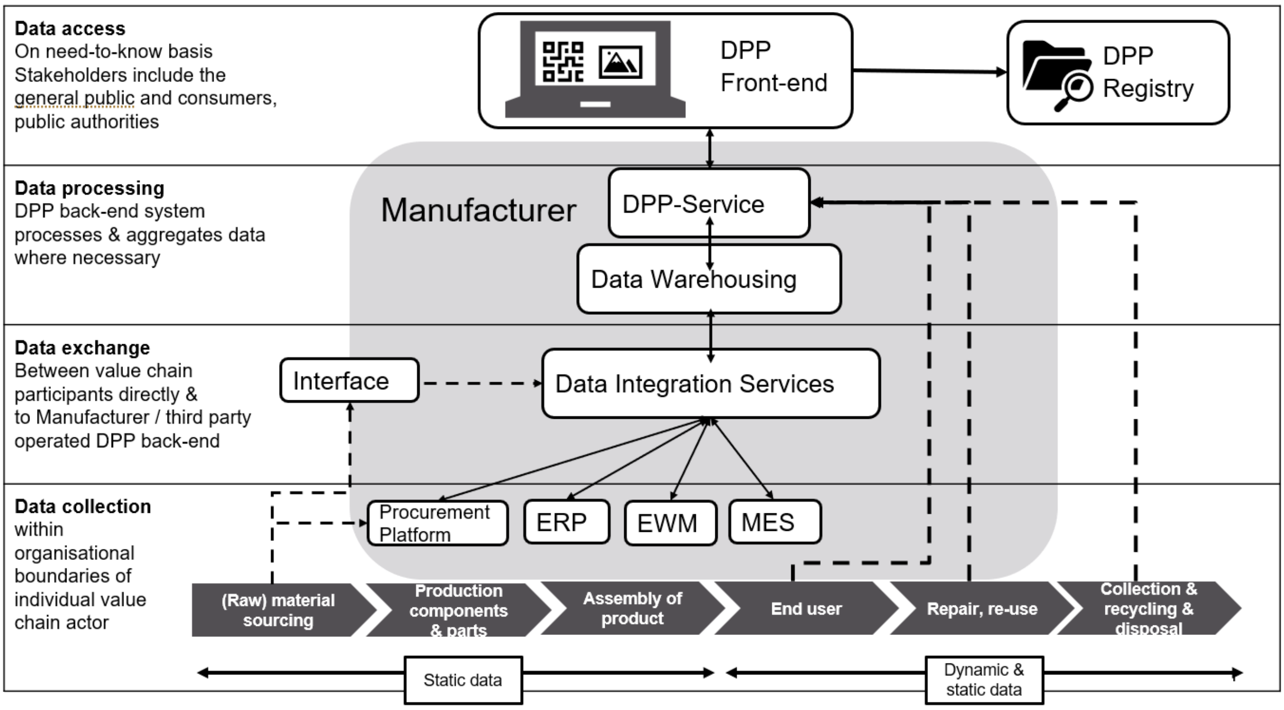


Figure 6.14: High level target architecture for a DPP system and necessary capabilities at the manufacturer , own representation based on [1], [2]

data from third parties involved in later stages of the product lifecycle (e.g., external repair centres) into the DPP system. Figure 6.14 outlines the high-level target architecture for the Manufacturer, considering the proposed battery passport [2]. It consists of four layers: data collection, data exchange, data processing, and data access. The data collection layer gathers information from various sources in the product's lifecycle, especially from early stages suppliers and stakeholders. Data exchange occurs through direct interfaces or the DPP system. The data processing layer encompasses the main DPP back-end, responsible for mapping, processing, and aggregating data from diverse sources. The data access layer includes a DPP repository, necessary for EC compliance. The focus is on the Manufacturer's DPP, highlighted in grey in Figure 6.14, comprising the back-end system and its connection to the front-end. External interactions with the system are modeled through three stakeholder types: Authorised users and unauthorised users accessing the DPP via the front-end. Stakeholders in the earlier stages of the product lifecycle provide data directly to the back-end, resembling the current scenario where suppliers transmit data to OEMs, often through systems procurement platforms.

The following design principles are proposed based on the analysed requirements and the interactions between the DPP system and other systems and stakeholders;

- Standardised, Rest-API based interfaces with JSON payload for interfaces between DPP front-end and back-end. Interfaces between the different back-end components and adjacent systems can be based on current data warehousing and data integration capabilities as well as vendor specific aspects that may influence the choice of service provider for integration components.

- Use of standardised data models based on the AAS standard to ensure semantic interoperability and compatibility with services and platforms potentially coming into place in the future
- Data processing and aggregation functionalities implemented at data warehouse level with standard interfaces to source systems to ensure compatibility with legacy systems
- Microservice-based design for data queries and processing, particularly for dynamic data input, to ensure scalability of the system and compatibility with existing IIoT pipeline.
- Event-driven design of back-end components to ensure data management and data integrity as well scalability
- Role based or hybrid access control and authorisation to DPP front-end on need to know basis
- Adoption of existing system for serial number generation based on ERP system currently used for unique identifier generation as basis for data carrier
- Automated link between product and batches either via automated mapping of ERP and EWM data on data warehouse level, or via life batch tracking system using IIoT as next level solution

Figure 6.15 specifies the envisioned capabilities for the manufacturer. At the heart of the proposed architecture lies the standardised representation of products through a standardised data model. Based on the discussed standards in context of DTs for DPP systems, this thesis proposes the AAS standard and meta model as baseline for the realisation of the data model (see section 4.3, 5.4). This way, compatibility with I4.0 assets and interoperability with other DPP initiatives can be ensured. The architecture recommends data warehousing for data integration from legacy systems due to its structure and alignment with standardised data models. Service components act as intermediaries connecting the data warehouse, source systems, and the DPP service. A Microservices-based architecture is proposed for the DPP front-end service, offering flexibility and scalability. Event-driven design is suggested for both the layers above and below the data warehouse, providing benefits like independent scalability, loose coupling, and data integrity. The combination of

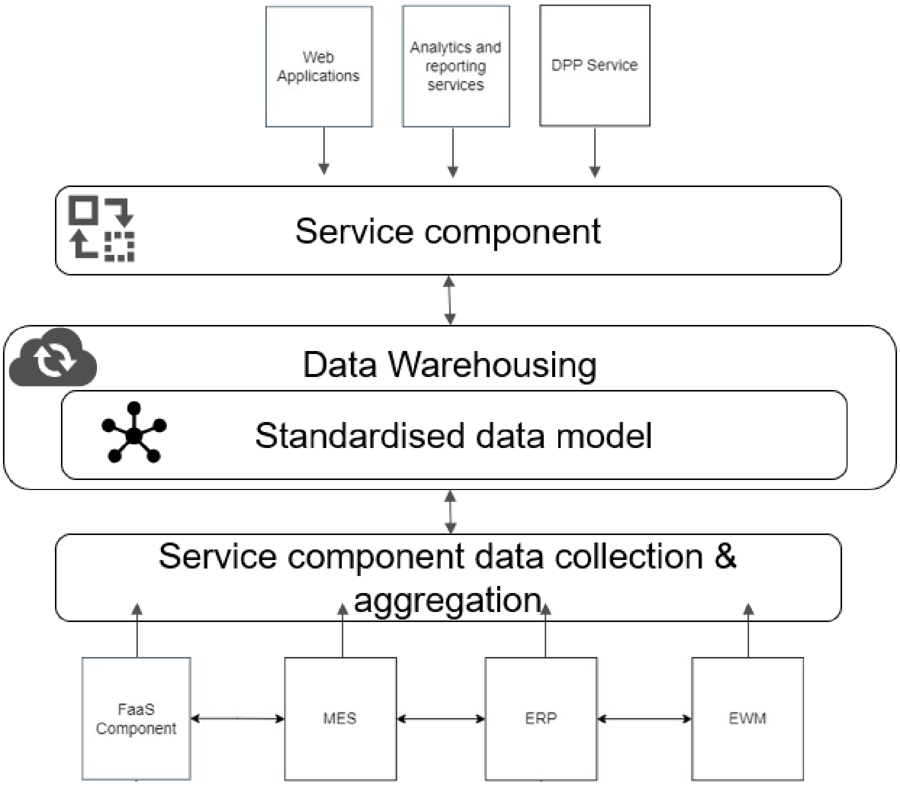


Figure 6.15: Target architecture including standardised data model for data integration and aggregation on product level

microservices and event driven design offers several advantages, including independent scalability of microservices based on demand and loose coupling between services through event-driven communication, facilitating individual service changes without impacting the entire system. In addition, events can help with data integrity, because the concept of notification is required which can function as data logging, essentially becoming a sort of version Control of the DPP data. Additionally, microservices align with DT implementation, making it modular and scalable. Existing DPP implementations using microservices are well-defined, as evidenced by the CIRPASS benchmark [123].
The choice of data warehousing for data integration in the proposed architecture does not contradict a possible decentralised approach to the DPP ecosystem. While data warehousing centralises data storage and management, it does so in a way that complements the broader decentralised architecture. Data warehousing offers a centralised repository for structured data (as opposed to data lakes), ensuring data consistency, security, and efficient querying. However, it does not imply centralisation of control or processing. In the context of the DPP, the decentralisation happens in the form of the proposed microservices and event-driven design. These

service components operate independently, handling specific tasks and processing data asynchronously. Through this proposed set-up, data warehousing serves as a reliable and organised data store, allowing the service components to access and process data as needed.

Figure 6.15 depicts how this architecture fits into the manufacturer's legacy infrastructure today, emphasising the importance of interfaces between data sources, the data warehouse, and service components. Specific interfaces of the data warehouse with internal data sources such as ERP and EWM system are system-dependent and not detailed in this section.

To answer the question of **How to address and develop the digital capabilities necessary for the digital product passport in the manufacturing domain?**, critical digital capabilities include architectural choices and technological strategies. The examination of a manufacturer in Europe operating under a high-mix, low-volume production model revealed two primary gaps. Firstly, the challenge of limited batch tracking within production and assembly processes, exacerbated by data structure issues, blurs the link between supply chain and product information. Secondly, the need for robust mechanisms to handle varying data granularity levels is intensified through the first gap. Resolving these gaps is crucial for the successful implementation of the DPP because they are at the hearth to the manufacturing processes responsible for generating a substantial portion of the relevant product data. This can be achieved through selected infrastructure components for data collection, processing, and integration. Standardised data models, such as the AAS standard, serve as the foundation for the DPP's data structure in this context, and can be supported through data warehousing. Leveraging a microservices-based architecture, combined with event-driven design principles, enhances scalability, flexibility, and decentralisation, facilitating real-time responsiveness and accommodating diverse supply chain scenarios. Overall, these capabilities align with circularity and sustainability objectives, facilitating efficient data exchange and promoting the transition toward a circular economy.

The following section demonstrates the proposed architecture through a proof of concept implementation.

Chapter 7

Proof of Concept

This chapter specifies the design, implementation and validation of the proof of concept and is divided into the respective sections for that purpose.

7.1 Reduced architecture design

The primary goal of the PoC is to showcase the proposed architecture's ability to integrate data, specifically addressing the complexities analysed in chapter 6. This demonstration should serve as motivation for manufacturers to tackle the identified gaps by outlining a path for manufacturers to streamline their data structures to meet the upcoming requirements of the DPP. The PoC features design core components implemented as Python programs. The data sources and the data warehouse are represented in separate SQL databases. While the PoC does not create a digital product twin, it illustrates how the precursor, namely the digital shadow (as described in Section 4.3), can be made accessible to stakeholders using standard data formats, interfaces, and data processing. Figure 7.1 presents the reduced architecture design for the PoC with the main components of python programs representing the service components and SQL databases representing both complex data sources and data warehousing capabilities, supported by complex and simplified data models respectively. Based on the reduced architecture design in figure 7.1, the following program sequence is defined:

1. User enters serial number into front-end
2. Front-end sends request with serial number via API
3. Python programs processes request:
    (a) Contact Database
    (b) Query relevant information

   (c) Process database response and send to front-end via API

4. Front-end visualises the information

7.2 Functionality and information requirements

The PoC demonstrates how a DPP can be implemented based on legacy infrastructure of manufacturers today (see section 6.1.3). A baseline of DPP information requirements can be identified via the discussion on information granularity. Given the proposed granularity levels in section 6.2 of chapter 6, the PoC needs to reflect a DPP on product item level (i.e. product with serial number 12345) and subsequent information aggregated on batch level (i.e. batch 1234 delivered by supply X) or individual component level (i.e. component with ID 1234 from supply X), if available. The DPP also requires information to be aggregated on product level based on information on product model level (e.g. material composition, the product contains 1 KG steel from 6 components based on bill of material specifications). Finally, the PoC also needs to distinguish between product model and product instance to ensure the DPP shows information on instance level where possible. The functionalities produced by the PoC are listed in table 7.1:

PoC functionality to address DPP information requirements
Display basic product information
Display components of the product
Display component properties (e.g. material information)
Display component properties (e.g. material weights) aggregated on product level
Display information about batches of components and basic supply chain information such as supplier information and origin of materials

Table 7.1: PoC functionality

7.3 Implementation

Given the design of the PoC as presented in 7.1, this section of the thesis briefly describes the main components and their implementation.

Digital representation of the product

This thesis supports the idea of digitally representing products on the basis of the AAS standard. The AAS meta model is available in different formats and sufficiently described under [106], [134], [135]. The Asset element of the AAS can capture information about the product itself, while submodels define the structure and behavior of the asset. Submodels in the AAS can be utilized to specify the different aspects of

the product, such as its physical characteristics, functional capabilities, and lifecycle information.
The PoC utilizes a common SQL database to demonstrate the benefits of standardized representation of products. To translate a simplified view of the AAS into SQL, the main structure of the metamodel needs to be mapped to common SQL schema. For the DPP, each AAS entity, such as assset, submodel, or property, can be represented as a table, and their attributes can be mapped to columns. Relationships between entities can be established using foreign keys. For the representation of products for instance, the asset element can be used, while components would be represented by submodels. Figure 7.2 presents the reduced data model used for the implementation of the PoC in SQL Server. The main aspects of the DPP information are covered through the four components of product, component, batch and supplier because the information that can be associated with these objects in the source systems corresponds with the information needs identified for the DPP (see section 5.1 and 6.9). The reduced data model is viewed as representative for the DPP information requirements for this thesis because it reflects both the core information needed for the DPP and the different levels of granularity in the data coming from the different dimensions of product, component and batch.

Service component for digital representation of product

The core value proposition of the PoC is the demonstration of ETL processes based on the replicated complexity of the data infrastructure at the manufacturing plant, specifically concerning the flow of materials supported by ERP, EWM and MES. The complete database diagram can be found in figure C.2 in appendix C.3. The database reflects the complex relationship between batches, components and products. In essence, the component is not individualised in the relevant core systems, therefore information is either available on batch level or on product level with the handling unit linking the two (see chapter 6). To capture the typical hierarchy within bill of materials structures, the sql database has a self-referencing relationship implemented. The implemented ETL programme in python utilises complex and recursive SQL queries to capture information about components on an individual level based on batch information and product serialisation. The ETL programme utilizes programmed views to get to the component and material information using a combination of recursive queries to fetch the bill of materials hierarchy and queries to fetch the batch information for product serial numbers via the handling unit. The ETl programme queries data from the complex database, aggregates information in individual component and product level based on the defined digital representation of the product, and inputs it into the simplified database representing the data warehousing component of the target architecture. This showcases how the core systems involved in the flow of materials at the manufacturing plant need to be integrated in order to provide the necessary information for the DPP. The complete code including all defined SQL queries and ETL processes is documented on GitHub and linked in appendix C.1.

Service component for DPP service

To implement the DPP service as part of the PoC, two python programmes are provided. The first establishes the front-end and processes the user input as well as the data that is returned from the second programme, which demonstrates the service component responsible for fetching data from the data warehouse component defined in the target architecture. The second programme queries the data from the sql database defined by the simplified product representation. This demonstrates the benefits of standardised data representation. An example output from the PoC demo of the DPP service is presented in figure 7.3. The complete service is shown in appendix C.4 By displaying essential information on product level in the provided DPP mock-up, the PoC demonstrates that a standardized representation of the product and its components contributes to the implementation of DPP requirements in terms of collecting and integrating the relevant data from legacy systems.

DTDL and Azure digital twins

To demonstrate the applicability of the target architecture, a part of the PoC is also tested in the Azure digital twins environment, showcasing the potential of standardised digital representations of products in the wider context of digital twin implementations.

The DTDL serves as a standardized modeling language for defining the characteristics and behaviors of digital twins in the Azure world. DTDL can facilitates the creation of standardized digital twin models [92], [117]. The DTDL was chosen based on the existing and current developments and efforts visible for this DT modeling language, including specifically the developments in the context of the AAS standard [107], [111], [134]. DTDL models are modelled in json-like format. Four DTDL models have been designed for this PoC, respectively for product, component, batch and supplier and based on the entities and relationships represented in the SQL database for the data warehousing component.
An interface in DTDL is used to describe the product, with properties like name, serial number, and relationships such as ”hasComponents.” Interfaces are key to cre-

ating a consistent framework for representing and communicating information about entities like products within a digital twin ecosystem using DTDL. The ”hasComponents” relationship establishes a connection with another interface, specifically, which can be used to model the relationship between product and component for instance [136]–[138]. Figure 7.4 presents the graph of the digital twin models based on the four DTDL models designed for this purpose. The figure is taken from the digital twin explorer and demonstrates that the specified DTDL models are compatible with the Azure digital twin environment.

In addition, sample data was uploaded to the explorer to generate instances of the DTDL models, i.e. digital twins. Figure 7.5 presents the final graph of the digital twin created; a product with three components which are linked to batches and the batches are linked to supplier. One of the components is directly associated with the supplier, which represents the example when components are directly built into products (for example batteries).

By testing the core component of the implemented PoC (the standardised digital representation of the product and components) in the Azure digital twins environment, the capability to create and manage and make accessible the digital shadows of products can be demonstrated. The PoC is a minimalistic implementation of architecture components that could be configured based on Microsoft Azure. By implementing it both standalone via python and translating core aspects into DTDLs, the PoC demonstrates compatibility with possible future developments in the context of DT implementations. The JSON files and sample data uploaded to Azure digital twins are like the rest of the PoC documented on Github under the link provided in appendix C.1.

7.4 Validation

This section outlines the validation process for the proposed target architecture, as described in Section 1.3. The validation methodology combines a single-case experiment with expert opinion. This approach assesses the target architecture vis-a-vis the proof of concept implementation (single-case experiment) and obtaining feedback from selected experts. The experts evaluate the proof of concept's ability to fulfil the desired objectives, including DPP information and system requirements. Additionally, they assess the proof of concept's applicability and potential for deployment in the manufacturer's production environment given the status quo and legacy infrastructure. This section covers the validation model, including the plan and survey design, followed by the discussion of the results.

Validation model

The validation model consists of a model of the artifact and a model of the problem context. Both are specified in their relation to the artifact and real problem context;

- **Artifact:** the modelled target architecture for the DPP system
- **Model of the artifact:** the proof of concept based on the reduced architecture model
- **Problem context:** Make product data available via DPP system architecture
- **Model of the problem context:** Make data about the product based on component and materials information available via proof of concept architecture

The artifact model interacts with the problem context by (1) focusing on a specific subset of DPP-required information and (2) making this information accessible through a subset of essential infrastructure components for data collection, processing, and transmission.

The validation plan, depicted in Figure 7.6 as an ArchiMate model, involves the author of the thesis conducting a validation round with experts. This round comprises three stages: Firstly, a presentation of the proposed target architecture for the manufacturer's DPP; Secondly, a presentation of the implemented proof of concept; and thirdly, conducting brief interviews and survey with the experts to get their input on meeting their goals and objectives. **Expert panel**: The experts involved in the validation of the PoC are listed in table 7.2. While the objective of the PoC is to demonstrate how a DPP could be implemented at manufacturing companies, this thesis has identified relevant overlaps between the needs and objectives of sustainability, quality and product lifecycle management. Experts for validation were selected based on their roles and backgrounds at the manufacturer in question, offering diverse perspectives on similar requirements. Therefore, the validation round has been performed with experts from machine connectivity, quality, in-house logistics and sustainability.

The validation focused on the key features of the PoC in the context of the DPP information requirements and the DPP system requirements. Specifically, the capability to extract, map and aggregate information about the product was validated with the experts. In general, the experts can be categorised into two groups; (1) Direct users or beneficiaries of the the DPP systems capabilities with similar needs for digital capabilities as the DPP in their work environments. (2) Direct users or beneficiaries of available DPP information itself with a need for easy access to relevant product information for different purposes. Table 7.3 presents the complete questionnaire mapped to the stakeholder goals that are validated against the target architecture vis-a-vis the proof of concept. The complete survey can be found in appendix C.5.

Validation results

This section presents the results of the validation, starting with the survey results and followed by presentations of individual expert feedback from the validation round.

Survey

The survey was designed with answers using a typical likert scale with five possible answers.

Question one validates the proposed architecture in terms of its capabilities to address current issues for retrieving information from legacy systems on product level. The results show that the capability of the architecture to integrate, collect and process data was perceived well, with four out of seven experts rating very well.

Question two validates the capabilities of the proposed architecture to integrate data from different systems, including aggregation capabilities for instance. This question scored moderate to well, indicating that the demonstrated interfaces need further specifications to operationalise the target architecture for the manufacturers specific systems.

Question three validates the architecture in its capability to support flexible and scalable information services. This question scored well, with the majority of experts rating for very well. This indicates that the components such as the standardised data model and data warehousing components are perceived as useful by the experts.

Question four validates if information requirements for the DPP are met by the target architecture. Question four collects feedback as to the contribution of the architecture to support the necessary levels of granularity for the DPP. With five out of seven rating this well, the answers indicate that the proposed level of granularity for the manufacturer matches the expectations of the experts for the DPP with limitations but might need additional attention for datapoints of the DPP that have not been further implemented into the PoC.

Finally, question five validates the potential of the target architecture to generate future insights and create competitive advantages beyond the initial implementation for the DPP. This question asks for feedback as to whether the proposed architecture holds potential to contribute to further capabilities such as for instance root cause analysis for quality issues and whether it alights with the manufacturers ambitions for digital twins. This question scores well to very well , indicating that stakeholders see the proposed architecture as suitable to generate benefits beyond the DPP use case.

Opinions

Machine Connectivity expert

The machine connectivity expert gave a dedicated opinion on elements of the target architecture connecting to the IoT pipeline. Based on the current architecture, the expert expressed the chosen microservices design and event-based data management as appropriate because of the compatibility with components such as the IoT platform and FaaS components processing IoT and MES data. Also, future suitability of the architecture to provide the baseline for the management of digital twins in the context of the AAS was expressed with regards to the DTDL component to create the model for the digital shadow instances. The expert raised questions regarding the compatibility of the data warehousing component with the existing solutions, highlighting that machine data is available from the SQL database in place and could be integrated with the proposed architecture from there also.

Expert for value creation and reporting

The expert for value creation and reporting gave dedicated feedback on those components of the architecture that collect, process and provide data from different source systems. One of the key challenges for comprehensive reporting and analytics services at the manufacturer today are individual and manual data flows, often aggregating similar types of information. Both the data warehouse and interfacing components where pointed out as especially useful for standardising reporting initiatives across departments.

Expert plant sustainability

The expert on plant sustainability was specifically interested in the concrete focus of the PoC and target architecture on the automation of the data mapping for material flow, requesting more information on concrete recommendations for the plants strategy. The expert also commented on the intrinsic complexities of products and components, noting that in the context of DPPs a product may well be a component from the manufacturers perspective and that the target architecture would benefit from differentiating terminologies as well as outlining the cases where DPPs may well be delivered in addition to the physical part, necessitating the question of how to integrate different DPPs. with one another.

Expert Quality

The expert on quality commented on the ability of the proposed architecture to cover quality use cases that require similar capabilities to those of the DPP. Specifically, the expert acknowledged that use cases such as market reclamation's and reverse engineering of the material flow may well be covered by the proposed digital capabilities. However, the expert also noted that more detailed information such as time periods and quantity ranges would be necessary in addition to information such as serial number range and batch number to indicate which products and batches are impacted by a quality incident. This information would especially be relevant if the manufacturer needs to notify suppliers, with information such as time frames likely accelerating root cause analysis.

Expert for sustainability and digital transformation

The expert for sustainability and digital transformation gave feedback on the proposed levels of granularity and the functionalities for mapping data from different levels of granularity. While the main source systems are agreed upon by the expert, it was pointed out that the environmental management system could in the future be both a data source for the DPP but vice versa the EMS could also benefit from the capabilities provided by the DPP system and the integration should be clarified based on system scope of the EMS. In the context of sustainability reporting, the expert also commented that the question regarding how to get data from the supply chain is only answered partially by the specification of internally needed capabilities.

Expert logistics

The expert for logistic processes at the manufacturing plant gave feedback especially with regards to the data processing and aggregation functionalities proposed in the architecture. While agreeing with the necessity to automate the link between individual product and batch. The expert also pointed out that complete batch tracking on individual batch or item level is likely not worth the resources due to the insubstantial amounts of requests for reverse-engineering of the event-chain with regards to the flow of materials. The expert however also commented on the fact that manual data extraction is not ideal and that the proposed reference architecture would be an important step into the right direction, especially by leveraging data warehousing and data integration capabilities that already exist.

Expert sustainability and data reporting

The expert responsible for product data enhancement in the context of sustainability gave dedicated feedback on the chosen levels of information granularity for the DPP. The expert agrees that an individual item level for all product components would need an inappropriate amount of resources to implement. The batch level granularity proposed to obtain more specific information from the supply chain is regarded as appropriate by the expert given a minimum effort required on the data processing side, therefore also not recommending a full implementation of batch tracking to meet this level of granularity. The expert further stated that a DPP could also bring competitive advantage if information if shared about the product in such a way that it promotes the product as opposed to competition. The expert gave the example of information related to durability of the product and said the final DPP should incorporate this in the design and digital competencies required. The expert also commented on the choice of data warehousing as opposed to data lake infrastructures, agreeing that the structured aspect of data warehouses is beneficial for the digital representation of the product.

Overall, the proposed target architecture was well received by the expert group.They highlighted the need for standardising reporting and underlined the benefits in the context of their own respective domains. The experts also noted opportunities for integration with other adjacent systems including environmental management systems.

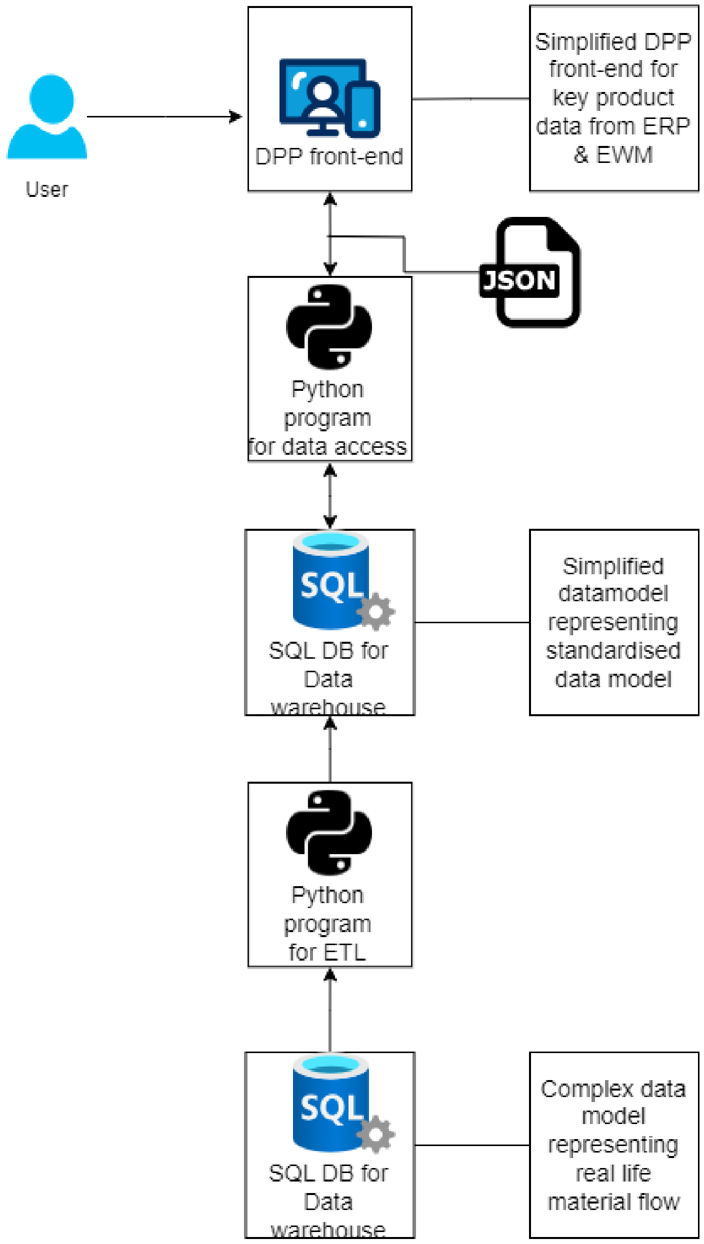


Figure 7.1: Reduced architecture design for the proof of concept, own representation

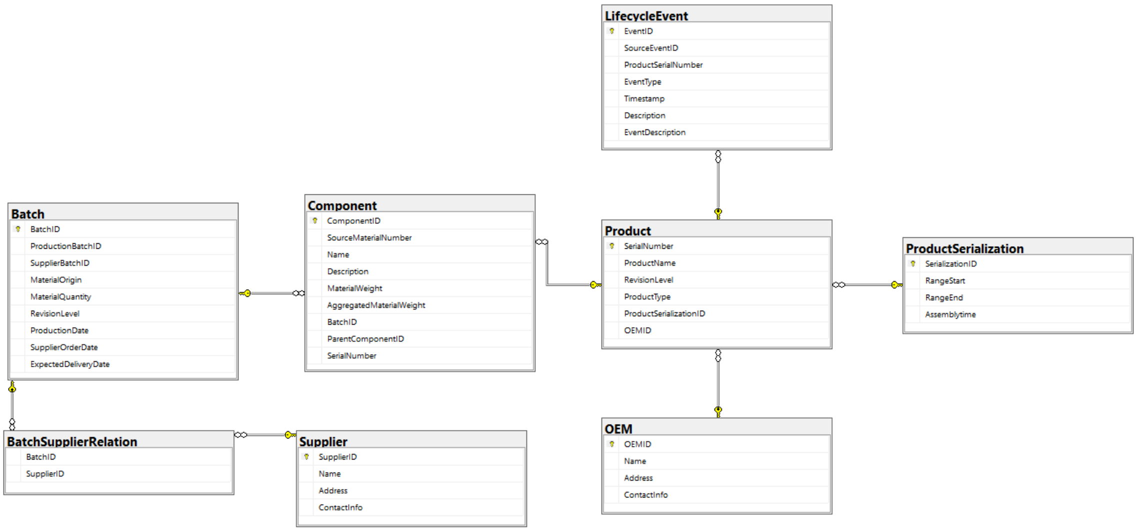
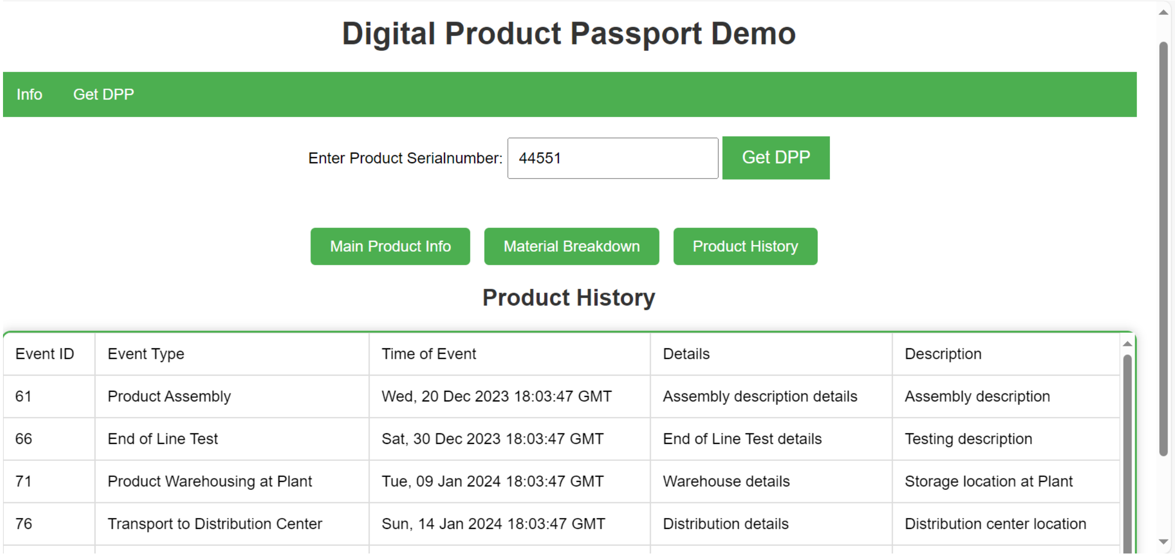


Figure 7.2: SQL schema of the PoC target database representing the data warehouse of the target architecture, representation of the database diagram from MS SQL Server



Digital Product Passport Demo

Enter Product Serialnumber: 44551

Product History

Event ID	Event Type	Time of Event	Details	Description
61	Product Assembly	Wed, 20 Dec 2023 18:03:47 GMT	Assembly description details	Assembly description
66	End of Line Test	Sat, 30 Dec 2023 18:03:47 GMT	End of Line Test details	Testing description
71	Product Warehousing at Plant	Tue, 09 Jan 2024 18:03:47 GMT	Warehouse details	Storage location at Plant
76	Transport to Distribution Center	Sun, 14 Jan 2024 18:03:47 GMT	Distribution details	Distribution center location

Figure 7.3: Screenshot of the implemented DPP mock-up with information displayed about the product event history

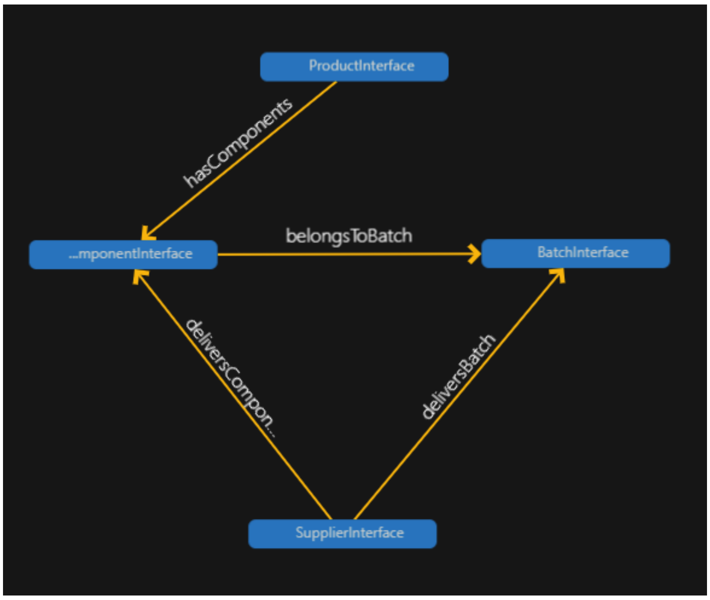


Figure 7.4: Model graph in Azure digital twin explorer

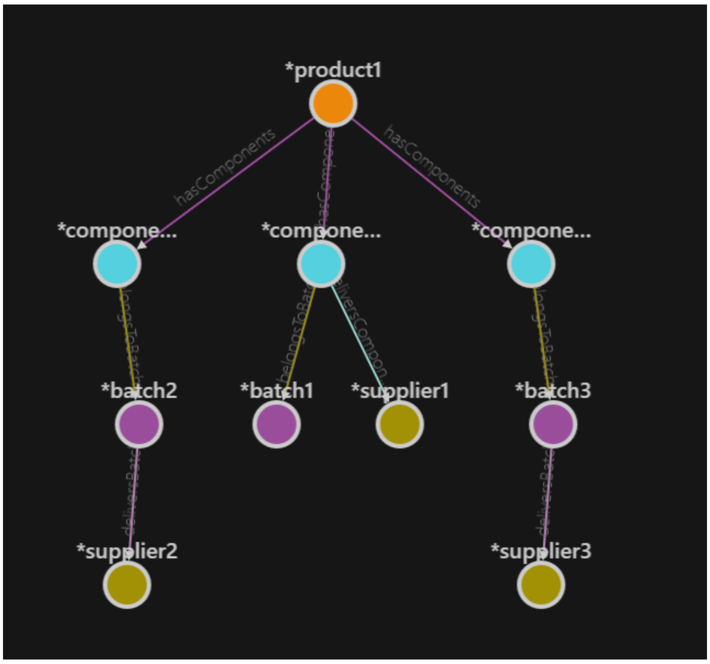


Figure 7.5: Digital twin graph in Azure digital twin explorer showing an instance of a product

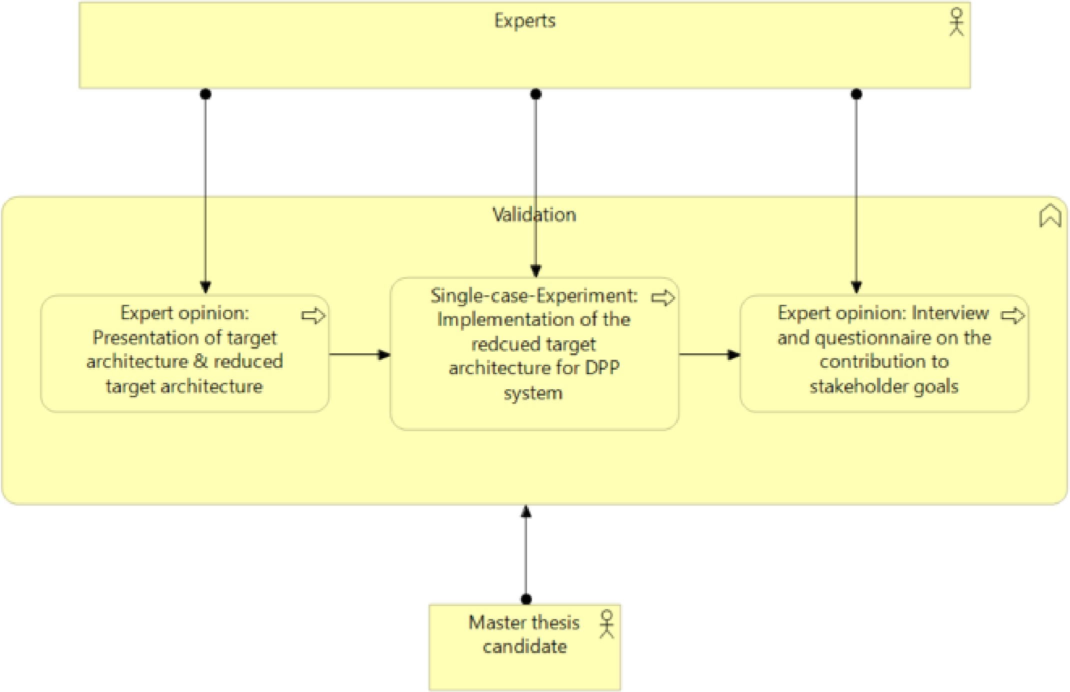


Figure 7.6: Validation plan presented in archimate model, own representation

Expert	Description of role
Expert Machine connectivity	Responsible for developing and managing the machine connectivity pipeline and connected data integration at the manufacturer
Expert value creation and reporting	Responsible for reporting and value creation at the manufacturing plant, including management of data integration between source systems and analytics dashboards
Expert Plant Sustainability	Responsible for managing all aspects of the manufacturing plant sustainability
Expert digital transformation and sustainability	Responsible for digital projects for sustainability at the manufacturing plant, including CO2 footprint calculations and roll-out of Environmental management system
Expert Logistics	Responsible for plant logistics including in-house logistics to assembly lines
Expert Quality control	Responsible for quality control at the manufacturing plant including incoming quality control processes
Expert Sustainability data and reporting	Responsible for product data enhancement for sustainability and circularity

Table 7.2: Expert panel for validation

Question number	Goal to validate	Question
1	Capability of integrating, collecting, and processing data from existing infrastructure	How well could the proposed IT architecture address the current challenges of retrieving product information?
2	Capability of integrating data from different sources in a standardised, interoperable way	How effective do you rate the ability of the proposed IT architecture to merge and aggregate data from different sources?
3	Capability to provide services such as the DPP with product data in a simple, fast and flexible way	How well could you imagine that the proposed IT architecture would enable simple and flexible access to product information?
4	Provision of the key information for the DPP, including aggregated information in appropriate granularity	How well does the proposed data integration and processing cover the information requirements for products in terms of the level of detail?
5	Capability to facilitate future objectives for digital transformation in manufacturing, such as digital twin implementation	How well would the proposed IT architecture contribute to achieving future goals in production?

Table 7.3: Questionnaire with 5 questions designed to validate the target architecture vis-a-vis the proof of concept demonstration with experts at the manufacturing plant

Chapter 8

Conclusions and recommendations

This thesis aims to provide a comprehensive understanding of manufacturing and their supply chains in the context of digital transformation. It offers insights into the challenges and opportunities presented by digital technologies for achieving sustainability objectives, with a particular focus on the concept of the digital product passport. The thesis not only explores the theoretical aspects but also delves into practical implications for manufacturers, while also paving the way for future research on the synergies between digital transformation and sustainability mechanisms within supply chains.

Chapter 2 sets the stage by defining the research problem and mapping the intricate landscape faced by resource-intensive manufacturing industries today. It provides an overview of current issues and the political dynamics influencing organisations. In Chapter 3, the concept of digital transformation for manufacturers and their supply chains is explored, framed within the paradigms of Industry 4.0 and 5.0. It examines the implications of related technologies, emphasising the concept of Supply Chain 4.0. and information transparency This chapter primarily focuses on the theoretical implications of digital transformation within manufacturing and their supply chains, discussing the key drivers that empower manufacturers to adopt more sustainable practices. Chapter 4 evaluates the current state of manufacturers using the Industry 4.0 maturity index and dedicates a section to the discussion of data sharing and the maturity of digital technologies within this context. This chapter provides he justification for the research focus on digital capabilities, showcasing the gaps between research and practice today and highlighting the significance of streamlining data infrastructures o achieve more transparent and sustainable manufacturing and supply chain operations. The chapter provides insights into key trends like Digital twins, their relationship to sustainability incentives and relevant standards.

Building on the insights from Chapter 4, Chapter 5 discusses the concept of digital product passports for the circular economy in greater detail. The chapter offers an in-depth examination of the information and IT infrastructure requirements, drawing from contemporary literature and existing prototypes. Up to this point, the thesis collectively identifies key trends, technological enablers, and major challenges associated with digital transformation and the development of digital product passports to achieve sustainability goals in manufacturing.

Chapter 6 presents a target architecture for the digital capabilities necessary for the digital product passport DPP. It commences with a thorough analysis of the existing infrastructure and digital capabilities at a manufacturing company in Europe using the findings as direct feedback for the digital capabilities needed. Requirements for the target architecture, tailored to meet the information requirements of the DPP, are outlined based on the identified capabilities and gaps at the manufacturer, as well as the previous chapter's requirements analysis.

The core components of the designed target architecture are implemented and validated through a proof of concept, detailed in Chapter 7. This proof of concept serves as a demonstration of the applicability of the defined target architecture by implementing the essential functionalities involved for data integration necessary for the DPP to align with the identified information requirements.

This final chapter of the thesis provides a discussion of key findings from both the theoretical part of the thesis and the lessons learned during concept and implementation phases.

8.1 Discussion and key findings

Supply chains within resource-intensive manufacturing industries are inherently intricate due to the effects of globalisation. This complexity arises from their geographical dispersion and decentralised structure, involving a multitude of stakeholders. Effective collaboration and communication become crucial for ensuring operational success. The alarming discrepancy between scope 3 and scope 1 and 2 emissions highlights the devastating impact of resource-intensive manufacturing on our planet when left unaddressed, with approximately 70 to 90 percent of emissions originating from supply chain operations.

In response to knowledge question 1, **What are the challenges and opportunities in achieving sustainability in manufacturing supply chains?**, it becomes clear that the complexity inherent to manufacturing and supply chains poses a significant challenge for manufacturers in measuring and enhancing their sustainability efforts. The level of sustainability achieved is intrinsically linked to the quality of the information utilised [29]. This underscores the importance of information transparency as a pivotal enabler for sustainability, facilitating effective communication and collaboration within supply chains and, consequently, elevating sustainability standards. The ability to effectively manage information across dispersed and complex supply chain operations and among diverse stakeholders lays the foundation for sustainability. In the contemporary landscape, and even more so in the future, manufacturers must navigate a political environment that exerts increasing pressure on transparency and the dissemination of sustainability-related information, as exemplified by regulation like the Supply Chain Due Diligence Act. However, the complexity of supply chains can also impede the utilisation of information for sustainability purposes, such as conducting life cycle analyses and assessing carbon footprints, by creating barriers to communication and information sharing. Consequently, manufacturing supply chains often grapple with information gaps among stakeholders and systems, hindering communication, collaboration, and, consequently, sustainability initiatives. In summary, while the complexity of these supply chains poses challenges to improving sustainability, enhanced transparency offers an opportunity to manage this complexity effectively and transition towards sustainability.

Digital transformation holds the promise of significantly improving transparency and bridging information gaps within manufacturing processes and supply chain operations. This potential is realised through the adoption of key technologies associated with Industry 4.0 and 5.0, including digital twins, data ecosystems, (Industrial) Internet of Things ((I)IoT), Big Data, artificial intelligence (AI), and cloud infrastructures. In response to Knowledge Question 2, **KQ 2: What are the implications of digital transformation in manufacturing supply chains and how can they promote sustainability?**, we can explore this within the frameworks of Industry 4.0 and 5.0 strategies. Industry 4.0 provides a practical maturity index that allows organisations to map their unique transformation journeys, providing insights into the essential capabilities required to achieve comprehensive flexibility and agility.

One of the crucial enablers for both economic efficiency and sustainability in digital transformation is the integration of information systems that encompass heterogeneous data sources. Within the context of Supply Chain 4.0, Industry 4.0 technologies play a pivotal role in streamlining supply chain processes, activities, and relationships by creating the much-needed information transparency. It's often the synergy between key technologies that fosters enhanced information transparency, facilitating more effective coordination of inventory, logistics, and production activities for instance. Industry 5.0 introduces a fresh perspective to digital transformation, emphasising sustainability and the human-centred application of technology. The principles of Supply Chain 4.0 can be extended to the realm of sustainable supply chains, where transparency serves as a powerful accelerator for achieving environmentally responsible manufacturing and supply chain operations. In essence, digital transformation, particularly within the frameworks of Industry 4.0 and 5.0, holds great potential to not only improve efficiency but also promote sustainability by fostering transparency and enabling more effective coordination of supply chain activities.

While the theoretical implications of digital transformation are considerable, practical implications for manufacturing supply chains lag due to the limited maturity of some Industry 4.0/5.0 technologies today and the industry's shortcomings in comprehensively addressing interoperability issues hindering information system integration. Manufacturers show a fragmented adoption and integration of key technologies, with minimal standardisation in communication and data exchange. IDS-based infrastructures and Blockchain-based platforms emerge as solutions that address the topic of communication and sovereign data exchange across company borders. However, technologies like Blockchain remain controversial, and emerging platforms and data ecosystems such as those based on IDS infrastructures have yet to encourage wider industry adoption. In summary, many manufacturers continue to rely on traditional methods of communication and still pick up the phone or send emails to their suppliers. However, IDS and similar initiatives address inter-organisational interoperability and get increased attention both from the public and the corporate world. Digital twin technologies and emerging standards, such as the asset administration shell, offer fresh insights into the challenge of achieving interoperability for Industry 4.0/5.0 technologies and legacy information systems and also have the potential to strengthen the case of IDS and related solutions. Digital twin technologies are considered important for advancing circular economy objectives due to their ability to support capabilities like lifecycle analysis. However, implementing digital twin technologies requires the integration of heterogeneous data sources. Consequently, IDS infrastructures and tracking-and-tracing supply chain platforms are being discussed as infrastructure solutions enabling digital twin implementations for supply chains as well. Regardless, while interoperability presents both challenges and solutions for implementing digital twin technologies today, the potential benefits, such as life cycle analysis and product life cycle transparency, provide strong motivation for companies to streamline their data infrastructures in preparation for DT adoption. The concept of digital product passports has received increased attention in recent years. This includes new and upcoming regulatory initiatives supporting the DPP as a policy instrument and companies providing platforms for supply chain collaboration and communication purposes starting to include DPP solutions as part of their service portfolio.

To answer **KQ 3: What is the concept of the Digital Product Passport and how can it be implemented in manufacturing and supply chains to support sustainability?**, the digital product passport is a product specific set of information that can be made accessible by digital twin technologies and underlying standards like the AAS. The DPP requires product-specific information including its identification, manufacturers and OEM information for parts and materials as well as functional and technical specifications and material compositions. In addition, a specific focus on sustainability metrics will be required for DPPs, such as CO2 footprint calculation, resource and energy consumption. In short, the DPP is expected to link information derived from different stages of the product life cycle including information from supply chain operations. The DPP system requires IT components that support the integration of data from different sources to ultimately provide a connection between the physical and virtual products. The current challenges of DPP systems are similar to the challenges discussed for general data sharing and DT implementation in the supply chain. DPP implementation is impacted by interoperability issues. The increasing regulatory pressure on manufacturers to cater sustainability-related information provision, including the trend for DPPs to gradually become mandatory for different product groups, could invoke organisations to work on their IT infrastructure and increase interoperability and supply chain transparency.

To summarise, the complexity of resource-intensive manufacturing supply chains is the foundation for the associated issues of interoperability and lack of standardised solutions supporting supply chain transparency. Similarly, it is this complexity aspect, that needs attention to solve the identified issues commonly associated with legacy IT and traditional communication in supply chain operations. Emerging technologies that address the highlighted issues are data ecosystems and SaaS platforms for tracking and tracing items through value chains and digital twin architectures to provide capabilities such as linking information from different sources for use cases such as life cycle analysis. In the future, a combination of these emerging technologies could provide comprehensive solutions to the interoperability issues that hamper supply chain transparency and sustainability today.

The above findings provide a picture of the problem context for the DPP implementation. The main research question that this thesis addresses is as follows;

How to address and develop the digital capabilities necessary for the digital product passport in the manufacturing domain?

This thesis presents the design of digital capabilities for the DPP for manufacturers based on their legacy infrastructure and common issues associated. The target architecture and PoC provide clear answers on the digital competencies required by manufacturers to comply with DPP related information requirements.

The integration of the DPP with legacy systems, which is needed to harness the relevant data needed for circular economy purposes, should be implemented through standardised, scalable and interoperable interfaces. Likewise, scalable data processing capabilities need to be built up in order to comply with the information requirements presented by the DPP. This thesis proposes an architecture that builds on digital twin capabilities, meaning that it is through the digital twin components such as standardised representation of the product that the DPP can be facilitated. DPP systems and digital twins for circular economy show common ground between in the context of interoperability. DPPs could provide both the necessary incentive as a mandatory requirement in the future and as a tool to start cleaning up interoperability issues in interfaces internally. For this reason, this research argues that the design of a DPP system for manufacturers provides an opportunity to address sustainability issues in resource-intensive supply chains while actively reviewing legacy infrastructure and relevant data integration. This in turn could provide clear directions for where digital transformation initiatives should be formed concerning supply chain transparency, supporting related emerging technologies such as IDS infrastructures in the long run.

8.2 Limitations

While this research successfully addresses the main question regarding the capabilities required for integrating Digital Product Passports (DPP) with legacy infrastructure, several limitations of this research should be acknowledged. Firstly, the absence of a digital twin and a live connection to legacy infrastructure introduces a notable constraint. The research emphasises the utility of a digital shadow, demonstrating its benefits over direct access to individual data sources or the need for new programming with each interface initiation. However, more exploration is needed due to the intrinsic complexity of digital twin implementation in this context. Secondly, the interaction between the DPP and adjacent systems such as the environmental management system should be investigated more closely. This is a somewhat chicken and egg problem, because a DPP based on digital twin capabilities can likely provide the much needed information to the environmental management system, while the later should logically be the single point of truth for the information stored.

Thirdly, The thesis focused on the internal capabilities needed for the DPP and more research is needed regarding the system's interaction with external parties, leaving opportunities for data ecosystems and third-party providers unexplored in their practical implications for the case of DPP. In this context, the maturity of technologies raises questions about the business case for comprehensive supply chain traceability, particularly in understanding manufacturers' motivations to participate in such initiatives. The research emphasises the utility of a digital shadow, demonstrating its benefits over direct access to individual data sources or the need for new programming with each interface initiation. However, more exploration is needed Finally, further investigation into the use cases for data collection and the reflection of manufacturers' data needs with regards to data sources outside of the organisational boundaries would enhance the overall robustness of the research findings.

8.3 Recommendations for future research

The World Manufacturing Foundation has acknowledged the need for companies to master their internal digital data infrastructure and management capabilities to achieve successful collaboration and data sharing with their supply chain partners and be able to harvest the fruits of such collaboration in the form of advanced risk management and planning [76, p.36]. By defining the digital capabilities for the DPP system in consideration of the common legacy infrastructure of manufacturers, this thesis has revealed where manufacturers should begin in terms of streamlining their data and system infrastructure. The main question arising from the implementation of a DPP is how to share data between different participants in the product's value chain.

While data ecosystems such as IDS and commercial SaaS platforms such as Circularise show promising capabilities for supply chain transparency, the emerging concept of digital product passports as policy instruments could strengthen the case for increasing transparency in supply chains. This research highlights specific areas of investigation, including; Examining how manufacturers can seamlessly integrate with other stakeholders along the product value chain in the context of the Digital Product Passport (DPP). And secondly analysing the business cases and value of data ecosystems and Blockchain technology for manufacturing and exploring strategies for their comprehensive integration. These questions are designed to delve into the interactions between diverse stakeholders in the product value chain. The discussion of maturity levels in emerging solutions like blockchain, IDS, and digital twin technologies underscores the need to strengthen the use case for supply chain collaboration to foster wider industry adoption. Consequently, this thesis recommends an exploration of the interface between a company's internal capabilities, including digital twin technologies, and their interaction with technologies that facilitate data sharing among various stakeholders.

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Appendix A

Current sustainability issues in manufacturing supply chains

This section of the thesis briefly explains the main negative impacts manufacturing activities create, in other words, why - if nothing changes - is it going to become more expensive for manufacturers?
Previous research finds the manufacturing industry slow to change as it is usually bound by tradition and any changes are costly and take time [133]. Manufacturing and their supply chains are resource-intensive due to the nature of manufacturing and machining itself and can generate a substantial amount of waste. Waste in manufacturing can come in a variety of shapes and sizes. Typical waste from manufacturing operations includes material scraps left over from operations such as casting or moulding, additives such as sand, liquids such as lubricants and coolants used in machining operations or solvents from cleaning procedures. Also, the materials used in the product itself, including any hazardous waste and toxic materials as well as smoke, pollutants and gases from burning fossil fuels usually count as waste from manufacturing activities.

The variety of waste associated with manufacturing activities indicates the amount of resources needed. Residual waste from operations is only one of the indicators as defined by the OECD sustainability indicators [19] that has sustainability issues associated. More generically, waste can occur in any manufacturing plant through the processes of transportation, inventory, motion, waiting, overproduction or overprocessing and defects [20].
The complexity of supply chains, including the dispersion over 4 or 5 tiers, makes it hard for companies to gain full visibility into operations such as raw material production of the subcontractors of their suppliers. This means there is a risk of non-compliance with environmental and labour standards and lack of overall control that firms can exercise over their supply chains [14, p.48]. The emission-intensive logis-

tics associated with complex supply chains is another challenge manufacturing supply chains are facing. Especially last mile operations concerning the delivery to the end-consumer seem to cause an increased effort in transport and resources necessary [7, p.29]. In the context of supply chains, risks associated with the bullwhip effect can impact the sustainability of SCs. This can happen for example through increased inventories due to larger safety stocks or, on the other end of the spectrum, stock-outs due to supply bottlenecks. Other effects include increased waste for example due to faulty products and quality issues [7, p.30]. Most likely, the uncertainties related to situations such as the above lead to increased efforts needed in the supply chain (i.e. increased logistic efforts, more materials ordered and produced etc.), which negatively impact the sustainability of the supply chain.
Decreasing the bullwhip effect and uncertainties in the supply chain highly depends on the information dissemination about delivery status and tracking products and materials through the different stages in the supply chain. Data exchange between companies however is significantly hampered today by heterogeneous systems and a lack of interfaces between data silos and companies [7, pp. 30-32].

In the context of sustainability, the notion of circularity, or circular economy, is likewise challenged by the above issues. The main barriers to introducing circularity in manufacturing have to do with the efforts necessary towards the end phase of the product. The disassembly and recycling of products can be a very time-consuming and expensive process, also because the information available about the product may be insufficient. Specifically for electric and electronic waste, disassembly and recycling can be difficult because biological substances have to be separated first. Another concern about re-using and recycling parts and materials is the quality aspect and impact on the final product. The lack of information about the product design and its production steps, combined with a lack of technical skills make the barriers and costs to introducing circularity very high (Manufacturers often don’t know the impact, negative and positive, of making products sustainable by design). In addition, the complexity of supply chains and challenging cooperation between supply chain actors are also noted amongst those factors hindering circularity for more sustainable manufacturing practices [133]. The discussed problems manufacturers face today in terms of the sustainability of their operations and supply chain also indicate a high potential for optimisation and automation regarding the exchange of information across supply chain actors [7, p.31], [133].

Appendix B

Solution design: Supporting materials

B.1 AS is analysis: Flow of materials

Figure B.2 shows the complete high level flow of materials, including the different business roles for warehousing, logistics, quality, production and assembly, with each of the above described processes associated to their respective roles. The archimate diagrams indicate how the flow of materials is supported through data integration between the different core systems ERP, EWM and MES in the manufacturing domain, and necessary for the coordination between warehousing, production and assembly. At the same time, figure B.2 also highlights the role of interfaces between the different departments or warehousing, logistics, quality, production and assembly.

B.2 As is analysis: IT infrastructure

Figure B.3 displays the complete IIoT pipeline at the manufacturer.

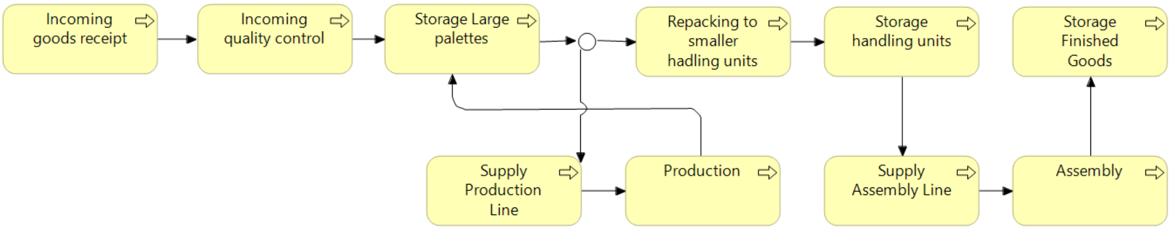


Figure B.1: Main business processes associated with the flow of materials at the manufacturing plant, own representation

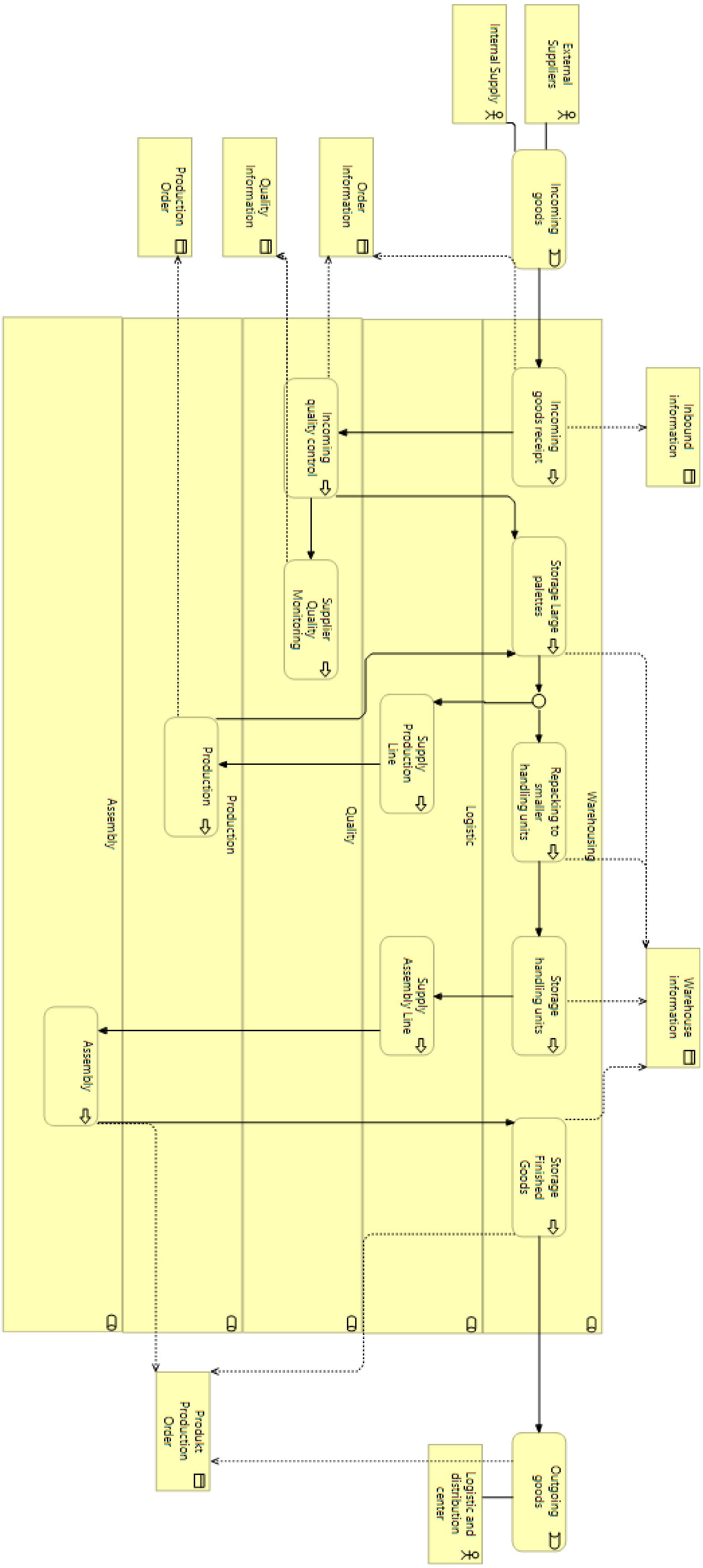


Figure B.2: Flow of Materials at the manufacturing plant, including information and supporting applications

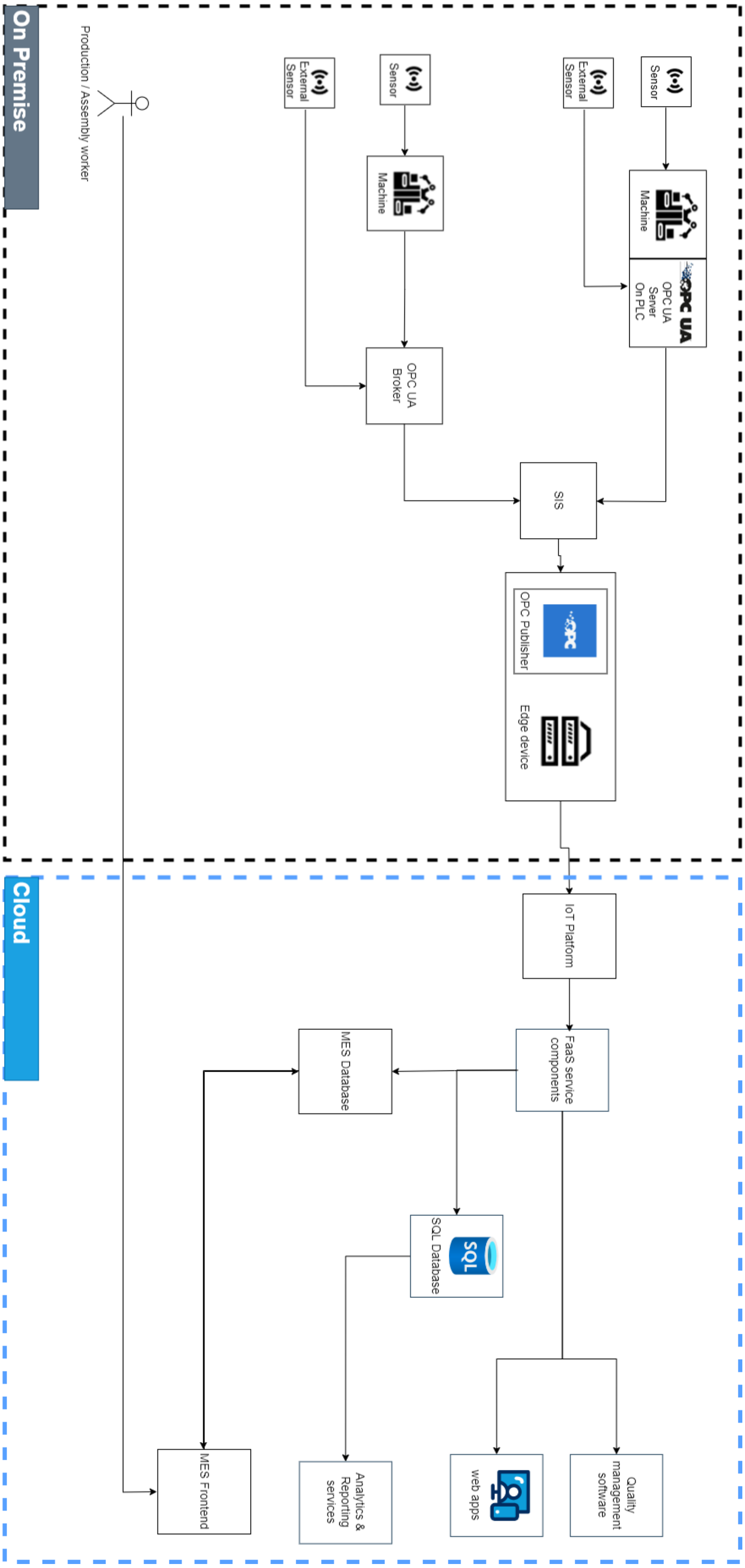


Figure B.3: Common IIoT Pipeline at manufacturing enterprises

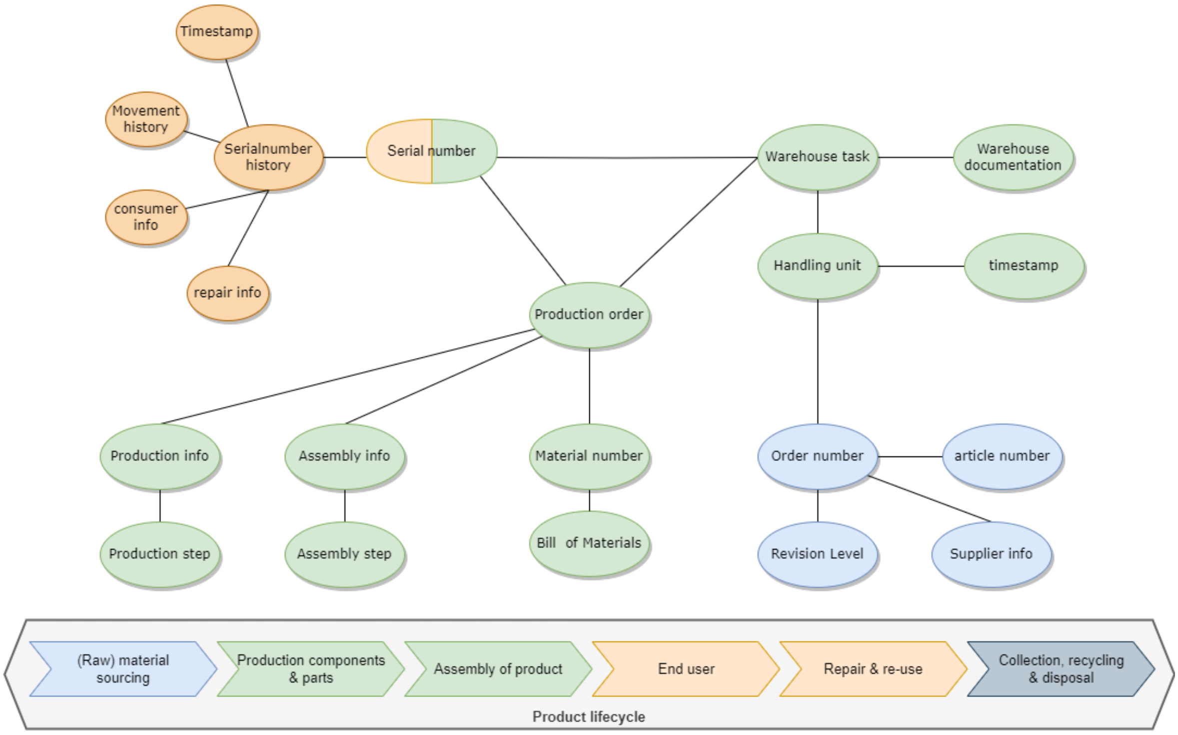


Figure B.4: High level information structure of product related information mapped to the main stages of the product lifecycle, own representation

B.3 As is analysis: Information structures

B.4 Target Architecture: Business scenarios and requirements

B.5 Target Architecture: Placing the defined capabilities into the existing infrastructure at the manufacturer

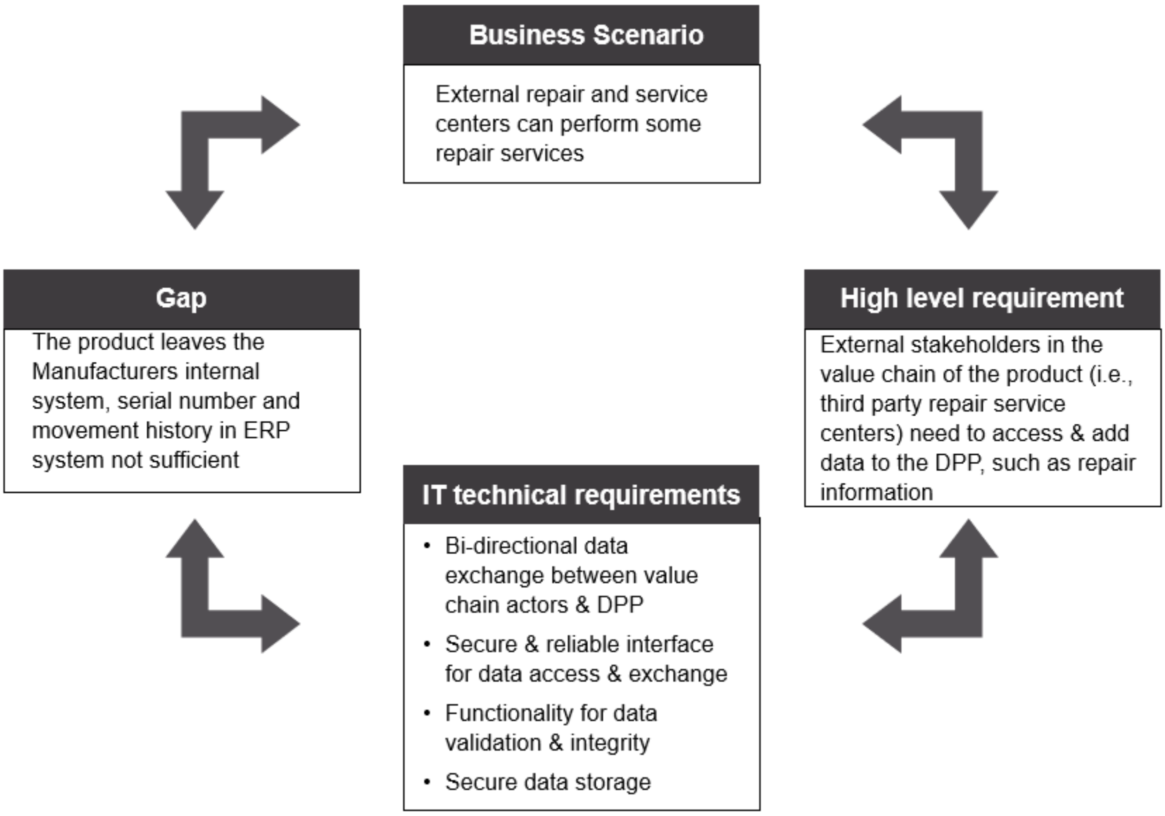


Figure B.5: DPP Business scenario demonstrating requirements for bi-directional data exchange for dynamic data in later stages of the product lifecycle, own representation

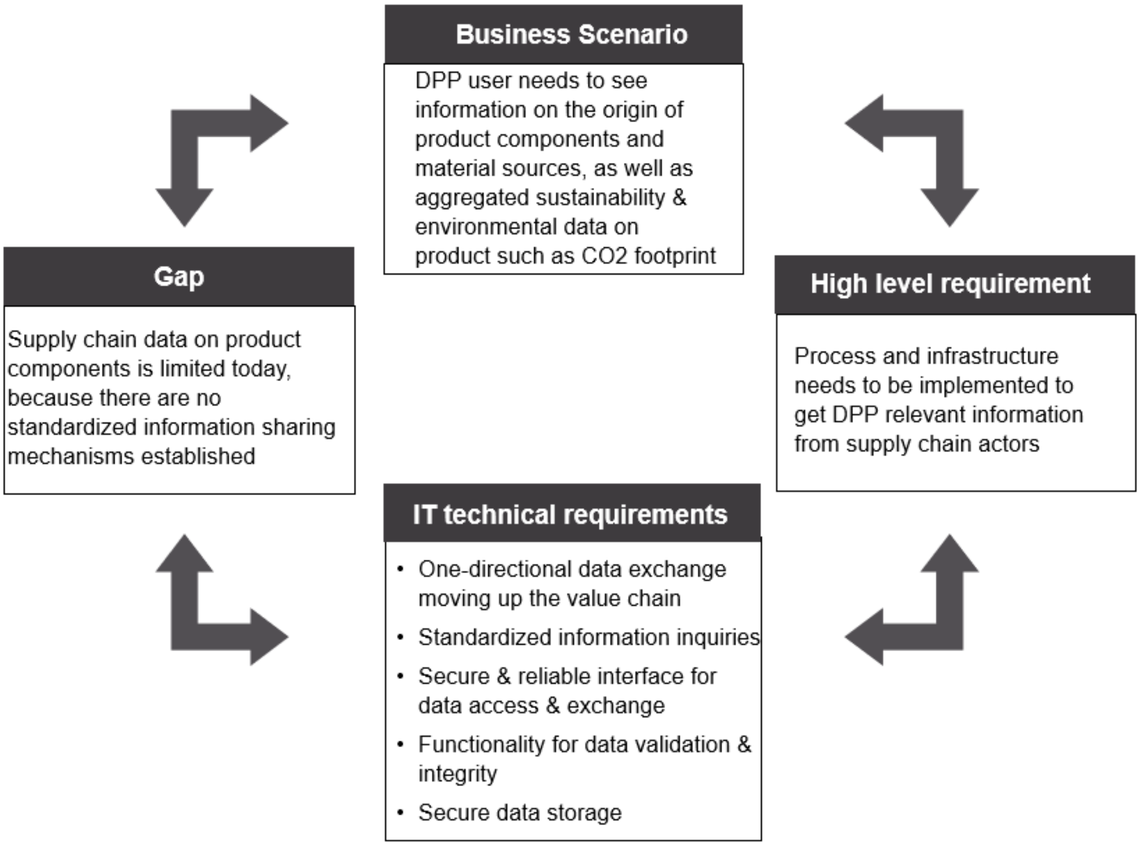


Figure B.6: DPP Business scenario demonstrating requirements for data exchange with supply chain stakeholders in the product lifecycle to get targeted sustainability information, own representation

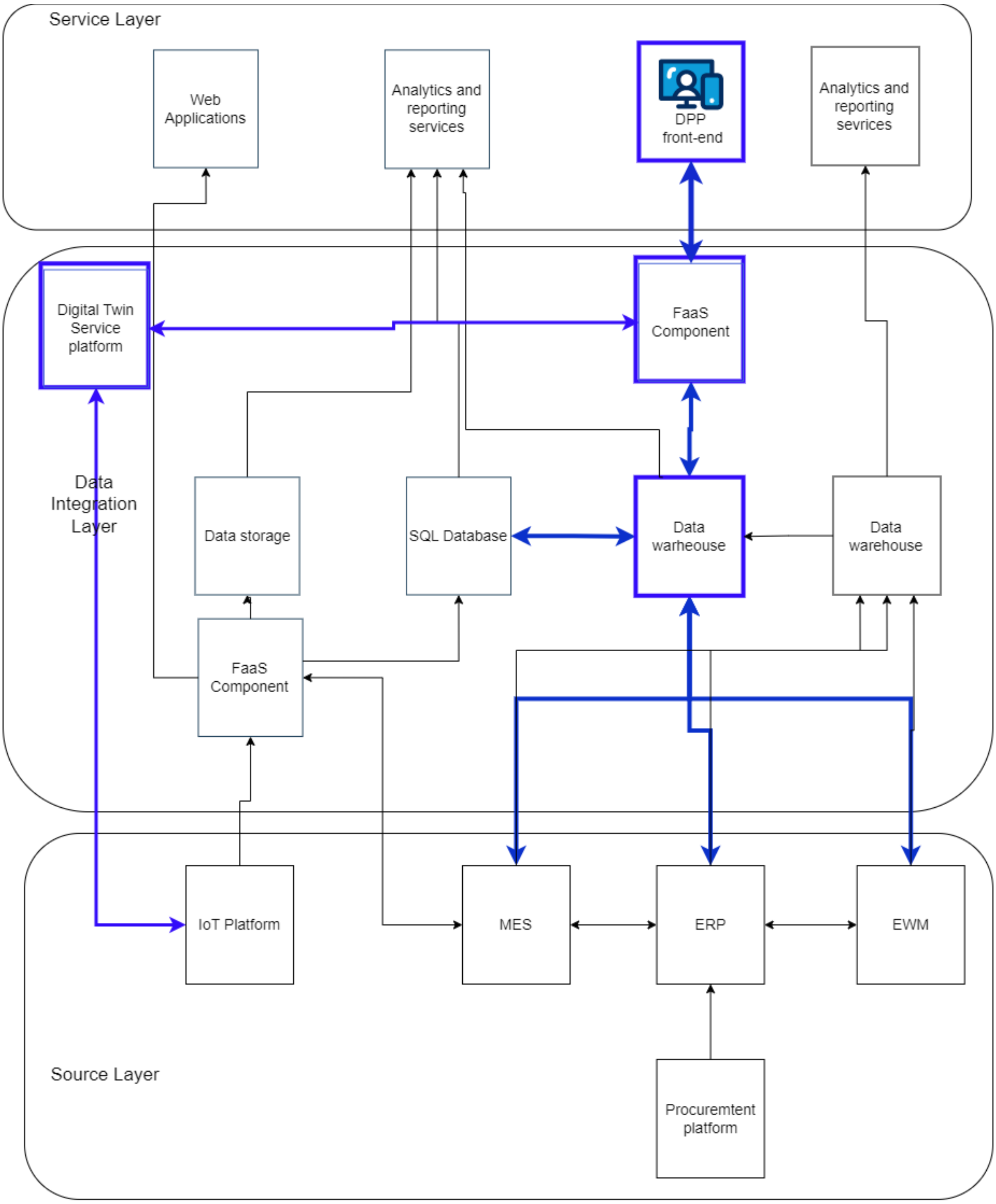


Figure B.7: Proposed architecture integrated at manufacturer to support DPP system implementation, own representation

Appendix C

Proof of concept

C.1 Implementation: Program Code on GitHub

The complete proof of concept implementation is available on GitHub:
`https://github.com/malina-w/DPP_PoC`

C.2 Implementation: Concept translation into proof of concept, own representation

C.3 Implementation: Design of complex database to represent common manufacturing systems

C.4 Implementation: DPP front end

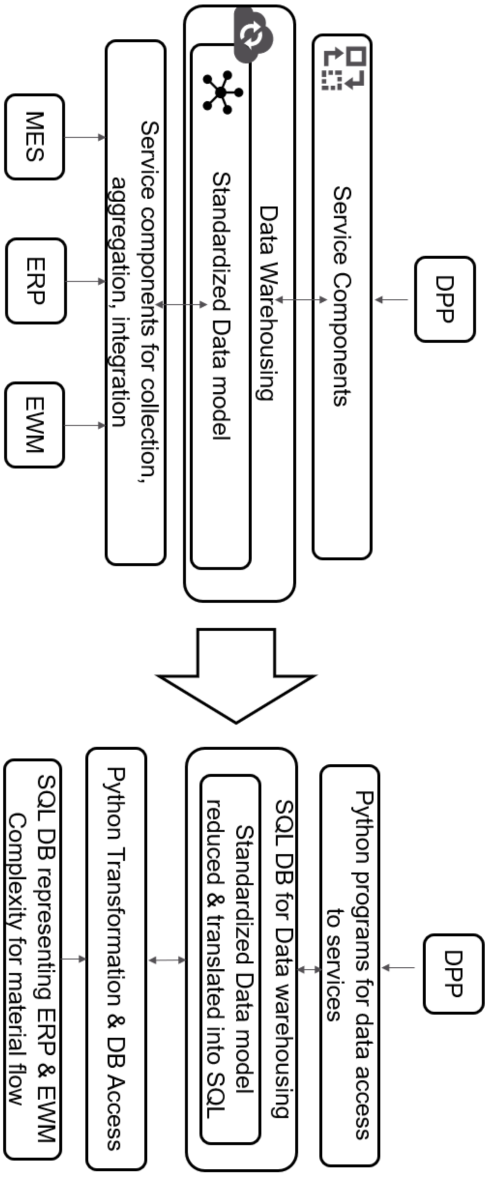


Figure C.1: Translation of main components from target architecture for the design of the proof of concept, own representation

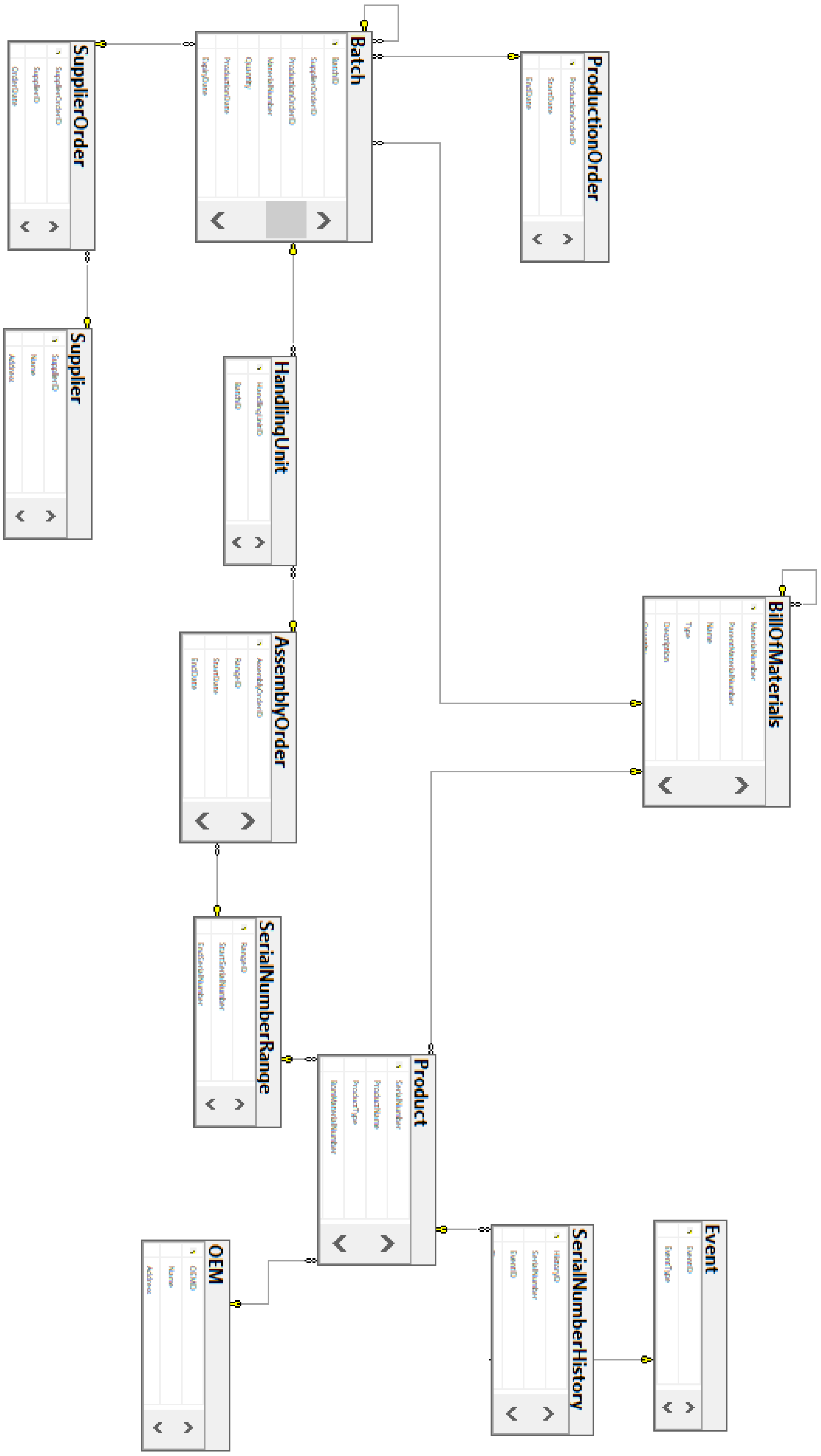
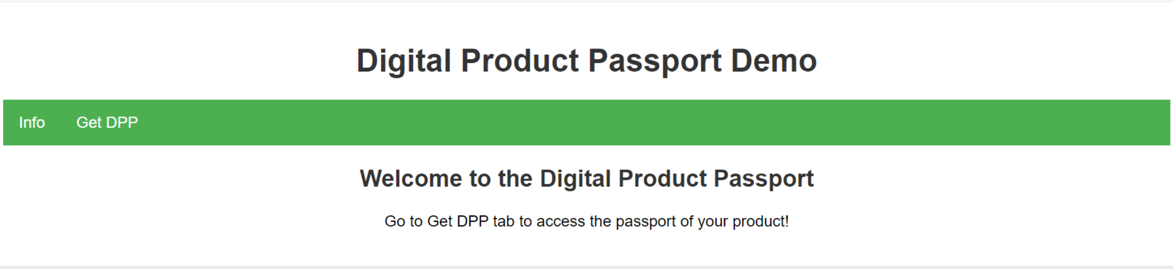


Figure C.2: SQL Diagram in MS SQL Server presenting the complex database designed to represent the complex data structures at the manufacturing plant

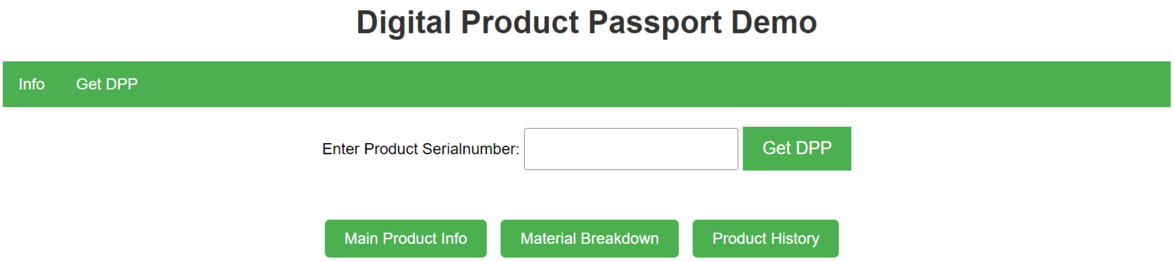


Digital Product Passport Demo

Welcome to the Digital Product Passport

Go to Get DPP tab to access the passport of your product!

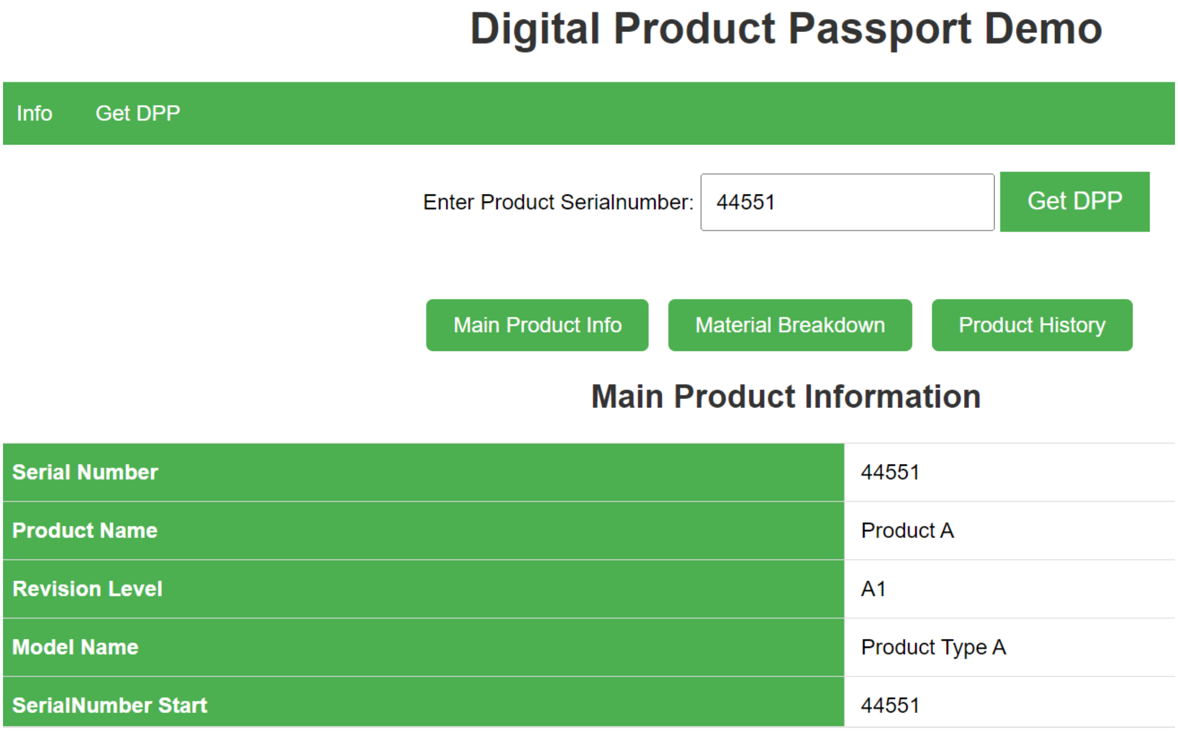
Figure C.3: Start screen of the DPP service



Digital Product Passport Demo

Enter Product Serialnumber:

Figure C.4: DPP screen to enter the product serial number for DPP information retrieval



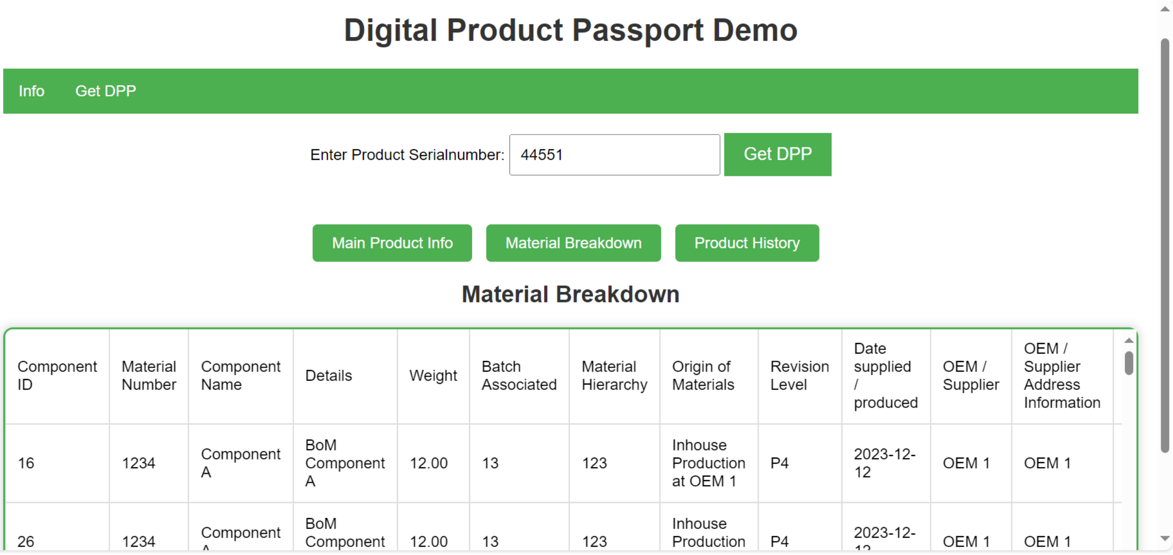
Digital Product Passport Demo

Enter Product Serialnumber: 44551

Main Product Information

Serial Number	44551
Product Name	Product A
Revision Level	A1
Model Name	Product Type A
SerialNumber Start	44551

Figure C.5: DPP service displaying results, here: main product information



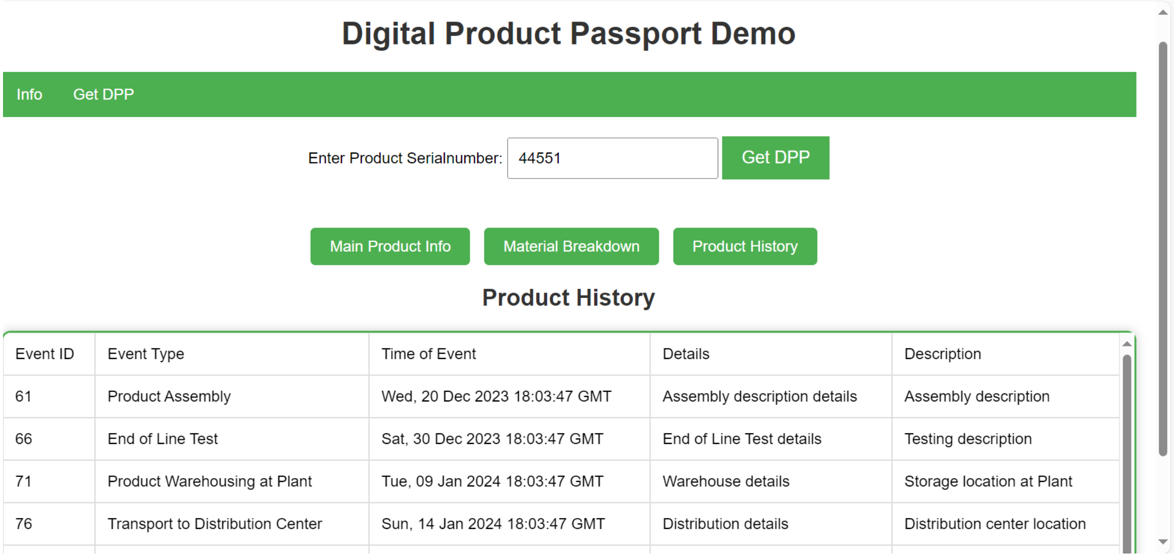
Digital Product Passport Demo

Enter Product Serialnumber: 44551

Material Breakdown

Component ID	Material Number	Component Name	Details	Weight	Batch Associated	Material Hierarchy	Origin of Materials	Revision Level	Date supplied / produced	OEM / Supplier	OEM / Supplier Address Information
16	1234	Component A	BoM Component A	12.00	13	123	Inhouse Production at OEM 1	P4	2023-12-12	OEM 1	OEM 1
26	1234	Component	BoM Component	12.00	13	123	Inhouse Production	P4	2023-12-	OEM 1	OEM 1

Figure C.6: DPP service displaying results, here: product component and material breakdown



Digital Product Passport Demo

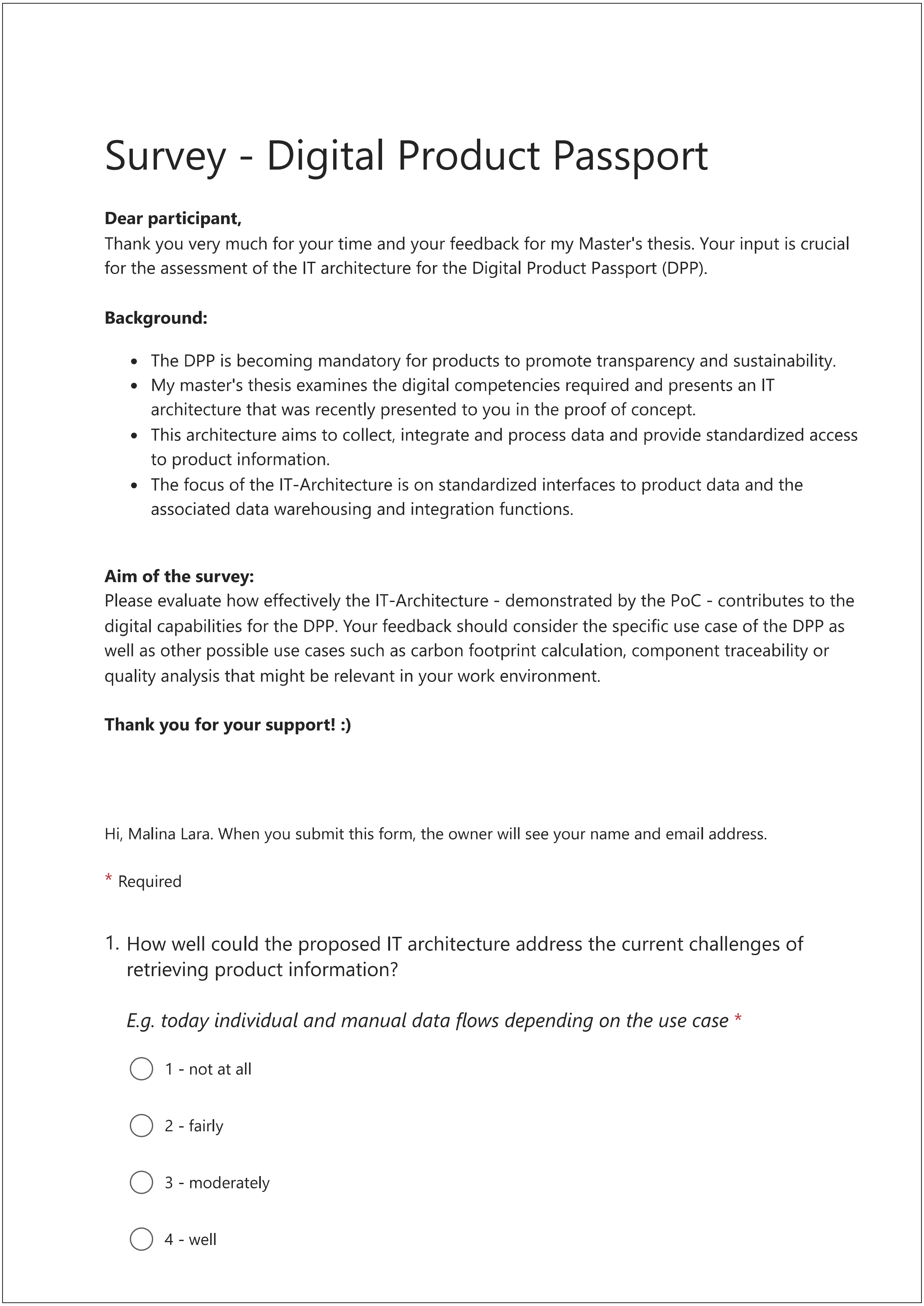
Enter Product Serialnumber: 44551

Product History

Event ID	Event Type	Time of Event	Details	Description
61	Product Assembly	Wed, 20 Dec 2023 18:03:47 GMT	Assembly description details	Assembly description
66	End of Line Test	Sat, 30 Dec 2023 18:03:47 GMT	End of Line Test details	Testing description
71	Product Warehousing at Plant	Tue, 09 Jan 2024 18:03:47 GMT	Warehouse details	Storage location at Plant
76	Transport to Distribution Center	Sun, 14 Jan 2024 18:03:47 GMT	Distribution details	Distribution center location

Figure C.7: DPP service displaying results, here: product event history

C.5 Validation: Survey



Survey - Digital Product Passport

Dear participant,
Thank you very much for your time and your feedback for my Master's thesis. Your input is crucial for the assessment of the IT architecture for the Digital Product Passport (DPP).

Background:

- The DPP is becoming mandatory for products to promote transparency and sustainability.
- My master's thesis examines the digital competencies required and presents an IT architecture that was recently presented to you in the proof of concept.
- This architecture aims to collect, integrate and process data and provide standardized access to product information.
- The focus of the IT-Architecture is on standardized interfaces to product data and the associated data warehousing and integration functions.

Aim of the survey:
Please evaluate how effectively the IT-Architecture - demonstrated by the PoC - contributes to the digital capabilities for the DPP. Your feedback should consider the specific use case of the DPP as well as other possible use cases such as carbon footprint calculation, component traceability or quality analysis that might be relevant in your work environment.

Thank you for your support! :)

Hi, Malina Lara. When you submit this form, the owner will see your name and email address.

* Required

1. How well could the proposed IT architecture address the current challenges of retrieving product information?

   E.g. today individual and manual data flows depending on the use case *

   ○ 1 - not at all

   ○ 2 - fairly

   ○ 3 - moderately

   ○ 4 - well

○ 5 - very well

2. How effective do you rate the ability of the proposed IT architecture to merge and aggregate data from different sources?

   E.g. integration of ERP, MES and EWM data at product level *

   ○ 1 - not at all

   ○ 2 - fairly

   ○ 3 - moderately

   ○ 4 - well

   ○ 5 - very well

3. How well could you imagine that the proposed IT architecture would enable simple and flexible access to product information?

   E.g. provision of information as required, new services for product data should be easy to set up and scalable - one service would be the DPP itself *

   ○ 1 - not at all

   ○ 2 - fairly

   ○ 3 - moderately

   ○ 4 - well

   ○ 5 - very well

4. How well does the proposed data integration and processing cover the information requirements for products in terms of the level of detail?

E.g. A part of the product data based on bills of materials and serial number history. *

○ 1 - not at all

○ 2 - fairly

○ 3 - moderately

○ 4 - well

○ 5- very well

5. How well would the proposed IT architecture contribute to achieving future goals in production?

   E.g. advanced data integration and analysis, future implementation of digital twins in production *

○ 1 - not at all

○ 2 - fairly

○ 3 - moderately

○ 4 - well

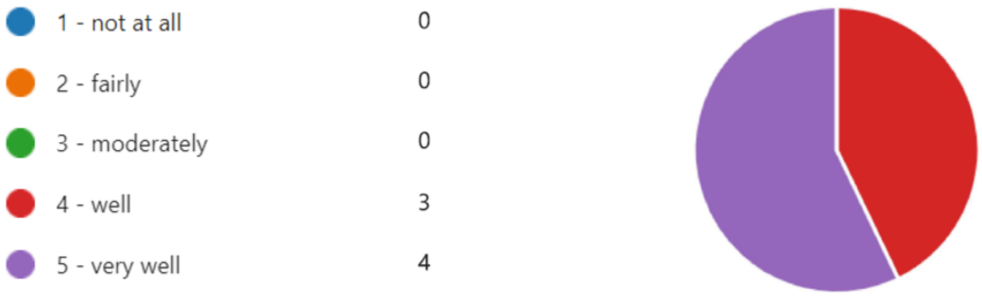
○ 5 - very well

6. Do you have any additional feedback, suggestions or concerns about the proposed IT architecture? Or would you like to give me some feedback on the demonstration and validation round itself?

   Enter your answer

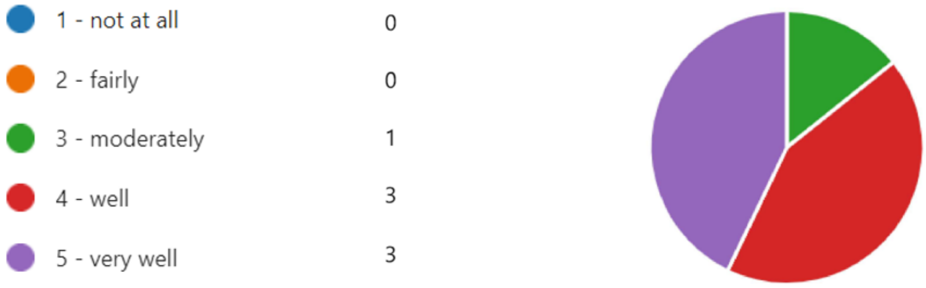
1. How well could the proposed IT architecture address the current challenges of retrieving product information?

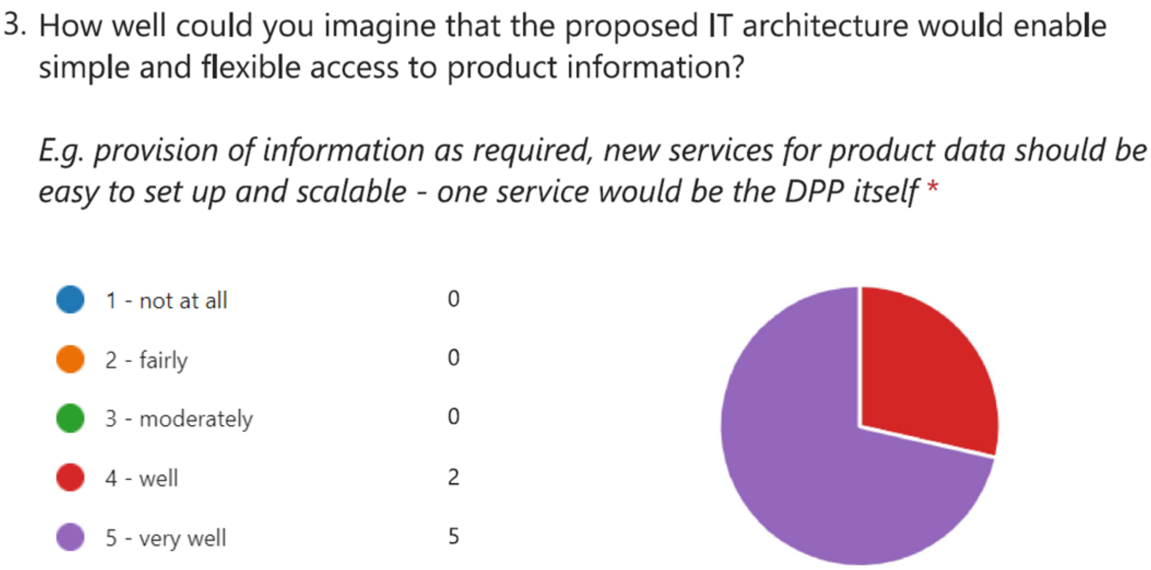
E.g. today individual and manual data flows depending on the use case *



2. How effective do you rate the ability of the proposed IT architecture to merge and aggregate data from different sources?

E.g. integration of ERP, MES and EWM data at product level *

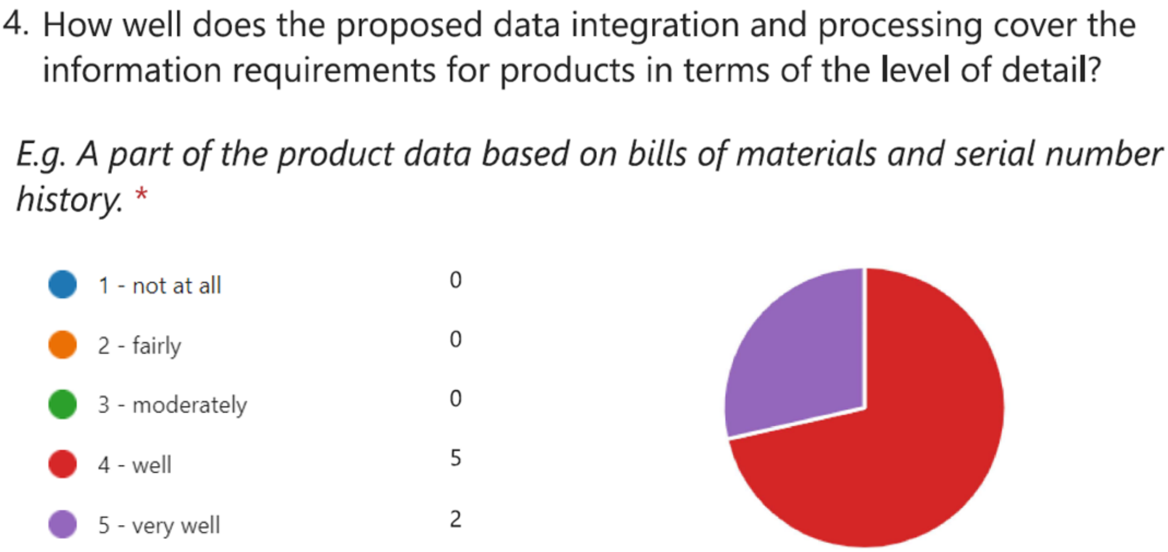




3. How well could you imagine that the proposed IT architecture would enable simple and flexible access to product information?

E.g. provision of information as required, new services for product data should be easy to set up and scalable - one service would be the DPP itself *

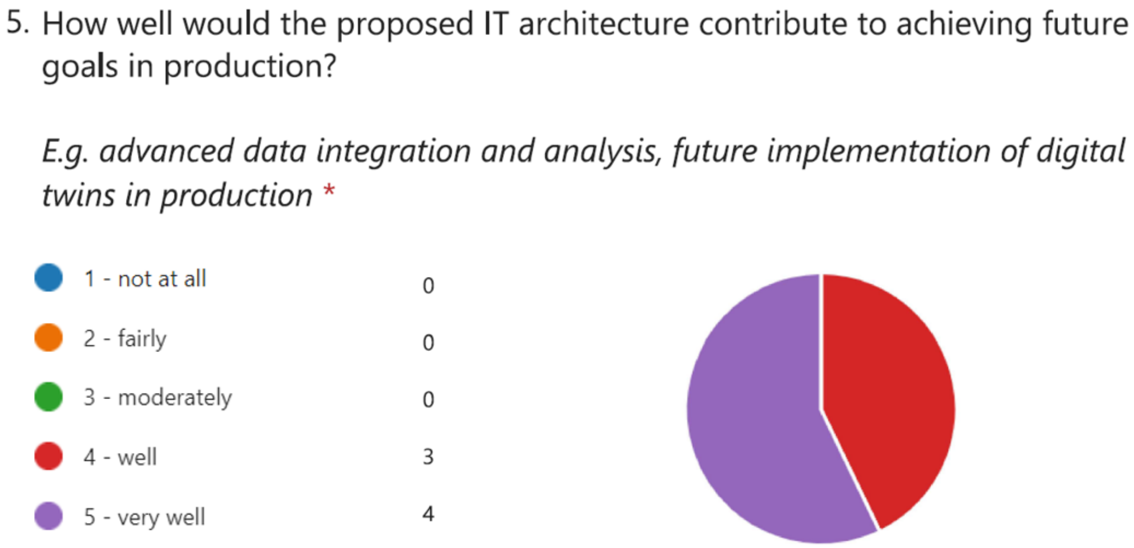
🔵	1 - not at all	0
🟠	2 - fairly	0
🟢	3 - moderately	0
🔴	4 - well	2
🟣	5 - very well	5



4. How well does the proposed data integration and processing cover the information requirements for products in terms of the level of detail?

E.g. A part of the product data based on bills of materials and serial number history. *

🔵	1 - not at all	0
🟠	2 - fairly	0
🟢	3 - moderately	0
🔴	4 - well	5
🟣	5 - very well	2



5. How well would the proposed IT architecture contribute to achieving future goals in production?

E.g. advanced data integration and analysis, future implementation of digital twins in production *

● 1 - not at all	0
● 2 - fairly	0
● 3 - moderately	0
● 4 - well	3
● 5 - very well	4