DEVELOPMENT OF A CONCEPTUAL FRAMEWORK FOR INTEGRATING INTELLIGENT-PRODUCT STRUCTURES INTO A FLEXIBLE MANUFACTURING SYSTEM

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DECLARATION

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ABSTRACT

Product complexity, shorter product life cycles, and short lead times to market challenge the manufacturing industry. Consequently, manufacturers seek to respond with a growing product variety and new business models to serve the customer's individual needs. Thus, there is a need for flexible manufacturing. In particular, multi-model production requires enhanced communication and decision-making of the manufacturing resources. Addressing these challenges without IoT technologies will be difficult. Thus, integrating intelligent-product structures is the leading pathway toward a flexible manufacturing system.

The industry 4.0 paradigm requires methods for integrating IoT Solutions into manufacturing. These solutions mainly consist of connected, intelligent products to increase flexibility and adaptability in smart factories. However, identifying the requirements and solution scenarios incorporating intelligent products presents a challenge for the manufacturing industry, especially in the SME sector. There are still uncertainties when implementing intelligent-product structures and managing mixed product-intelligence structures holistically.

This thesis aims twofold: firstly, contextualising flexibility, intelligent products, and their required technologies. Secondly, providing a conceptual framework to analyse the existing manufacturing environment and derive intelligent-product structures.

In the context of flexibility, intelligent products only directly influence the four dimensions: Material handling flexibility, Process flexibility, Routing flexibility, and Program flexibility. The systematic literature review provides comprehensive models for defining and classifying intelligent products in manufacturing. A generic product classification regarding its functionalities across the entire product lifecycle is established, and fundamental technologies for each functionality are derived. Thus, the literature review addresses the first part of the research aim.

The Intelligent-Product Initiation Decision-Support (IPIDS) framework, as a designed result of the requirement specification, defines, analyses, designs, and executes intelligent products and resources within the context of flexible manufacturing. Methods, tools, and processes are provided to guide the user through the four stages of the IPIDS framework. The first stage of definition assesses the existing infrastructure of the manufacturing by classifying the products and resources according to functionalities. In addition, manufacturing problems are identified and classified. Subsequently, a feasibility study of the identified problems derives the desired solution to manage the manufacturing problem with intelligent products. Stage 3 specifies design requirements based on the target functionalities of the products. Finally, the design requirements are used to develop intelligent products. Thus, the IPIDS framework addresses the second part of the research aim of providing a holistic concept to assess the existing manufacturing environment, identifying value-adding factors through intelligent products, and deriving design and implementation concepts.

The evaluation of the IPIDS framework is addressed through a theoretical verification and a prototype implementation in a learning factory. The implementation findings showcase that the IPIDS framework provides applicable, valuable and practicable methods for assessing the manufacturing environment based on the functionalities of the products and resources and deriving implementation concepts for intelligent-product structures. The validation is based on a comprehensive application of the IPIDS framework and statistical analysis, comparing the initial situation with the developed solution. The validity and applicability of the IPIDS framework provide a premise for intelligent-product structures in flexible manufacturing systems.

UITTREKSEL

Produkkompleksiteit, korter produklewensiklusse en kort aanlooptye om produkte op die mark te kry is van die uitdagings in die vervaardigingsbedryf. Vervaardigers probeer hierop reageer met ’n al hoe wyer produkverskeidenheid en nuwe bedryfsmodelle om in kliënte se individuele behoeftes te voorsien. Dít skep ’n behoefte aan buigsame vervaardiging, veral multimodelproduksie, wat beter kommunikasie en besluitneming vereis. Dit sal moeilik wees om hierdie uitdagings sonder IoT-tegnologieë die hoof te bied. Daarom is die integrasie van intelligente produkstrukture die beste roete om ’n buigsame vervaardigingstelsel te skep.

Die Nywerheid 4.0-paradigma vereis die integrasie van IoT-oplossings by vervaardiging. Hierdie oplossings bestaan hoofsaaklik uit gekoppelde intelligente produkte om buigsaamheid en aanpasbaarheid in slimfabrieke te verhoog. Nogtans vind die vervaardigingsbedryf, en veral die KMO-sektor, dit uitdagend om die vereistes en oplossings vir die integrasie van intelligente produkte te identifiseer. Daar is steeds heelwat onsekerhede met betrekking tot die implementering van intelligente produkstrukture en die holistiese bestuur van gemengde produkintelligensiestrukture.

Die doel van hierdie tesis is tweërlei: eerstens, om buigsame intelligente produkte en die tegnologievereistes daarvan te kontekstualiseer, en tweedens, om ’n konseptuele raamwerk te voorsien om die bestaande vervaardigingsomgewing te ontleed en intelligente produkstelsels af te lei.

Wat buigsaamheid betref, het intelligente produkte slegs ’n direkte invloed op die vier dimensies van materiaalhantering, proses, wegbepaling en programmering. Die stelselmatige literatuuroorsig bied omvattende modelle om intelligente produkte in vervaardiging te definieer en te klassifiseer. ’n Generiese produkklassifikasie word op grond van die produkvermoëns deur die hele produklewensiklus bepaal, waarna fundamentele tegnologieë vir elke vermoë afgelei word. Die literatuuroorsig beantwoord dus aan die eerste deel van die navorsingsdoel.

Die besluitnemingsteunraamwerk vir die implementering van intelligente produkte (IPIDS), wat volgens die vereiste spesifikasie ontwerp is, bepaal, ontleed, ontwerp en ontwikkel intelligente produkte en hulpbronne in die konteks van buigsame vervaardiging. Metodes, instrumente en prosesse word voorsien om die gebruiker deur die vier fases van die IPIDS-raamwerk te begelei. Die eerste fase – bepaling – beoordeel die bestaande infrastruktuur van die vervaardigingsbedryf deur die produkte en hulpbronne op grond van vermoë te klassifiseer. Boonop word vervaardigingsprobleme geïdentifiseer en geklassifiseer. Daarna dui ’n haalbaarheidstudie van die geïdentifiseerde probleme op die gewenste oplossing om die vervaardigingsprobleem met behulp van intelligente produkte te bestuur. Fase 3 spesifiseer ontwerpvereistes op grond van die teikenvermoëns van die produkte. Laastens word die ontwerpvereistes gebruik om intelligente produkte te ontwikkel. Die IPIDS-raamwerk beantwoord dus aan die tweede deel van die navorsingsdoel deur ’n holistiese konsep te bied om die bestaande vervaardigingsomgewing te beoordeel, waardetoevoegingsfaktore deur intelligente produkte te identifiseer, en ontwerp- en implementeringskonsepte af te lei.

Die IPIDS-raamwerk word geëvalueer deur ’n teoretiese stawing en ’n prototipe-implementering in ’n opleidingsfabriek. Die resultate van die implementering toon dat die IPIDS-raamwerk gepaste, nuttige en praktiese metodes bied om die vervaardigingsomgewing op grond van produk- en hulpbronvermoëns te beoordeel en implementeringskonsepte vir intelligente produkstrukture af te lei. Die stawing is gegrond op ’n omvattende toepassing van die IPIDS-raamwerk en statistiese ontleding wat die aanvanklike scenario met die ontwikkelde oplossing vergelyk. Die geldigheid en toepaslikheid van die IPIDS-raamwerk dien dus as grondslag vir die implementering van intelligente produkstrukture in buigsame vervaardigingstelsels.

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Nomenclature

Acronyms

ADC	Analogue to Digital Converter
ALFUS	Autonomy Levels for Unmanned Systems
AP	Attention Point
BC	Boundary Condition
CPPS	Cyber-Physical Production Systems
CPS	Cyber-Physical Systems
CPU	Central Processing Unit
DR	Design Restriction
DSRM	Design Science Research Methodology
EAN	European Article Number
FMS	Flexible Manufacturing System
FR	Functional Requirement
I2C	Inter-Integrated Circuit
IoT	Internet of Things
IPIDS	Intelligent-Product Initiation Decision-Support
MES	Manufacturing Execution System
NCAP	Non-Contextual Autonomy Potential
OCR	Optical Character Recognition
RFID	Radio Frequency Identification
RMS	Reconfigurable Manufacturing System
RO	Research Objective
ROM	Read-Only Memory
SCL	Serial Clock Pin
SDA	Serial Data Pin
SME	Small and Medium-Sized Enterprise

SMED	Single-Minute-Exchange-of-Dies
sPSS	Smart Product-Service Systems
TCP	Tool Center Point
ToF	Time of Flight
UGV	Unmanned Ground Vehicle
UMS	Unmanned System
UR	User Requirement
VW	Volkswagen

Chapter 1. Definition of research

Chapter 1 provides the background to the research and highlights the scope of the thesis by the problem statement. Furthermore, the research aim and objectives are discussed, which leads to the research design and the thesis structure.

1.1 Research introduction

The globalisation process has gained new strength in the last third of the twentieth and early twenty-first centuries and continues to rise steadily. This evolution is based on technological advances in transportation, IT, and communication, leading to free labour division and globally distributed production. Thus, globalisation impacts every country regardless of economic, political, or social situation. In this context, globalisation is characterised by a high product individualisation, an increasing product complexity, and shorter product lifecycles (Ernst & Haar, 2019).

Manufactures are encouraged to provide a growing product variety to serve customers' individual needs. The more individualised the product becomes, the more complex the product tends to be due to a large number of product components and extensive interactions among these components (Shou et al., 2017, p. 298). Figure 1 presents a new production paradigm of sustainable value creation. It emerged in 2000 and required individualisation, regionalisation, and globalisation. Before globalisation accelerated in the last third of the twentieth century and early twenty-first century, the global manufacturing revolution consisted of the three stages craft production, mass production and mass customisation. The second industrial revolution occurred between 1850 and 1870 through craft production based on the division of labour using electrical energy, especially in the electrical, chemical, and automotive industries (see Figure 1). However, after introducing the T-model in 1913, Henry Ford set new standards in mass production, reaching the zenith in 1955 with the Volksauto VW Käfer. The third industrial revolution in 1960 enabled automation-driven rationalisation and multi-variant series production through the integration of electronics and information technology in manufacturing automation. From this point on, the phase of mass customisation emerged in 1980, characterised by decreasing product volume per variant and increasing product variety (Bauernhansl et al., 2014, 11 ff).

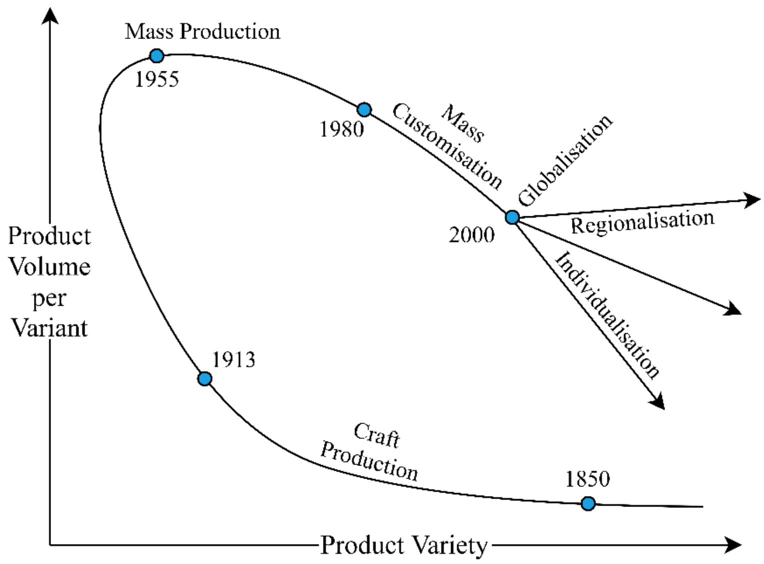

Figure 1: Historical development of production based on (Koren, 2010)

In addition to the increase in complexity and individualisation of products, the trend of shorter product life cycles is dominant. The increasing product variety and complexity and the shorter product lifecycles result in smaller lot sizes, increasing order numbers and rising data and information processing for manufacturing companies (M. Ostgathe & M. F. Zaeh, 2013, p. 138). The fourth industrial revolution was officially initiated through the implementation guidelines for the future project Industry 4.0 by Kagerman et al. in 2013 to cope with these challenges for manufacturers (Kagermann et al., 2013). In the context of Industry 4.0, Cyber-Physical Systems (CPS) have received significant attention as the technological basis for future projects. According to E. A. Lee (2008), CPS is defined as follows:

> "Cyber-Physical Systems (CPS) are integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa" (E. A. Lee, 2008, p. 363).

Therefore, Cyber-Physical Systems are complex and multi-disciplinary systems that integrate embedded computers into the physical processes, mainly including observation, communication, and control aspects in the physical environment (Gunes et al., 2014, p. 136). The continuously increasing connection of information processing components and processes has been state-of-the-art in automation technology in the last years, enabling data and services availability. This connection leads to the vision of Cyber-Physical Production Systems (CPPS), which are characterised by autonomy, self-reconfiguring and highly flexible capabilities (E. A. Lee, 2008, p. 365). The increasing demand for decentralised autonomy and flexibility for dynamic manufacturing processes and the ability of direct communication with the products lead to CPPS. Figure 2 displays the hype cycle for emerging technologies, according to Gartner (Gartner, 2021).

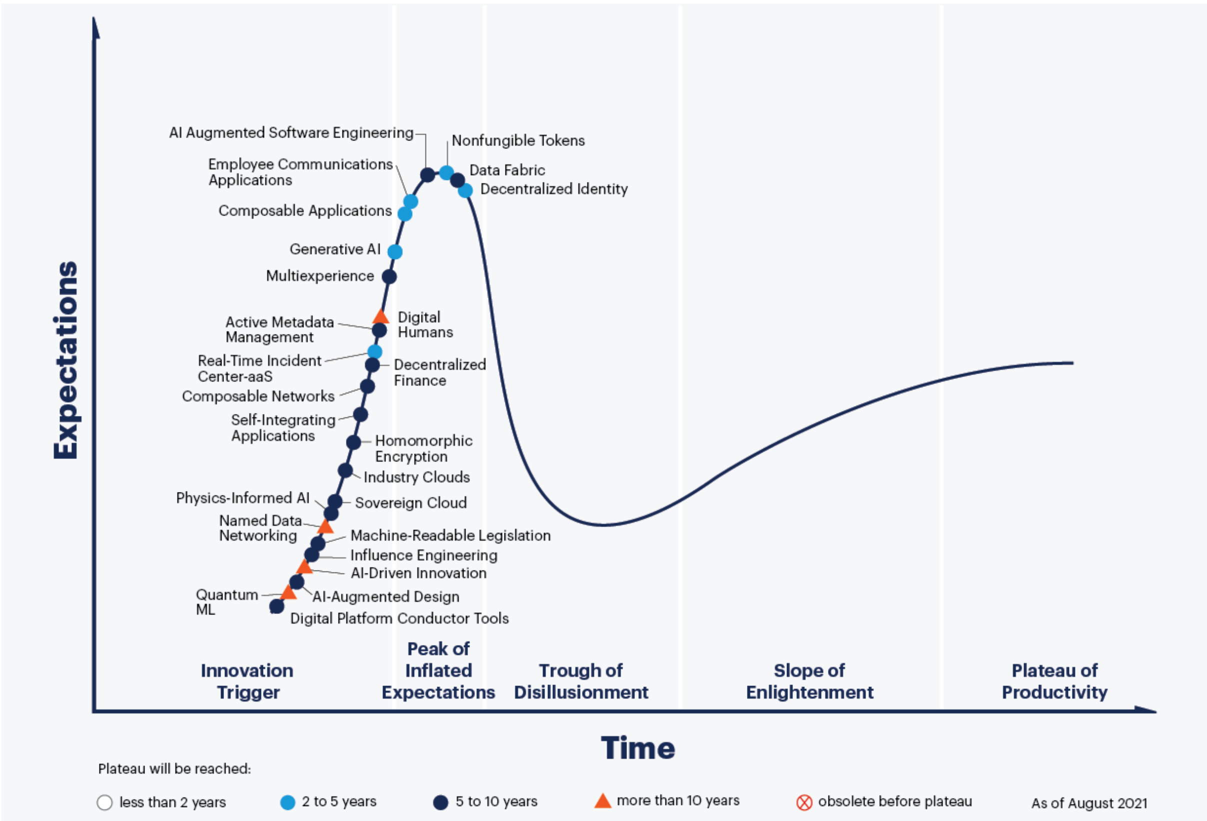

Figure 2: Hype cycle for emerging technologies based on (Gartner, 2021)

Gartner's yearly published hype cycle exemplifies the trend of CPPS with data fabrics, which require the manufacturer's capability to quickly respond to rapidly changing business needs. Data fabrics sits right at the peak of inflated expectations, which indicates that organisations recognise the value of the concept but it is still an emerging technology. According to Gartner, this modular business model enables a company to shift from rigid, traditional planning to dynamic agility and responsiveness in their manufacturing processes (Gartner, 2021). Especially when applying intelligent-product structures to manufacturing, companies have high expectations of increasing flexibility and responsiveness with product-based control in complex manufacturing systems (McFarlane et al., 2013).

1.2 Background and rationale of the research

The challenge of the widely adopted mass customisation is to produce a growing mix of individual products at a cost near mass production. Manufacturing companies are facing increasing challenges of providing manufacturing systems with sufficient flexibility to meet customer-specific product requirements while being efficient at the same time. In particular, small and medium-sized enterprises (SMEs) are facing the trend of customised individualisation and higher product variety. In combination with lower manufacturing volumes in SMEs compared to large enterprises, the increased product variety often implies complexity in manufacturing costs (Brunoe & Nielsen, 2016, p. 39). For the order-based manufacturing of products, the high product variety leads to decreasing batch sizes, increasing order numbers and thus increasing data and information processing within the process automation and order management in the company (Bertelsmeier et al., 2016, p. 755).

Automatic identification technologies, for example, barcodes, biometric systems, optical character recognition, and radio frequency identification (RFID) are state of the art for identifying products. Since most identification technologies only have the functionality to store information, integrating embedded sensor technologies in the product can be beneficial. Based on this information, manufacturing process measurements enable new types of applications (Meyer et al., 2009, p. 141). For the implementation of CPPS in flexible manufacturing systems (FMS) or reconfigurable manufacturing systems (RMS), intelligent products or product carriers can play an active role in the production planning and control of their manufacturing processes (McFarlane et al., 2013, p. 80). Compared to passive identification technologies of barcodes and RFID, active sensor and processing technologies are introduced to enable new applications (Meyer et al., 2009, p. 141). Therefore, a decentralised provision of product- and process-specific data at the corresponding machines and systems can be provided. Especially for SMEs, this provides an alternative to cost-intensive, operational planning systems, such as Manufacturing Execution System (MES) in workshop production (Ostgathe, 2012, p. 141).

The potential of integrating intelligent objects has been recognised several times in product-based control of FMS or RMS (Chemnitz et al., 2010; M. Gaham & B. Bouzouia, 2009; McFarlane et al., 2013). Various use cases have been developed in manufacturing, production planning and control, and supply chains (Meyer et al., 2009, pp. 144–147). However, integrating intelligent-product structures is fundamental for more flexibility and autonomy in the distributed manufacturing process and is required to deal with the rising data and information processing. A present research gap lies in improving the overall integration process of intelligent-product structures. Managing mixed product-intelligence structures in FMSs introduces a challenge that must be mastered (Bertelsmeier et al., 2016, p. 760).

1.3 Problem statement and research questions

This work aims to investigate how manufacturing companies can increase flexibility in the production environment. In that context, the thesis focuses on the flexible manufacturing of parts. Therefore, distributed production systems and intelligent products are frequently associated as promising enablers to increase flexibility (Meyer et al., 2009).

Bertelsmeier et al. (2016, p. 760) set research focus on overall system integration, an evaluation concept, and mixed product-intelligence structures in FMSs. This research gap seems to be a critical aspect that has hardly been considered so far, which leads to the problem statement that describes specific conditions and actions to solve the problem to achieve mission success. The problem statement is the realisation of the conceptual framework through the application of intelligent products or product carriers considering mixed product-intelligence structures in FMSs. The framework result should represent further modules in the realisation of CPPS.

The primary research question in Table 1, investigates how manufacturing companies can integrate intelligent-product structures to enable a flexible production environment.

Table 1: Primary research question

Primary research question	How can manufacturing companies integrate intelligent-product structures to enable a flexible manufacturing environment?

To adequately answer the primary research question, the following four secondary research questions need to be considered (see Table 2). Answering the secondary research questions leads to findings that clarify the primary research question.

Table 2: Secondary research questions

Secondary research question 1	How can the physical objects on the manufacturing shop floor be classified into the different intelligence classes and aggregation levels?
Secondary research question 2	How can a methodology for analysing and implementing the application potential of intelligent products in manufacturing be structured?
Secondary research question 3	What are the design and technical requirements of an intelligent product or product carrier to be eligible for a flexible manufacturing system?
Secondary research question 4	What does a practical realisation of intelligent products or product carriers look like?

Answering Secondary question 1 describes a context analysis to classify the physical objects on the manufacturing shop floor, as there are numerous definitions and classifications of intelligent products or objects. In this context, research on the nature of problems and intelligence is required to develop a conceptual framework that aims to reduce or even eliminate manufacturing problems by integrating intelligent-product structures. Secondary question 2 describes the methodology developed to identify the application potential of intelligent-product structures in manufacturing. The methodology aims to cover various steps of problem and resource classification, the definition of target functionalities of the intelligent product, and a feasibility study to identify the application potential. Secondary Question 3 defines the design and technical requirements of an intelligent product or product carrier to be eligible for a FMS. Therefore, the design rules and technical requirements of CPPS are used as a basis, which needs to be supplemented with product-intelligence aspects. At his stage, the cooperation aspect of mixed product-intelligence structures needs to be considered. Finally, secondary question 4 involves practically realising intelligent-product structures using the developed conceptual framework.

1.4 Research objectives and contribution

This research aims to increase practical and feasible development practices for intelligent products or carriers within FMS and RMS. The development practices lay the foundation for effectively analysing and integrating intelligent-product structures in manufacturing. The specific aim of this research includes a conceptual model, which assists manufacturing enterprises with classifying the existing production infrastructure and realising intelligent products or product carriers, considering mixed product-intelligence structures.

Table 3: Research objectives, sub-objectives and corresponding chapters

RO number	Research objective description	Corresponding chapter
RO1	To contextualise flexibility, intelligent products, and their required technologies from a theoretical and practical perspective to support the rationale of this research.	Chapter 2
RO1.1	Review the purpose and definition of flexibilities in manufacturing and measuring approaches.	Chapter 2.1
RO1.2	Explore the factors that lead to complex problems and intelligence in psychology. Investigating and comparing smart/intelligent products in literature through a bibliometric analysis to define and classify the term and provide application fields.	Chapter 2.2
RO1.3	Review the required technologies for the functionalities of intelligent products.	Chapter 2.3
RO2	Develop and evaluate a conceptual framework that analyses the existing manufacturing environment and derives intelligent-product structures.	
RO2.1	Define the requirement specification for the conceptual framework.	Chapter 3
RO2.2	Develop the conceptual framework for integrating intelligent-product structures.	Chapter 4
RO2.3	Verify and validate the developed framework to identify whether it is feasible and fits its intended purpose.	Chapter 5

The Research Objectives (ROs) and sub-objectives guide the study in the intended direction and keep the focus on the aim of this research work, presented in Table 3.

Given the nature of the problem statement and the research objectives, the current research aims to develop a new conceptual framework. The theoretical aspect is presented by the research on flexibility and intelligence, whereas the conceptual research focuses on classification models of smart/intelligent products and their application in manufacturing. The intended outcome of this research is a conceptualisation of constructs that provide the premise for the possible integration of intelligent-product structures.

1.5 Research design and methodology

The thesis will be conducted as a Design Science Research Methodology (DSRM). A. Hevner and Chatterjee (2010) provide an approach to DSRM, where the research project should yield a valuable and fundamental artefact for problem-solving (A. Hevner & Chatterjee, 2010, p. 5). In addition to the design and development of the artefact, three different activities are required for the cognitive process, according to Österle et al. (2010). Different methods are used for four activities, which are linked below to the research questions. The four steps of the DSRM shown in Figure 3.

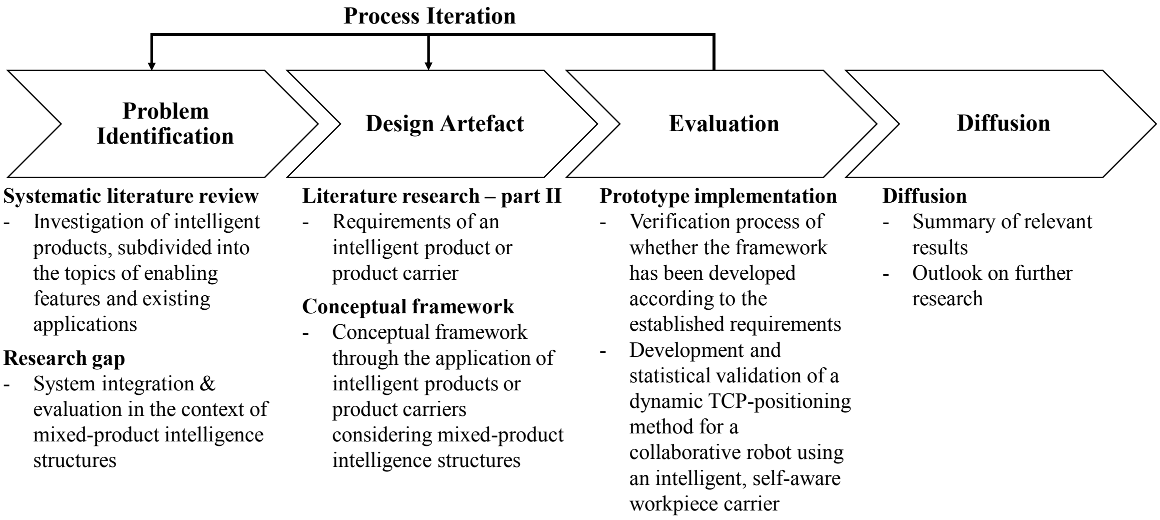

Figure 3: Research methodology author's own representation based on (A. Hevner & Chatterjee, 2010; Österle et al., 2010)

The first step describes the problem identification to examine the current state of the art and identify a research gap or problem. Therefore, a literature review is provided to investigate FMSs, intelligent products, and the design and technical requirements of an intelligent product or product carrier. By classifying the records, an unsolved problem is identified with a relevant focus on the system integration, the evaluation concept, and mixed product-intelligence structures in FMSs. Further investigation displays a research gap regarding a cooperation system for mixed product-intelligence structures.

In the second step, a solution for the previously identified problem is designed. It is divided into the steps "Artefact Design" and supporting "Literature Research". On the one hand, a supporting "literature review" is essential to keep track of ongoing activities and react to research findings changes. On the other hand, the requirements of an intelligent product or product carrier must be defined. In addition, the conceptual framework is developed. The utilised methodology for the conceptual framework development is adapted from Jabareen (2009, p. 51) and Meredith (1993, p. 7). A conceptual framework is defined as a network or plane of interlinked concepts to provide a broad understanding of a phenomenon. The components of the conceptual framework are essential as these support each other and thus constitute the phenomenon or phenomena (Jabareen, 2009, p. 51). The conceptual framework represents the researcher's own constructed model to explain the relationship between the main variables in the study (Adom et al., 2018, p. 440). According to Meredith (1993), a concept has various meanings and characteristics. A concept represents, identifies, communicates, or understands events, objects, or conditions. A conceptual framework is thus a description and explanation of a phenomenon through observed relationships between the system elements (Meredith, 1993, p. 5). Jabareen (2009) defines seven phases to guide the developer of the conceptual framework, which are used as a procedure in the research design of this thesis (see chapter 4). In addition, Jabareen (2009) suggests basing a conceptual framework on existing multidisciplinary literature as it is a process of theorisation. Therefore, the respective fields are examined in the literature review, which serves as a basis for the subsequent framework development.

The third step of the DSRM is to evaluate the artefact by comparing the objectives of the solution to the actual observed results by quantifiable system performance measures. At this stage of designing and evaluating the artefact, several iteration loops are possible to check practical relevance and applicability (Offermann et al., 2009, p. 7). The evaluation phase of the artefact is twofold: firstly, the verification process examines whether the conceptual framework has been developed according to the predefined requirements. Secondly, the validation of the prototype implementation includes a dynamic Tool Center Point (TCP) positioning method for a collaborative robot using an intelligent, self-aware workpiece carrier. The results are summarised at the end of the research process, and an outlook on further research aspects is established. There is an interest in the most significant diffusion through the publication of the master's thesis.

In this study, a purely deductive research approach is of limited assistance in achieving the practice-oriented scientific goal. Therefore, an abductive research approach is considered, which establishes causal connections in terms of theories or hypotheses after the observation is examined. The abductive approach is characterised as a mixture of the deductive and inductive approach, with the researcher's aim to discover new things and generate new concepts (Dubois & Gadde, 2002, p. 559). The abductive research approach proposes a learning loop between the theory and empirical study to develop a concept or theory suggestion (Kovács et al., 2005, p. 139).

The DSRM is selected in the thesis based on several reasons. A. Hevner and Chatterjee (2010) state that design science research's primary purpose is the development of an artefact to achieve knowledge and understand the problem domain. The thesis addresses the problem of a missing overall system integration process and evaluation process for mixed product intelligence structures and provides knowledge and understanding of the conceptual framework. In addition, the DSRM aims to develop valid and reliable knowledge for designing a solution, which corresponds to the problem-solving capabilities of van Aken and Berends (2018), used for the requirement specification. Furthermore, the DSRM focus on end-user research to discover the needs and values of the users, which aligns with the research objective of analysing the specific manufacturing environment and deriving intelligent-product structures. With the development of the conceptual framework, the focus lies on utility to solve the problem in an application-oriented way. The development of a new theory is not addressed. The artefact relies on general theory, experience, creativity, and general problem-solving processes (A. R. Hevner & March, 2003, p. 111). This two-sided approach of general theory and soft factors seeks to enhance the creation of innovative artefacts such as the conceptual framework of intelligent-product structures.

1.6 Thesis structure and chapter outline

The thesis structure is derived from the research questions, objectives, and design. The first part includes the chapters of the introduction, the extensive literature review, and the contextualisation of the research and provides the foundation for the conceptual framework development. In the second part, the requirement specification and the development of the conceptual framework according to the guidelines of Jabareen (2009) and van Aken and Berends (2018) are conducted. Nevertheless, information research on side aspects of the framework will continue in the development and evaluation phase of the framework. The framework evaluation consists of verification and validation and is presented in the third part of the thesis. It is essential to mention that iterative processes are possible after the framework evaluation is examined. Therefore, a critical reflection of the predefined requirements and their feasibility is required in the framework development and evaluation phase. Finally, the fourth part of the thesis provides the summary and further research. In Figure 4, the detailed chapter layout provides insights into how the research progressed.

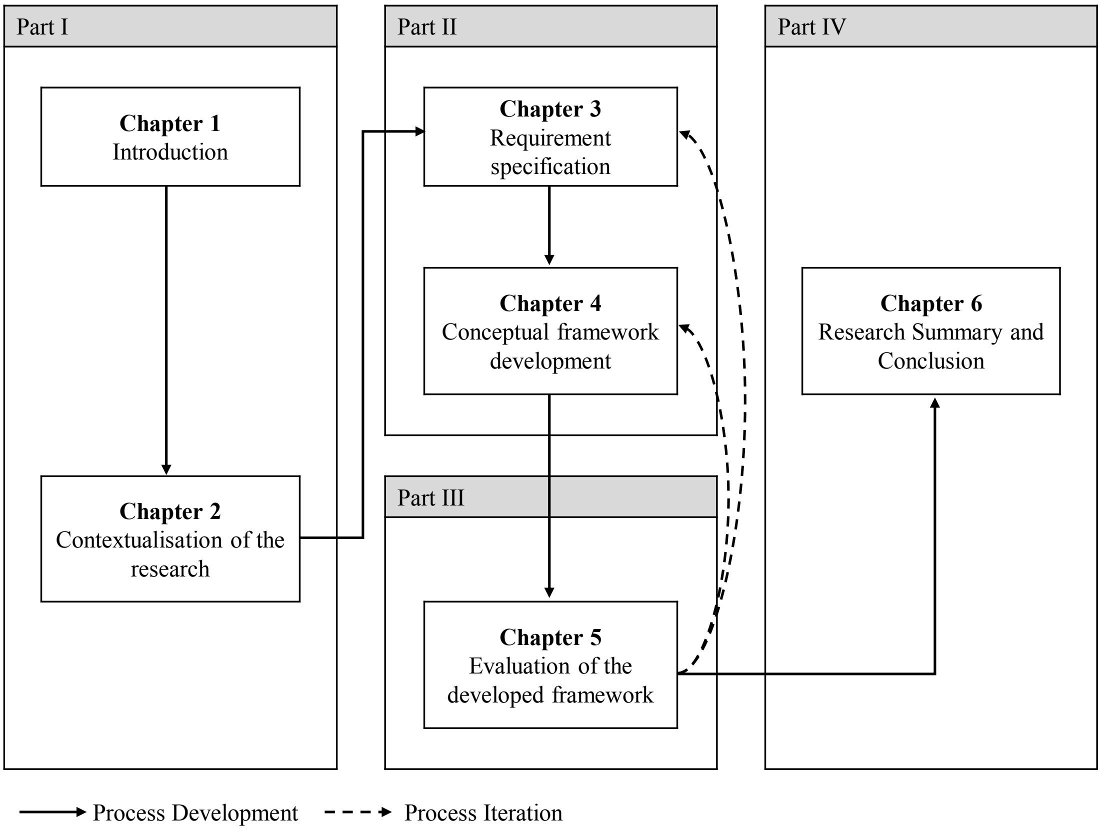

Figure 4: Detailed chapter layout schematic

Chapter 2. Contextualisation: FMS, intelligent product, and technology

The following chapter is devoted to reviewing different topics in the literature that are relevant to the described problem statement. The literature review consists of three parts which build on each other. First, fundamental knowledge about flexibilities in manufacturing is provided. Subsequently, the focus is shifting to intelligent products in flexible manufacturing systems. Finally, the chapter establishes the fundamental technologies for intelligent products. The overriding goal of the literature review is to evaluate the current state of intelligent products for manufacturing systems on which the remainder of the project can be based.

2.1 Flexible Manufacturing System - FMS

The idea of FMS was proposed in England in the 1960s by David Williamson and described a machining system that could operate the whole day (24 hours) without any human operator (Yadav & Jayswal, 2018, p. 2464). An acknowledged definition of FMS in manufacturing research has been provided by Browne et al. (1984), who defined an FMS as “an integrated, computer-controlled complex of automated material handling devices and numerically controlled machine tools that can simultaneously process medium-sized volumes of a variety of part types”. Therefore, the workstation, automated material handling, and computer control are the three main elements in a FMS. FMS aims to improve performance with analytical methods, simulations, and artificial intelligence (Yadav & Jayswal, 2018, p. 2464). Section 2.1 focuses on manufacturing flexibilities, its purpose, dimensions, and measurements, based on Browne et al. (1984) and Sethi and Sethi (1990).

2.1.1 Definition and purpose of various flexibilities in manufacturing

Manufacturing flexibility is the primary mechanism to survive the current market environment. The degree of flexibility for a manufacturing company represents a critical issue. On the one hand, flexibility is required to compete with firms and deal with the critical factors of product individualisation, short lead times, frequent market changes and cost pressure. On the other hand, flexibility is not always desirable, as it influences the company's profitability (Terkaj et al., 2009, p. 48). The current manufacturing environment has become highly uncertain and continuously changing due to shorter product life cycles, increased product variety, and increased level of customization. Academics and practitioners must work in a highly uncertain and constantly changing environment. The trend will continue to increase in the twenty-first century (Prasad & Jayswal, 2019, p. 187) and requires flexibility. According to a study with managers, Upton (1995) reported that 40% of the flexibility improvement efforts are unsuccessful. The causes for these failures are the precise identification of the individual and relevant flexibility dimensions, the approaches for measuring flexibility, and the influencing factors (Upton, 1995). It demonstrates that flexibility has been recognized as a tool. However, managers find it challenging to use. Today there still exist open research issues and problems with manufacturing flexibilities (Pérez Pérez et al., 2016, p. 3133), which require product-tolerant manufacturing systems.

The need for flexibility arises from the already mentioned uncertainty and the continuously changing environment. There is an important distinction made between unplanned and planned changes. According to Jain et al. (2013), unplanned changes occur independently of the system’s intentions. On the other side, planned changes arise from management action, aiming to change an aspect or relationship of the environment (Jain et al., 2013, p. 5948). There is no general agreement on the definition of manufacturing flexibility because researchers and companies perceive it in their own way. However, researchers and companies agree that manufacturing flexibility must be divided into multi-dimensional concepts (Jain et al., 2013, p. 5947). In this thesis, the classification of Browne et al. (1984) and Sethi and Sethi (1990) is applied, as both studies provide a comprehensive definition of flexibility dimensions, measurements and their purposes. The multi-dimensional concept that Browne et al. (1984) introduce consists of eight dimensions. Sethi and Sethi (1990) extended this classification by adding three more flexibility dimensions. The resulting 11 dimensions are organised into the three levels of essential or component flexibility, system flexibility, and aggregate flexibility (Sethi & Sethi, 1990, p. 297). Table 4 represents the three levels of flexibility and the associated flexibility dimensions.

Table 4: The three flexibility levels with the associated flexibility dimensions based on (Sethi & Sethi, 1990, p. 297)

Level 1: Basic flexibility or component flexibility	Level 2: System flexibility	Level 3: Aggregate flexibility
Machine flexibility	Process flexibility	Program flexibility
Material handling flexibility	Routing flexibility	Production flexibility
Operation flexibility	Product flexibility	Market flexibility
	Volume flexibility	
	Expansion flexibility	

Table 5 shows the flexibility dimensions of Sethi and Sethi (1990) along with their definition and purpose. It is essential to mention that flexibility has multiple dimensions. The flexibilities marked with an asterisk are particularly relevant to the present work on intelligent products. However, the selection and subsequent relationship of the flexibility dimensions also depend on the company's manufacturing's environmental conditions and usage factors (Parker & Wirth, 1999, p. 447).

Table 5: Flexibility dimensions and their definitions and purposes[1]

Flexibility dimension	Definition	Purpose
Machine flexibility	The ability of a machine to execute multiple operations without significant effort in switching between the operations.	Machine flexibility represents the basis for other flexibilities. It has the potential to save inventory costs by smaller batch sizes and increase utilization.
Material handling flexibility*	The ability to efficiently move parts for proper positioning and processing through the manufacturing facility. It covers the loading and unloading of parts and the transport from machine to machine.	Material handling flexibility acts as a basis for various system flexibilities. It has the potential to improve machine availability and utilization.
Operation flexibility	The property of a part that can be produced with alternative process plans. An alternative process plan can be a substitute consisting of different operations replaced by the original steps.	Operation flexibility mainly contributes to routing flexibility. It has the potential to simplify the scheduling of parts in real-time and increases machine reliability and utilization.
Process flexibility*	The ability of a manufacturing system to produce a set of part types without significant setups. Here, the manufacturing costs are nearly stable over widely ranging product mixes.	Process flexibility has the potential to reduce batch sizes and inventory costs. In addition, machines can be shared across different processes, and there is no need for machine duplicates.

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[1] The asterisk highlights the flexibility dimensions, which the intelligent products can influence.

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Routing flexibility*	The ability to produce a part of a product by alternative routes through the system. This may include the usage of different machines and different operations.	Routing flexibility enables flexible scheduling of parts by better balancing of machine loads. It makes it possible to continue producing a set of parts even in the event of a machine failure.
Product flexibility	The ability to add or substitute new parts for existing products in a manufacturing system. The addition of parts always involves some setup.	Product flexibility enables the potential for companies to respond quickly to market or customer changes through newly designed products.
Volume flexibility	The ability of the manufacturing system to produce profitably at different production volumes.	Volume flexibility allows companies to adjust the production system to fluctuations in demand upwards and downwards.
Expansion flexibility	The ability of the manufacturing system to increase the capacity (output time) and capability (quality, the technological state) when needed.	Firms should consider expansion flexibility with growth strategies, reducing implementation time and costs for new products.
Program flexibility*	The ability to operate a manufacturing system unattended for a long enough period.	Program flexibility increases the throughput by fewer setup times, as the system can work untended. In addition, the adequate capacity of the production system increases through the higher throughput.
Production flexibility	The ability of the manufacturing system to produce several part types without adding major capital equipment.	Production flexibility minimises the implementation time for new products or modifications to existing products.
Market flexibility	The ability of the manufacturing system to adapt to a changing market environment.	Market flexibility enables a firm to survive in constantly changing market environments.

The main criteria for selecting the relevant flexibility dimensions for this work is whether there is a possible direct influence by the intelligent product or product carrier. Therefore, the reasons for excluding some flexibility dimensions are explained.

In the category of essential flexibilities, machine flexibility is not considered in this work, as the intelligent product or product carrier has no direct influence on the manufacturing system. According to Sethi and Sethi (1990), the technological sources of machine flexibilities are in the machine and can be improved by numerical control, easily accessible programs, or tool-changing devices. However, it is necessary for other levels of flexibility. Therefore, it influences intelligent products indirectly to the extent that the more operations a machine can perform, the more transportation and processing opportunities the intelligent product has. In addition, intelligent products or carriers do not directly influence the operation flexibility since the product refers to the number of different processing plans. The operation flexibility is high if the product consists of modular and standardized components, easily accessible for various operations. An intelligent product and carrier use the operational flexibility for communication and task allocation to the resources, enabling flexible processing plans. Likewise, there is no focus on product flexibility, as it mainly depends on machine flexibility like an efficient CAD interface, rapid exchange of tools and dies, and flexible fixtures (Sethi & Sethi, 1990, p. 305). Intelligent products or product carriers can influence the flexibility dimensions of volume and expansion in terms of speed of response and range of variants, as well as the ease of achieving capacity and capability improvements. However, the thesis does not focus on these dimensions of flexibility, as there is an indirect correlation. In addition, production flexibility and market flexibility are not directly influenced by intelligent products or product carriers. The production flexibility depends on the variety of various entities, such as the variety and versatility of the machines, the flexibility of the material handling system, and the control system (Sethi & Sethi, 1990, p. 312). As the intelligent product or product carrier does not directly influence all three entities, this dimension of flexibility is not particularly relevant. Furthermore, the market flexibility depends on the product, volume, and expansion flexibilities, which are already not classified as particularly relevant to the thesis. In the next chapter, different approaches for measuring flexibility are presented for the intelligent product-relevant dimensions of flexibility.

2.1.2 Approaches for measuring flexibility in manufacturing

Since flexibility is a multidimensional and situational variable, it is difficult to measure. Slack (1983) states that one indicator cannot measure flexibility. Thus, there is not a single concept for defining flexibility measurements in manufacturing, and the different concepts need to be applied to other production objectives of the product specification. In addition, flexibility indicates potential, which relies on relevant expert or manager opinions to establish the system's capabilities (Slack, 1983, p. 12).

Due to difficulty in measuring flexibility, the researchers distinguish between two approaches of qualitative and quantitative approaches for the measurement of flexibility. The difference between these two approaches is that the qualitative approach uses linguistic assessment, whereas the quantitative approach identifies exact numerical values (Jain et al., 2013, p. 5955). Previous researchers have attempted measurements for most of the flexibility dimensions listed for the relevant flexibility dimensions. Table 6 explains the relevance of the flexibility dimension to intelligent products or carriers in manufacturing by referring to existing use cases. In addition, the quantitative measurements method is provided to the extent possible (Sethi & Sethi, 1990, pp. 296–314).

Table 6: Measurement of flexibility dimensions and their relevance for intelligent products or carriers

Flexibility dimension	Relevance for intelligent products or carriers	Measurements
Material handling flexibility*	The transportation of the workpiece or workpiece carrier is crucial for developing intelligent-product structures, as it influences the movement time between machines. In the supply chain, intelligent products can manage information such as updating the location of shipments or updating product information while passing a checkpoint (Meyer et al., 2009, p. 142).	The number of paths the system supports is divided by the total number of possible paths in the universal system (Sethi & Sethi, 1990, p. 301). It is essential to mention that this ratio closely connects to the routing flexibility. The material handling flexibility also depends on the transport system, as for instance belt conveyors are less flexible than automated guided vehicles. Therefore, Browne et al. (1984) evaluate the various material handling devices regarding their flexibility level (Sethi & Sethi, 1990, p. 301).
Process flexibility*	Considering that the routing versatility improves through an increasing number of alternative ways for processing a part, this positively impacts the ability to change between the production of different products with a minimal delay, according to Parker and Wirth (1999). Therefore, an intelligent product or carrier can manufacture customised products more efficiently, as it can adapt work routing and direct materials to where they are needed. (Meyer et al., 2009, p. 144).	The volume of the set of part types without primary setups (Sethi & Sethi, 1990, p. 303). Process flexibility can be increased through an increasing level of versatile material handling systems and adaptive fixtures (Parker & Wirth, 1999, p. 433).

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Routing flexibility*	Intelligent Products can manage and assist in production planning and control. QSC Audio Products serves as an example for tracking and controlling the movement of the product through the facility by optimising the routing of work (Meyer et al., 2009, p. 144). Multi-agent systems can be applied in shopfloor planning and controlling to solve process planning and integration problems (Meyer et al., 2009, p. 144). The self-organizing manufacturing control system of Bussmann is called West, which determines the routing of the workpiece through the process. Therefore, the workpiece negotiates with one of the following machines. The workpiece auctions its current operations to the machines that bid. In the next step, the workpiece can award a bid to a specific machine, making the workpiece's next target the selected machine (Bussmann & Schild, 2000, p. 13).	(1) Routing versatility: The average number of alternate ways a part can be processed in the given system (Sethi & Sethi, 1990, p. 307). The more alternative routes exist, the more flexible is the system. (2) Routing efficiency of alternative routes: The efficiency of a route considers time, cost, quality and quantity variables (Chang, 2007, p. 125). In general, the more routing alternatives are available for a part, the more flexible is the system. (3) Routing variety: The difference between the routes of producing a part. The difference between the two routes can be calculated as the ratio of the number of different machines visited and the total number of machines in the two alternative routes. (Chang, 2007, p. 128). The greater the differences between the routes are, the more flexible is the system.
Program flexibility*	Intelligent products and product carriers can also speed up and reduce set-ups and change-over in manufacturing. Thereby, the system can run for a more extended period. Applying the single-minute-exchange-of-dies (SMED) confirms the need for intelligent products or product carriers in manufacturing. Therefore, material and tool tracking is required to locate and prepare the parts and feeders in this manufacturing system (Meyer et al., 2009, p. 145).	Sethi and Sethi (1990) mention that program flexibility is evolved due to process and routing flexibilities. Through the usage of sensors, computer controls for detection and the capability of handling unexpected problems, program flexibility can reduce the throughput time. However, there are other scales for classifying the level of automatization, which focus on reducing the throughput time and increasing adequate system capacity (Sethi & Sethi, 1990, p. 311).

The statement of Browne et al. (1984) that ideally, all FMSs would possess the most significant amount of all flexibility dimensions also applies to the relevant dimensions of the intelligent product. However, the costs would be prohibitive on that assumption. In general, the measurement is too simplistic if only the potential of flexibility in the manufacturing is considered, as the degree of equal desirability and cost of the potentials are not negligible. Figure 5 shows different factors and their contribution to affecting the flexibility level. Slack (1983) ranks six facts into hard and soft flexibility fields. Hard factors at the top are process technology, facility layout, job design, production planning, and control system, which are easy to quantify. The other two factors are soft flexibilities, which indicate qualitative and challenging measures of the operation’s readiness and management support. Hard and soft flexibilities have a considerable impact on the behaviour of the manufacturing system.

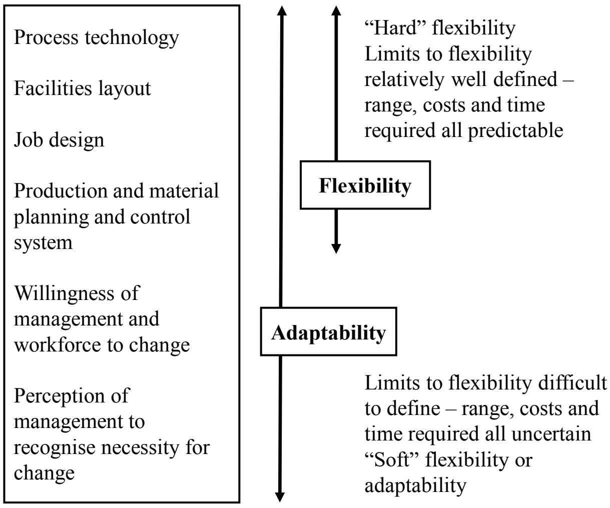

Figure 5: Factors contribution to FMS based on (Slack, 1983, p. 11)

2.2 Intelligent products in flexible manufacturing

This section provides research on intelligent products and starts with its state-of-the-art. This thesis uses the terms smart product and intelligent product interchangeably. Therefore, different authors' notion of intelligence and product intelligence is examined. The second step classifies passive and active products according to their functionalities. In the third step, a linkage between the selected viewpoints of Dörner (1984) and Zbib et al. (2008) is established for a practical problem in an intralogistics context of a FMS.

2.2.1 The nature of problems – complexity factors

A title and abstract analysis are carried out to identify which problems are frequently encountered in manufacturing. Therefore, the two keywords problem and manufacturing are interlinked by the connector "AND" in the title, abstract or author-specified keywords category. For the research subject, Science Direct, IEE, and Web of Science are used as the primary source for the keyword search because they are identified as the most relevant databases for scientific publications in the engineering and management science field. An additional review of similar databases such as Emerald, EBSCO and WISO did not lead to significant differences in the resulting research studies.

The selection of databases indicates that the language is restricted to English, as most of the literature is published in English. Using the same inclusion and exclusion criteria as in Table 7 for a German literature review with the keywords "Problem" and "Produktion" only leads to five papers. In addition, a qualitative analysis of the German results indicates a different scope, as the paper address use cases in the hospital. However, the German search term results in three articles, which have already been covered. Accordingly, the search term is used only in English. In order to narrow down the timeframe, the selected research studies are limited to a time period from 2017 to 2020, aiming to investigate the current problems in manufacturing systems. In addition, all paper types are considered for the research. Using these inclusion and exclusion criteria yields 7618 paper results.

Table 7: Keywords and framework of the database research

Keywords	Language	Timeframe	Paper Type[2]
Problem Manufacturing	English	2017 – 2020	J-AR CO-P RE BO

The following step concerns the title and abstract analysis of the 15929 papers from Science Direct, IEE, and Web of Science databases. The title and abstract fields are analysed by using the software package VosViewer. The fields from which the terms are extracted are based on keywords using a full counting method. In addition, the minimum number of occurrences of a keyword is 20, compiled by 2991 thresholds. For the 2991 terms, a relevance score is calculated. The relevance score is calculated to avoid general terms. For instance, terms such as "conclusion", "new method", and "interesting results", as these general terms provide only a limited amount of information. Therefore, terms with a low relevance score are more general and are consequently filtered out. The focus is on terms with a higher relevance score representing specific topics.

In the final step, the items are filtered by the term problem. The filter aims to provide a classification structure to the question: "What problems can occur in the manufacturing?". It results in 31 different classes, which are listed in Appendix A. Besides the occurrences, the relevance score is presented, defining a topic's specificity. Thereby, the terms: significant, serious, environmental, and combinatorial problem represent more general terms. In comparison, the scheduling and balancing problem comprises more specific topics with more information.

To identify the top five classes in the field of problem and manufacturing, Table 8 represents the ranking according to their occurrences. It is essential to mention that the classes have been grouped into super classes. There are five different scheduling problems (such as job shop scheduling problem, parallel machine scheduling, production scheduling problem, hybrid flow shop scheduling problem, and single machine scheduling). However, it shows that the class scheduling problem is the most common term with an occurrence of 1789. Secondly, there is the control problem ranked with an occurrence of 164, followed by the planning problem with 158 results. The process problem shows an occurrence score of 156, followed by the environmental problem with an occurrence of 131.

Table 8: Top 5 identified problems from the bibliometric analysis

Classes	Occurrences
Scheduling problem	1789
Control problem	164
Planning problem	158
Process problem	156
Environmental problem	131

After identifying and classifying problems in manufacturing, it is essential to scale and categorise them to understand further what kind of problem the manufacturing deals with. In addition, it is crucial to distinguish

[2] Journal Articles (J-AR), Conference Papers (CO-P), Reviews (RE), Books (BO).

between problems because there are different approaches and methods to solve them. The three-part distinction of Glouberman and Zimmerman (2002) is used as a basis for the definition of simple, complicated, and complex problems. A simple problem includes some fundamental issues of technique and terminology with a high assurance of success. According to Betsch et al. (2011), simple problems are well-defined with a single gap that is recognisable. This known gap is to be filled in a plan of action like following a recipe. As a final requirement for simple problems, the existence of a solution needs to be available (Betsch et al., 2011, p. 154).

While simple problems require no expertise, complicated problems such as sending a rocket to the moon require expertise in various fields. There are lots of moving parts, but they operate in patterned ways (Sargut & McGrath, 2011, p. 70). For instance, preparing for a moon landing requires many interactions, but they usually follow a pattern. Knowing the starting conditions, one can usually predict the outcomes of a complicated problem. Generalising complicated problems is not a construction of simple problems. It is not only about the scale of a problem but also about coordination or specialised expertise in a particular area (Glouberman & Zimmerman, 2002, p. 21).

Compared to complicated problems, where one can usually predict the outcomes, the same starting condition can produce several outcomes in a complex system. Thereby, it includes multiple domains with interchangeable effects to one another. According to Betsch et al. (2011), a complex problem consists of several gaps, which partly only appear during the processing of the problem. In addition, it is sometimes difficult to see whether a draft solution is goal-oriented and problem-solving (Betsch et al., 2011, p. 154). Therefore, complex problems involve significant elements of ambiguity and uncertainty of outcome, like raising a child. The problem-solving process is not linear, even if the problem encompasses both complicated and simple subsidiary problems (Glouberman & Zimmerman, 2002, p. 22). The comparative Table 9 examines the distinction between simple, complicated, and complex problems using an orientation framework.

Table 9: Simple, complicated, and complex problems based on (Glouberman & Zimmerman, 2002, p. 22)

Simple	Complicated	Complex
The recipe is essential.	Formulae are critical and necessary.	Formulae have a limited application.
Recipes are tested to assure easy replication.	Sending one rocket to the moon increases the assurance that the next will be OK.	Raising one child provides experience but no assurance of success with the next.
No particular expertise is required, but cooking expertise increases the success rate.	A high level of expertise in a variety of fields is necessary for success.	Expertise can contribute but is neither necessary nor sufficient to assure success.
Recipes produce standardized products.	Rockets are similar in critical ways.	Every child is unique and must be understood as an individual.
The best recipes give good results every time.	There is a high degree of certainty of the outcome.	Uncertainty of outcome remains.

Kurtz and Snowden (2003) have developed the sense-making framework Cynefin to affect the decision-making functionalities of the users by providing powerful new constructs for a wide range of unspecified problems (Kurtz & Snowden, 2003, p. 468). Compared to classification frameworks, consisting of logical arguments or empirical verifications to reach a desirable solution, the Cynefin framework focuses on examining dynamic situations, decisions and perspectives of situations to define a consensus for decision-making under uncertainty (Kurtz & Snowden, 2003, p. 468). The Cynefin framework consists of five domains, including a central area of disorder, which can be seen in Figure 6.

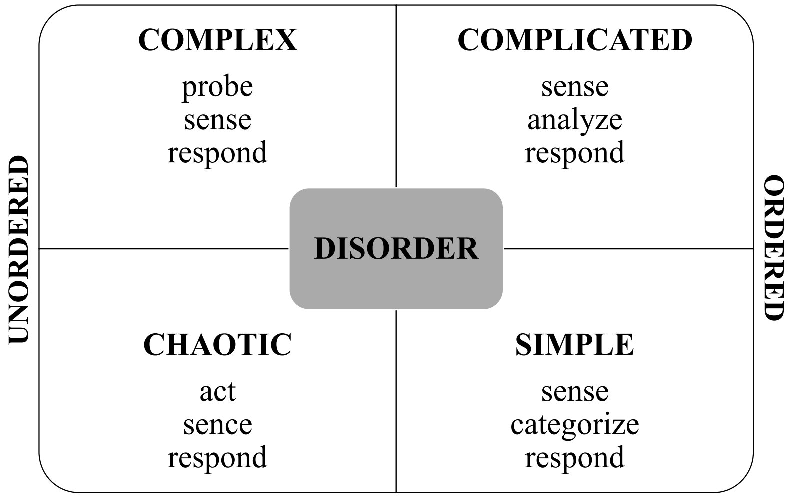

Figure 6: Cynefin framework based on (Snowden & Boone, 2007)

Each domain of the framework requires different actions. The ordered domain includes the simple and complicated contexts of perceptible cause and effect relationships in an ordered universe. The correct answer can be determined for simple problems based on facts and predictive models for repetitive usage. Here, the focus lies on efficiency by using standard operating and structured procedures. The decision-making process includes the three steps of sensing, categorising, and responding according to redetermined practice (Snowden & Boone, 2007, p. 2).

The second domain of complicated contexts consists of stable cause and effect relationships. However, they might be not fully known or visible to everyone, as there is more than one correct answer. According to Snowden and Boone (2007), the category of complicated problems is in the realm of "known unknowns". The terminology known and knowable in this context does not refer to a person's knowledge. It refers to the society or organisation's knowledge. While problem solvers in a simple context follow the standard procedure of sensing, categorising, and responding to a situation, those in a complicated situation need to sense, analyse, and respond to a situation. Analysing data requires experiments, expert opinion, scenario planning, and fact-finding techniques. However, complicated problems desire structured techniques, but assumptions need to be open to examination and challenge (Kurtz & Snowden, 2003, p. 468).

The unordered domain of problems contains complex and chaotic contexts with no apparent relationship between cause and effect. Compared to fact-based management in an ordered universe, the unordered world requires pattern-based management. Many contemporary businesses have shifted to complex situations with unpredictability and flux issues. Therefore, complex problems require creative and innovative approaches to achieve a more experimental management mode. The decision model for complex problems starts with creating probes to make patterns more visible. Afterwards, sensing of these patterns is conducted to respond to the stabilized pattern. Emerging patterns can be stabilised, and their path appears logical afterwards, but a prediction is impossible (Kurtz & Snowden, 2003, p. 469).

The fourth chaotic domain does not have visible relationships between cause and effect. The system is turbulent, and there is no response time to investigate and probe the situation. In chaotic systems, there is no point in searching for the correct answers, which is the realm of unknowable. Regarding the decision model, chaotic situations require quick and decisive actions to mitigate turbulence and immediately sensing the intervention's reaction to establish a response. The response has the chance to shift a situation from chaos to complexity, where the application of pattern-based management is possible. Thereby, the trajectory of the intervention differs according to the nature of space and enables a shift to be complex or complicated (Kurtz & Snowden, 2003, p. 469).

The nature of the fifth context is disorder, which represents the framework's centre (compare Figure 6). The classification of a disordered situation is complicated to identify because multiple perspectives jostle for prominence. The main objective for situations in the context of disorder is to shift to known domains to take appropriate actions. The situation is often divided into constituent parts, which are assignable to one of the surrounding domains to achieve the shift to other domains (Snowden & Boone, 2007, p. 4).

Comparing the Cynefin framework of Kurtz and Snowden (2003) with the problem classification of Glouberman and Zimmerman (2002) indicates several differences. The Cynefin framework is much more than a classification tool, as the framework addresses actives for each domain and proposes a range of interventions to shift issues between different domains. In addition, the Cynefin framework considers five domains, whereas the problem classification framework of Glouberman and Zimmerman (2002) only distinguishes between simple, complicated and complex problems. The aspects of chaotic and disordered situations are not investigated in Glouberman and Zimmerman (2002). The potential of the Cynefin framework has been demonstrated by various applications in the field of product development and innovation (Shao et al., 2022) and portfolio management (Shalbafan et al., 2018) or market creation (van Beurden et al., 2013). Glouberman and Zimmerman (2002) apply the problem classification to the Canadian health care system and argue that repairing the system identifies a complex problem. However, both frameworks aim to improve users' decision-making functionalities, even though the Cynefin framework provides advanced and additional constructs to make sense of a wide range of unspecified problems.

In the following step, the problems from Table 8 are categorised according to the problem classification of Glouberman and Zimmerman (2002) and the Cynefin framework of Kurtz and Snowden (2003). The problem classes' results are displayed in Table 10, and the column "Nature of problem" classifies the problem according to described models.

Table 10: Assessment of the manufacturing problems in terms of simple and complex problems

Classes	Sub-Classes and examples	Nature of problem
Scheduling problem	There is the wrong splitting of tasks among different workstations. The aim is to find the sequence of jobs and transport paths that optimise predefined objectives (Komaki et al., 2019, p. 2927).	Complicated One objective of the scheduling problem is the minimum makespan, where formulae are critical and necessary. The expertise in production workflows or linear programming formulation increases the success rate.
Control problem	Vertical communication at the control level and horizontal communication between the entities at the shop floor level must be managed. A sub-category of control problems is balancing issues. Unbalanced station workloads aim to assign tasks to work stations of an assembly line to minimise the sum of all idle times (Scholl, 1995, p. 1).	Complicated In order to achieve manufacturing plant control, automation and information technologies are required. Dealing with a high degree of complexity leads to complicated problems in manufacturing control systems. Feedback control methods (Xu & Wang, 2017) or event-driven optimal control methods (Nenchev et al., 2018) enable a high degree of certainty of outcomes.
Planning problem	The diversity of the products and fluctuation of the order stream makes resource planning and allocation difficult (Rekiek & Delchambre, 2006). Machinery breakdowns or late arrival of production parts can lead to unstable manufacturing.	Complicated It is complicated to identify the set of products because there are gaps that partly appear during the processing. Even if there are frequent engineering and production disturbances changes, there is a high degree of certainty of outcomes.

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Process problem	Manufacturing process planning functions aim to author, simulate and manage manufacturing information. Manufacturing process planning involves scheduling problems such as operation sequencing, machining, assembly process planning, and assembly line planning (L. Chen et al., 2020).	Complicated Manufacturers face the complicated challenge of producing individual and high-quality products within a short development time. There are solution approaches such as multi-agent systems, evolutionary algorithms, or game theory to solve process problems (Erden et al., 2019). A high level of expertise and knowledge increases the likelihood of success.
Environmental problem	Today's production exploits natural, biological, chemical, and physical resources. Besides the profit-driven goals, carbon emissions get awareness in the manufacturing industry(R. Zhang, 2018).	Complicated Environmental issues are introduced into manufacturing strategies and influence nearly all departments. Therefore, formulae are critical and necessary to decide on the potential implications. Having expertise in the field of sustainability increases the likelihood of success.

The identified problem classes can be managed by hierarchical organisational structures and decision-making methods, which would not be suitable for complex problems. Therefore, the identified problem classes in manufacturing are classified as complicated. Kurtz and Snowden (2003) state that complicated manufacturing problems require experiments, expert opinion, scenario planning, and fact-finding techniques. However, these problems can also get complex when the rules in a particular problem class must be adjusted or changed. Especially in optimisation processes for the FMS, several of the identified problem classes interact together, leading to multiple or even competing objectives with different solutions. These complex problems are often more generic and cover a broader topic. The following chapter details solving complex problems and examines Dörner's operational intelligence concept.

2.2.2 Definition of intelligence from a psychological perspective

Intelligence is the most researched characteristic in psychology, which has many definitions.[3] The thesis is based on Dörner's definition of operational intelligence as the ability to solve complex problems (Dörner, 1986, pp. 295–298). Typical attributes of complex problems are:

i. Complexity.
ii. Multiple and contradictory objectives.
iii. Lack of transparency.
iv. High connectivity with many interactions.
v. The momentum of its own.

According to Dörner (1984), complexity is caused by numerous individual variables. Therefore, the complexity of the problem situation is determined by the number of individual variables of the system, the number of possible interventions, and their mutual influence. The attribute expresses an actor who needs to optimise a reality section regarding multiple and contradictory objectives. Many variables in the complex situation are not accessible to the actor, which defines the lack of transparency. The situation's dynamic reflects the role of time and developments within the system. High connectivity describes the phenomenon that variables do not remain isolated and have mutual dependencies between the involved variables. An

[3] The different views of the term intelligence are examined in Rost (2013).

intervention that is intended to affect a specific part of the system also influences other parts of the system. The last attribute of complex problems is the momentum of its own, which describes a system that evolves independently of the actor's intervention (Dörner, 1986, pp. 295–298).

In addition, Dörner (1984) has defined the structure of the problem-solving process with a focus on the process determinants. He defined problem-solving as an attempt to manage a situation without a priori knowledge of behavioural patterns or learning processes. Problem-solving involves synthesising new behavioural patterns or reprogramming processes (Dörner, 1984, p. 11), which are displayed in Figure 7. The process starts with a problem statement. Consequently, the affected person explores his or her memory for a problem relevant material. There are two possible outcomes of the exploration.

In the case of direct exploration, the memory has appropriate or analogue operators for transferring the existing problem to the target situation. Based on the memory's material for problem-solving, the action planning will follow, consisting of a goal-oriented operator chain. Thus, the memory provides a path of actions to solve the problem successfully. However, the problem-solving process consists of more iterative phases for complicated or complex problems, as shown in Figure 7.

In case the memory does not incorporate an action chain to solve the problem, a trial-and-error process starts to combine individual elements into a chain of actions. The problem-solving of a chess game illustrates the problem-solving process descriptive by combining known individual elements in the memory to construct a solution. However, there is also the scenario in which the memory structure does not provide the required elements to solve a problem. In case of an unsuccessful memory search, the start of the action planning is not possible, and an information gathering and exploration phase is required to develop appropriate memory structures. The development of memory structure can be realised by information collection or questions (Dörner, 1984, p. 11)[4].

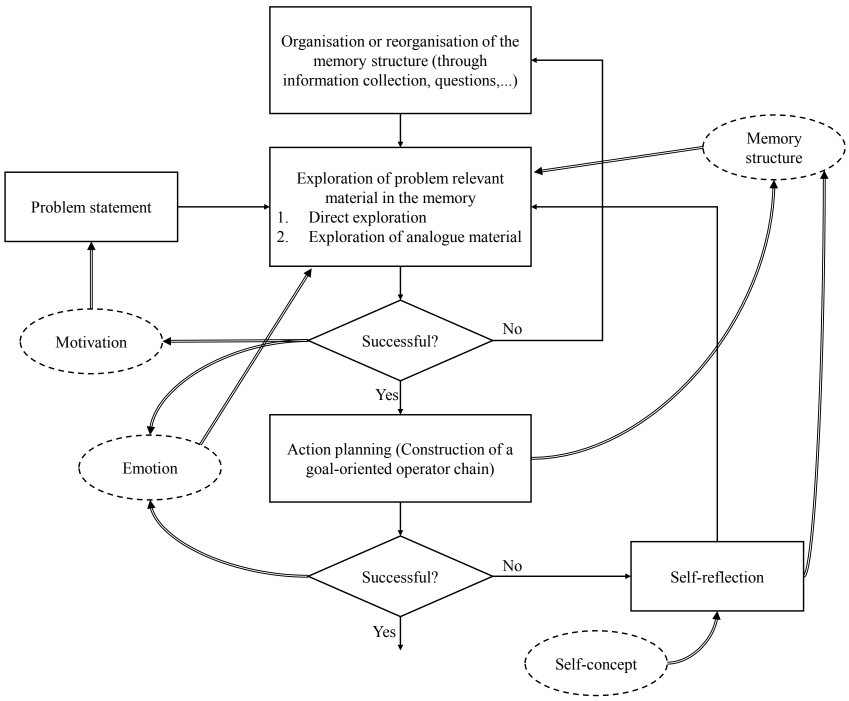

Figure 7: The organisation of problem management author's own representation based on (Dörner, 1984, p. 11)

[4] The theory of question asking for building memory structures is addressed in Flammer (1981).

Besides the global structure of problem-solving, motivational and emotional factors modify the problem-solving process. However, the modifications are not considered in the thesis, as it does not apply to product intelligence, addressed in the next chapter.

2.2.3 Systematic literature review on smart/intelligent products

This chapter aims to systematically review the current knowledge and state of the art for intelligent/smart products. The research follows the Systematic Literature Review (SLR) method (Moher et al., 2009) and the Meta-Analysis (PRISMA) Statement (Nightingale, 2009) to collect and analyse studies neutrally. A particular emphasis is directed on recent developments in industrial research. In particular, the author wants to understand how intelligent/smart products have evolved in recent years. The main research question is: What are intelligent/smart product structures? More precisely, it is subdivided into the topics of classification models and existing applications. Based on this research question and sub-questions, the relevant search keywords are "Intelligent Product" and its synonym "Smart Product", which are combined by the operator "OR". Thus, the studies should contain at least one of the two search terms in their title, abstract, or author-specified keywords. The reference databases are Science Direct, Web of Science, and IEEE, representing the most relevant engineering and management science studies. The timeframe of the studies is limited to the period from 2017 to 2020. These studies investigate the current definitions and classifications of intelligent/innovative products. The SLR only considers English articles published in journals, conference proceedings, or book series. "Intelligent Product" and "Smart Product" are English-language inventions. Therefore, German is not included as a language in the search.

To ensure an objective assessment of the study, inclusion and exclusion criteria are defined for the initial review process. The initial review process contains a title and abstract screening. This process excludes studies that do not focus on the research of intelligent or smart products by providing a definition or classification. In addition, the studies without DOI or ISBN labels are excluded. The eligible studies related to the research questions are studied in full detail by conducting a full-text screening.

Table 11: Inclusion and exclusion criteria

I/E	Criteria	Criteria Explanation
Inclusion	Closely Related (CR)	The focus of the study lies precisely in the research of smart or intelligent products.
	Partially Related (PR)	The focus of the study does not lie on smart or intelligent products. Only part of the content is related.
Exclusion	Without DOI / ISBN or duplicate (WDID)	The study does not provide a DOI or ISBN label or represents a duplicate.
	Loosely Related (LR)	The analysed studies do not focus on the research of intelligent or smart products and do not provide a definition or classification. In this case, smart or intelligent products only appear a few times or are used as a part of another expression.

Table 11 shows the structured research process using the predefined inclusion and exclusion criteria. The first step of identification examines the current state of research using the keywords "Intelligent Product" and "Smart Product" in Science Direct, Web of Science and IEEE databases. The process of identification resulted in 362 studies. Before screening the paper's title and abstract, studies with neither DOI nor ISBN and duplicates are removed. In total, there are 105 studies identified by conducting the WDID exclusion, which leads to 257 papers in the second step. Screening of title and abstract is conducted and results in 43 studies to identify the eligibility of the papers in the context of the research questions. All 43 studies provide a definition or classification of intelligent or smart products. However, only six studies primarily focus on intelligent or smart products and therefore belong to the inclusion category of closely related. Based on these 43 studies, descriptive and content analyses are performed.

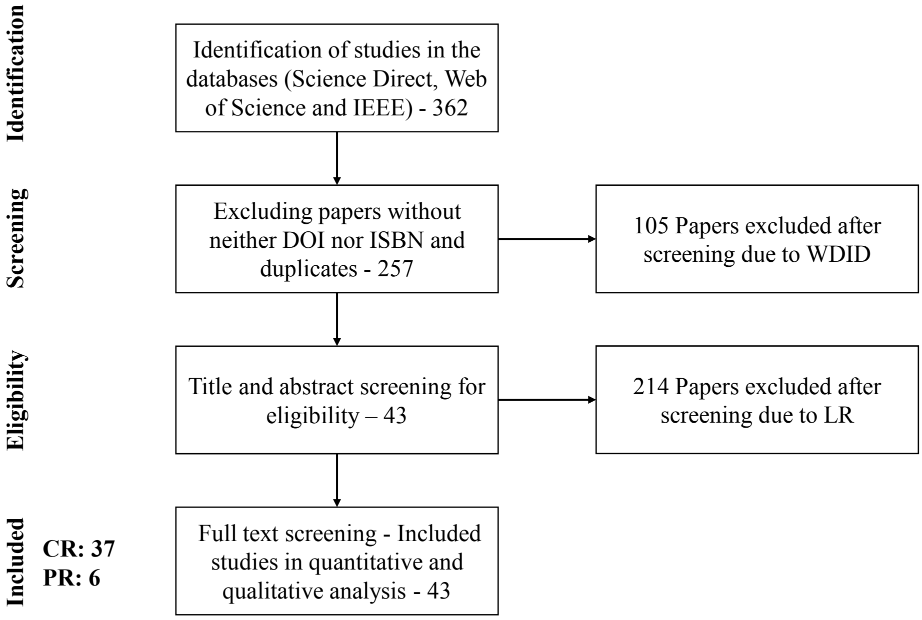

Figure 8: Process steps of the systematic literature review based on the PRISMA flow chart (Moher et al., 2009)

A title and keyword analysis of the relevant papers from the three databases is presented in Figure 8. The software package VosViewer creates a map based on the titles and abstracts of the 43 studies. The criteria for the analysis include a full counting method and a minimum number of occurrences per term of ten. Eleven terms fulfil the criteria. As expected, the term with the highest occurrence is “smart product”, with a total occurrence of 98, followed by the term “product” and “system”. In Figure 9, the size of the dots reflects the frequency of the keywords and can be applied as the distribution key for the remaining terms. The term “smart product” has a central role, as there is a strong linkage to the other terms. In addition, the analysis provides evidence that the included papers focus on smart/intelligent products. Applying the same criteria from the conducted title and keyword analysis to the 257 studies from the screening phase demonstrates a different result. In the context of the 257 studies, the most frequent term is “smart pss”, which represents the shortage of smart product-service systems.

In conclusion, using the initial keywords of “Smart Product” and “Intelligent Product” does not lead to the desired solution of providing a selected review on smart/intelligent product definition and classification. Thus, the 214 papers focus on Smart Product-Service Systems (sPSS) are excluded and not further examined in the analysis. The 214 papers focus on business-to-business-oriented artefacts and models to provide more customer value, extending over the entire lifecycle (Boßlau, 2021, p. 566). Thus, the papers do not focus on the research of intelligent or smart products and do not provide a definition or classification. In addition, the exclusion is verified by the results from the title and keyword analysis.

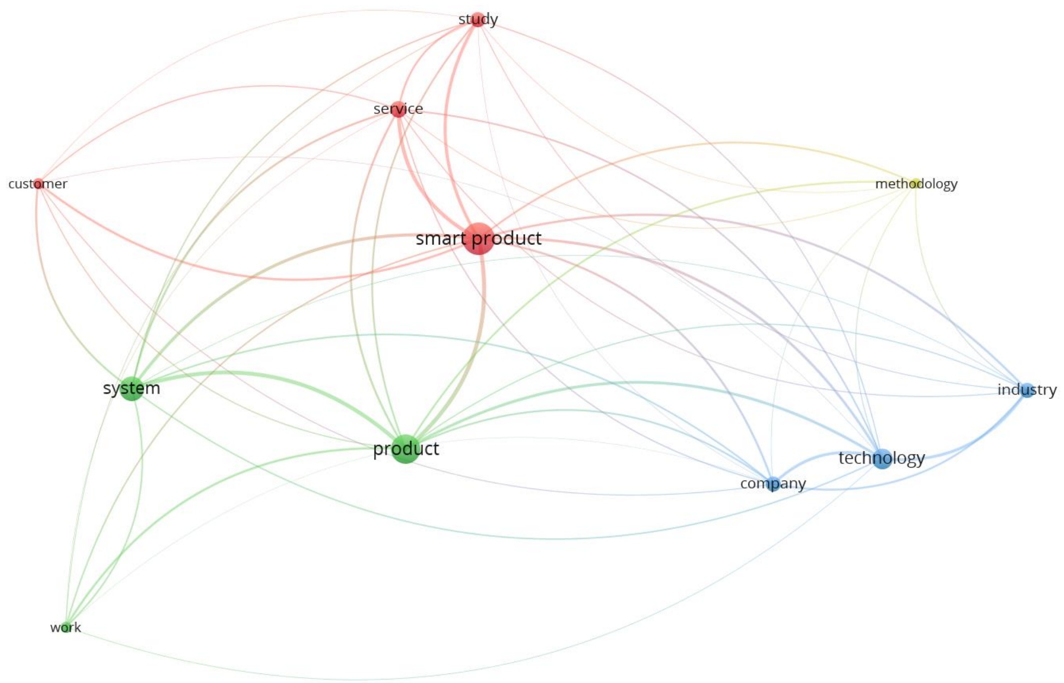

Figure 9: Analysis of title and keywords of 43 studies

Besides Dörner's definition of intelligence, many authors have interlinked the notion of intelligence with the notion of product. However, they often use the terms in different ways. Thus, there are various definitions of smart or intelligent products observed in the SLR:

i. Smart/intelligent products can sense, record and communicate information about themselves and their environment for specific targets (Alcayaga et al., 2019, p. 624).
ii. Smart/intelligent products use data throughout the life cycle to improve energy and resource efficiency (Kondoh et al., 2021, p. 382).
iii. The physical component of smart/intelligent products is supported by technologies to collect, monitor, control, and optimize user data (Meindl et al., 2021, p. 4).
iv. Smart/intelligent products have three core elements: physical components, smart components, and connectivity components (Miranda et al., 2019, p. 2385).
v. Smart/intelligent products consist of physical and digital parts (Pardo et al., 2020, p. 205).
vi. Smart/intelligent products are characterised by physical, intelligent, and connected components with the ability of a digital upgrade using internet-based services (Schuh et al., 2019, p. 229).
vii. Equipping smart/intelligent products with sensors, identifiable components, and processors, which carry information about the customer, enables the data transmission to the manufacturer (Ahmed et al., 2019, p. 7182). Thus, the manufacturers can understand the customer's behaviour and needs almost in real-time.

These definitions focus on specific perspectives, application fields, and different parts of the product lifecycle. Most researchers such as Lenz, MacDonald, et al. (2020), Attajer et al. (2019), Romero et al. (2020), and Schuh et al. (2019) use intelligent and smart products as a synonym, as most of the characteristics are similar (Schuh et al., 2019, p. 229). However, there is a distinction in the application area and perspective. Most smart products are considered from a user-centred perspective. They are utilized during the middle-of-life phase of the product lifecycle to provide additional services to their original purpose. However, intelligent products incarnate a manufacturing-centred perspective, such as connected machines or tools (Lenz, Pelosi, et al., 2020, p. 39).

Table 12 shows a synopsis of the selected perspective and individual definition approach studies. It highlights that most articles from the SLR (43 papers) are based on one established definition or a combination of definitions. It is essential to mention that column four also includes the combined definitions. In total, 37 articles refer to existing definitions, of which ten are based on combined definitions. Merely six articles provide their definition and interpretation of intelligent/smart products.

Additionally, the analysis categorises three definition perspectives: Product, Product User, and Manufacturing. Most articles focus on the product perspectives (21 articles) and define the product's functionalities using technical and functional terms. Since there is a compelling interest in the innovation and marketing field, 15 definitions of intelligent products focus on the product user. The SLR analysis also indicates an application potential in the manufacturing field. Thus, seven definitions of smart/intelligent products examine a manufacturing perspective.[5]

Table 12: Synopsis of selected studies on perspective and respective definition approach

Definition Perspective	Article	Own definition	Based on established definition	Based on combined definitions
Product	(Alcayaga et al., 2019; Cao et al., 2021; Dehnert & Burkle, 2020; Jiang et al., 2019; W. J. Lee, 2019; Lenz, Pelosi, et al., 2020; Y. P. Li et al., 2019; Oluyisola et al., 2020; Pan et al., 2019; Pardo et al., 2020; Popolo et al., 2021; Raff et al., 2020; Riedelsheimer et al., 2021; Romero et al., 2020; Schuh et al., 2019; Tomiyama et al., 2019; Wan et al., 2021; W. M. Wang et al., 2020; X. Gu, 2020; Zheng et al., 2020)	3	18	3
Product User	(Ahmed et al., 2019; Attajer et al., 2019; Dong et al., 2022; Frank et al., 2019; Gentner et al., 2018; Henkens et al., 2021; Holst et al., 2020; Kahle et al., 2020; Kondoh et al., 2021; Lu et al., 2019; Meindl et al., 2021; Miranda et al., 2019; D. Thomas et al., 2019; Zapata et al., 2020)	1	14	5
Manufacturing	(Antons & Arlinghaus, 2020; Kovalenko et al., 2019; Najlae et al., 2021; Sanchez et al., 2020; Thurer et al., 2021; Yang et al., 2021; H. Zhang et al., 2020)	2	5	2
Sum		6	37	10

The listing mentioned above of product intelligence definitions refers to and adapts existing explanations of McFarlane et al. (2013), Porter and Heppelmann (2014), Meyer et al. (2009) and further authors. To provide an overview of the relevant smart/intelligent references, a ranking of the most cited authors in the 43 studies is conducted. The criteria for counting a study are:

i. The study refers to a definition of intelligent products and provides a reference in which the corresponding author is relevant for the frequency counting.
ii. A study can only be counted once, even if the study lists more than one reference from the same author.

[5] A more detailed analysis of the 43 articles is provided in Appendix B.

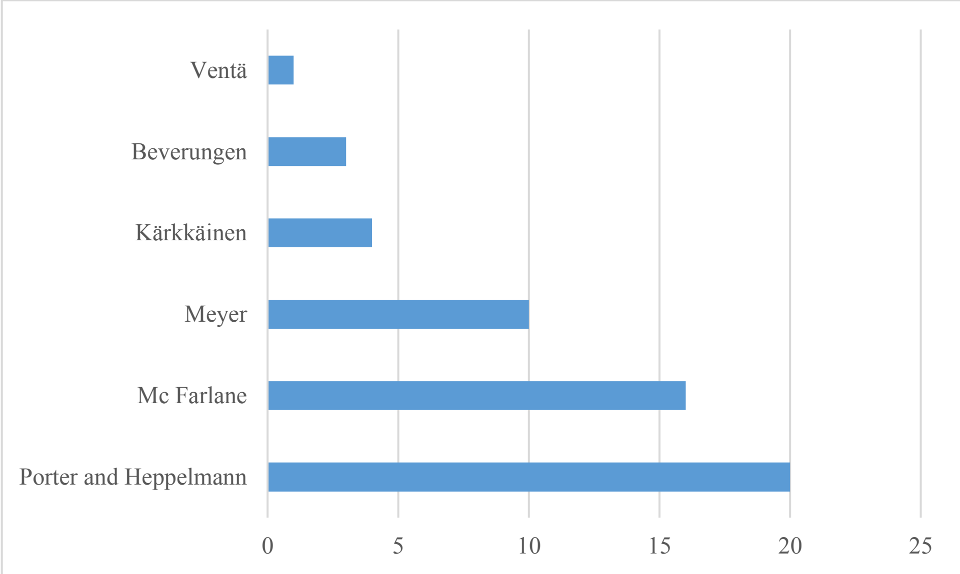

Figure 10: Frequency ranking of corresponding authors in the SLR

Figure 10 presents the frequency ranking of the corresponding authors of the 43 studies. Considering the abovementioned criteria of frequency ranking provides the result that Porter and Heppelmann appear 20 times in the 43 studies. Thus, his definition of smart/intelligent products occurs most frequent. According to Porter and Heppelmann (2014), the technologies of smart/intelligent products are grouped into connectivity, monitoring, control, optimization, and autonomy. Monitoring and connectivity describe the usage of sensors and external data sources to enable notifications of changes. The embedded sensors provide connectivity as they allow the communication of products in a system. Remote control is possible if the products are connected to cloud services. The usage of monitoring enables optimization of product operation and predictive diagnosis for maintenance. The combination of monitoring and optimization enables autonomy for self-diagnosis and self-maintenance. In addition to the functionalities, each smart/intelligent product consists of three core elements: physical components, smart components, and connectivity. Consider a car as a smart/intelligent product. It consists of the engine block and tyres as physical components, the sensors and microprocessors as smart components, and the ports and antenna as connectivity components. (Porter & Heppelmann, 2014, p. 72).

The second most frequently cited study in the SLR is provided by McFarlane et al. (2002), which examines intelligent products in manufacturing control and management. 16% of the 43 related studies have referenced the "Auto ID systems and intelligent manufacturing control" study, which provides a comprehensive definition of smart or intelligent products (McFarlane et al., 2002). Considering the studies in which McFarlane participated as the corresponding author leads to a frequency of 16 studies. According to McFarlane et al. (2002), intelligent or smart products are physical and information-based representatives of an item with the following functionalities (McFarlane et al., 2002, p. 53):

i. Unique identification.
ii. Communication to agents in its environment.
iii. Retention of data about itself.
iv. Deployment of a language to display its features.
v. Relevant decision-making to its destiny.

Meyer et al. (2009) have been referenced in ten studies and are therefore ranked in the third place. In 2009, Meyer et al. provided a survey on intelligent products by describing existing definitions and classifications for intelligent products. The definition of intelligent products focuses on McFarlane et al. (2002), Kärkkäinen et al. (2003), and Ventä (2007) (Meyer et al., 2009, p. 139). According to Kärkkäinen et al. (2003), intelligent/smart products are defined in the context of the supply chain, in which products should be aware of where they are transported and how they are handled. The phenomenon is called inside-out control of products

(Kärkkäinen et al., 2003, p. 143). Ventä (2007) does not focus on manufacturing or supply chain management applications but on running and maintaining products in the use phase. Smart/intelligent products require sufficient embedded computing power to react, adapt to environmental conditions, and communicate directly to other agents (Ventä, 2007, p. 13). Both smart/intelligent product definitions of Kärkkäinen et al. (2003) and Ventä (2007) are addressed in the survey of intelligent products by Meyer et al. (2009).

With only one reference in the 43 studies, the second least cited author is Beverungen et al. (2019). They define smart/intelligent products by eight properties: Unique identification, localizing, connectivity, sensors, storage and computation, actors, interfaces, and invisible computers. However, the usage and combination of the eight properties enable smart services. Smart/intelligent products are required to deliver smart services, but Beverungen et al. (2019) focus on business models and smart product-centred marketing and sale approaches (Beverungen et al., 2019, p. 10).

In addition to Beverungen et al. (2019), various research in the SLR focused on the consumer's advanced services and product-service systems (PSS), which are not included in the final analysis of intelligent or smart products. PSS focuses on providing business models for real consumer needs by combining the product and services into a single solution. Thus, PPS enables an innovative business approach and addresses the design phase of products to provide pro-environmental outcomes (Lu et al., 2019, p. 2).

The next step provides existing classification models, which are based on the results from the SLR. Therefore, Table 13 summarises the different classification models provided in the articles from the SLR. The summary focuses on the classification levels, their definition, and elaboration on whether it refers to already existing works. 21 % of the 43 SLR studies (nine articles) provide a classification model for intelligent/smart products. The following paragraphs systematically present the models.

Besides the definition of smart/intelligent products from Meyer et al. (2009), referenced ten times in the SLR, they additionally provide a three-dimensional classification model for smart/intelligent products. Since the individual definitions do not cover all aspects of the field, a comprehensive classification for analysing different information architectures is required. The three orthogonal dimensions consist of Level of intelligence, Location of Intelligence, and Aggregation level of intelligence. The level of intelligence rages from passive products to pro-active entities. Thus, the dimension consists of three categories: Information handling, problem notification, and decision making. The second dimension of smart/intelligent products distinguishes between intelligence through network and intelligence at the object. The third dimension of aggregation level of intelligence is crucial, as various products are composed of parts, which can also be individual products. There is a distinction between intelligent items and intelligent containers, which are aware of their components (Meyer et al., 2009, p. 140). The two articles from Lenz, MacDonald, et al. (2020) and H. Zhang et al. (2020) refer to the three-dimensional classification model of Meyer et al. (2009) (see Table 12). However, H. Zhang et al. (2020) extend the three-dimensional model by the product life cycle as the fourth dimension.

Similar to the level of intelligence from Meyer et al. (2009), Bertelsmeier et al. (2015) provide a product classification of four levels: (i) identification, (ii) memory capacity, (iii) data processing, and (iv) interaction. The product in Class 1 only has limited identification functionality, such as a unique identification. In addition to the identification, a Class 2 product has the memory capacity to store information. If the product consists of data processing capacities such as a nearfield communication chip, it is classified in Class 3. In Class 4, the product can interact with its environment (Bertelsmeier et al., 2015, p. 2). The four levels of intelligent products are referenced once by Antons and Arlinghaus (2020) (see Table 12).

Najlae et al.(2021) provide a further classification model derived from McFarlane et al.'s five functionalities of smart/intelligent products. The classification distinguishes between two levels. In the first level of intelligence, the product can communicate its current state, which represents the functionalities of unique identification, communication, and data storage. The enhancement in level two also enables decision-making based on the observed product state. Participation in the decision-making process is guaranteed by the product's deployment of a language to analyse its characteristics and current state (Najlae et al., 2021, p. 452).

Another morphology model of digital functions for smart/intelligent products has been established by Schuh et al. (2019). The model consists of eight different features and individual functions. At least one feature function must be fulfilled to express a smart/intelligent product. Likewise, to the classifications mentioned above, the digital features contain aspects of the place of the intelligence, degree of product intelligence, and type of connectivity. Nevertheless, it provides a more detailed overview and focuses on the type of data collection, interaction, or degree of independence (Schuh et al., 2019, p. 231). A further distinction of the features and explanation of each digital function is provided by Schuh et al. (2019).

W. J. Lee (2019) reviews the existing classification models and develops an individual smartness scale for products. The scale is based on various previous scales, such as the leading model of Rijsdijk and Hultink (2009) and Swallow et al. (2005) and is extended to meet today's smart products. The scale consists of eight constructs: Multifunctionality, human-like touch, ability to cooperate, autonomy, situatedness, network connectivity, integrity, and learning functionality. Each of the constructs is characterised by items. For instance, the first construct of multifunctionality has five items, which refer to the product's functionality to perform multiple tasks and needs (W. J. Lee, 2019, p. 156). Further information on the remaining seven constructs is provided by W. J. Lee (2019).

Popolo et al.(2021) also contribute to classifying smart/intelligent products by classifying them according to four archetypes: Digital product, connected product, responsive product, and intelligent product. The model is an extension of Raff et al. (2020). It defines an intelligent product as the highest archetype in the ranking, with the functionalities to interact with the entities in an Industry 4.0 environment. Communication between humans and objects requires basic hardware and intrinsic characteristics of sensors, actors, and processing on the product. The third rank, and therefore the rank previous to the intelligent products, is represented by the responsive products, which also consist of sensors, actors, and connectors to enable a two-way exchange between humans and objects. In this category, the technologies of the Internet of Things (IoT), Cloud Computing and Big Data are represented. However, most current products are classified into the second rank, i.e., the connected products. These products are equipped with basic hardware and connectors such as RFID, sensors and communication technologies. The first rank of digital products is equipped with basic hardware to upgrade the human-machine interface (Popolo et al., 2021, p. 311).

The product requirement classification model of X. Gu distinguishes between the two dimensions of composition and intelligent characteristics. The composition characteristics focus on the unique identification functionalities, the core components of physical, intelligent and connected components, and network functionalities. The second dimension of smart characteristics distinguishes between product and stakeholder-oriented characteristics. The product characteristics address the product's functionalities, such as Perception and monitoring, interconnection, self-decision-making, and self-learning. In comparison, the stakeholder requirements refer to the customer needs and related parties, including human-machine interaction and customized experience (X. Gu, 2020, p. 12).

Table 13: Synopsis of classification models from SLR

Article	Classification	Classification explanation
(Antons & Arlinghaus, 2020)	4 Levels	Identification, memory capacity, data processing, and interaction (Bertelsmeier et al., 2015).
(Lenz, MacDonald, et al., 2020)	3 Dimensions with a maximum of 3 levels each	Location of intelligence (Intelligence at the object, Intelligence through the network), aggregation level of intelligence (intelligent item, intelligent container), and level of intelligence (information handling, problem notification, decision making) (Meyer et al., 2011).

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(Najlae et al., 2021)	2 Levels	L1: Storing of product's data and communication with its environment. L2: Participating in decision-making and deploying a language.
(Schuh et al., 2019)	8 Digital features	Type of collection, place of product intelligence, place of data retention, degree of product intelligence, type of interaction, type of interconnectedness, type of connectivity, and degree of independence.
(W. J. Lee, 2019)	8 constructs	Multifunctionality, human-like touch, ability to cooperate, autonomy, situatedness, network connectivity, integrity, learning functionality.
(Popolo et al., 2021)	4 Archetypes	Digital product, connected product, responsive product, intelligent product (Raff et al., 2020).
(Raff et al., 2020)	4 Archetypes	Digital product, connected product, responsive product, intelligent product.
(H. Zhang et al., 2020)	4 Dimensions with a maximum of 3 levels each	Location of intelligence (Intelligence at the object, Intelligence through the network), aggregation level of intelligence (intelligent item, intelligent container), and level of intelligence (information handling, problem notification, decision making) (Meyer et al., 2011), Extended by the product lifecycle (Leitão et al., 2015).
(X. Gu, 2020)	Two dimension-composition characteristics	Composition and smart characteristics.

After answering the first research question, "What are intelligent/smart product structures?", which includes the definition and classification of smart/intelligent products, a brief overview of existing applications is examined. In total, 60% (26 studies) contain case studies related to smart or intelligent products, grouped by the application field in Figure 11.

- **Product Driven Manufacturing:** The eight studies focused on improving production efficiency. In "Designing decision-making authorities for smart factories" from Antons and Arlinghaus (2020), a distributed control system has been developed to improve the path of the product through the manufacturing process. Likewise, Kovalenko et al. (2019) contribute toward an optimization approach for fulfilling production requirements for a product. Therefore, the product agent explores the local environment, plans, schedules events, and requests desired actions from the resources. Both Lenz, MacDonald, et al. (2020) and Lenz, MacDonald, et al. (2020) optimize the smart manufacturing system by using active sensor systems within smart products in the manufacturing phase. Using the measured data enables improvements in quality and scheduling. Schuh et al. (2019) provide a methodology to improve a development project using digital technologies and smart products. Both, Oluyisola et al. (2020) and Thurer et al. (2021) provide concepts for smart production planning and control and evaluate their concepts based on case studies or simulations.
- **Smart Product Services:** 4 of 7 studies focus on smart product design and development methods for smart products (Ahmed et al., 2019; Gentner et al., 2018; Holst et al., 2020; Pan et al., 2019). Due to the data generated in the manufacturing and product life cycle, there is a higher interaction between the users and designers in the product development phase (Gentner et al., 2018). W. M. Wang et al. (2020) observe the usage phase of smart products to develop future business models according to the trends of usage situations. Therefore, data management and technological infrastructure are required. In addition, Lu et al. (2019) suggest that smart services such as mobile apps and smart shared products significantly influence consumers' perceived ease of use (Lu et al., 2019).
- **Product Life Cycle Data Acquisition:** Studies provided the collected data throughout the product's entire life cycle (Kondoh et al., 2021). According to Gentner et al. (2018), only 23% of the businesses can use and analyse the data from smart products, which is collected from the user in the usage phase

of the product (Gentner et al., 2018, p. 36). The product's lifecycle ends with the process of recycling, which is addressed by Jiang et al. (2019), who developed a decision-making methodology for the recycling choice of smart product components. A more comprehensive investigation on product life cycle management considering the product's enhanced functionalities has been established by Popolo et al. (2021) with a particular focus on end-of-life recovery options.

- **Digital Business Model:** Both studies by Pardo et al. (2020) and Dong et al. (2022) investigate multiple use cases for new digital business models. For instance, there are cases of smart farming, smart tire, smart pumping, or smart crane analysed to become smart products (Pardo et al., 2020, p. 208). In addition, strategic direction and coordination mechanism for the transformation of manufacturing enterprises are achieved by case analysis of smart product ecosystem evolvement (Dong et al., 2022, p. 1035).
- **Product Information Management:** Henkens et al. (2021) provide a scenario-based experiment that investigated the level of smartness and customer engagement and observed that higher levels of smartness result in a higher perceived personalisation than intrusiveness. The results enable companies to boost customer well-being with higher levels of smartness (Henkens et al., 2021, p. 439). Yang et al. (2021) examine different use cases in the field of product information management. An intelligent agent-based prediction system improves operational performance and customer service quality by predicting product demands (Yang et al., 2021, p. 11864).

Due to the minor significance, Maintenance Engineering and Supply Chain Management categories have been excluded from the qualitative analysis.[6]

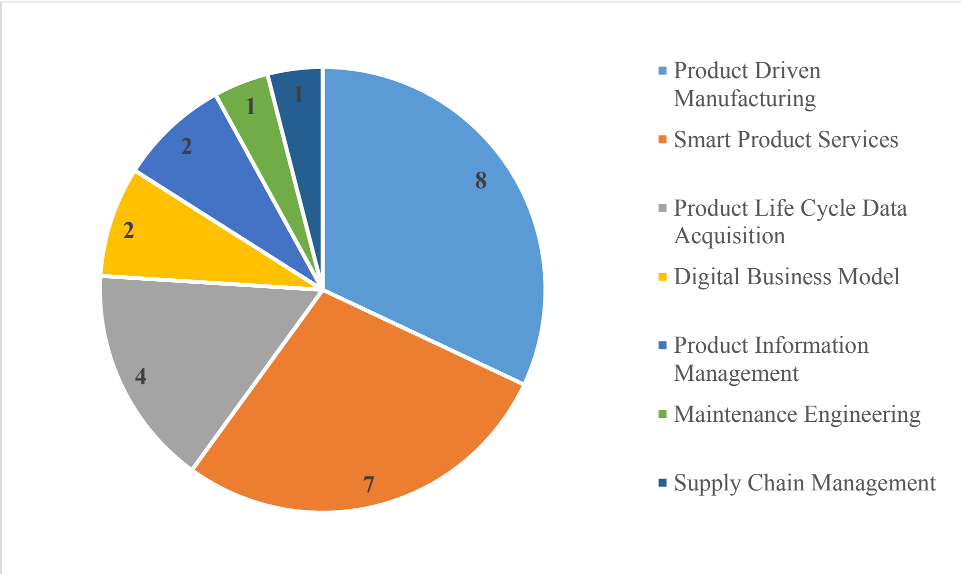

Figure 11: Number of Papers by application field

In summary, no smart/intelligent product definition applies to the entire product life cycle of products. Therefore, the thesis focuses on manufacturing systems and does not highlight business models but provides approaches to developing strategies for value-creation of information handling. Even though Porter and Heppelmann (2014) provide a framework for developing a business strategy to gain competitive advantages in a connected world, they also explain the functionalities of smart, connected products by grouping the products into the four areas of monitoring, control, optimization, and autonomy. Intelligent product definition has been referenced in 20 of 43 studies from the SLR and is applicable for products in the manufacturing

[6] Further information about the application field of Maintenance Engineering and Supply Chain Management is provided in Najlae et al. (2021) and Wan et al. (2021).

environment. Thus, the further development of the conceptual framework is based on Porter and Heppelmann (2014). In addition, McFarlane et al. (2002) define the intelligent product in the manufacturing environment, which directly addresses the scope of the thesis. Furthermore, the synopsis of the smart/intelligent product definitions manifests that the manufacturing product definition all refer to McFarlane et al. (2002) or base their definition on the characteristics (see Appendix B). In combination with Porter and Heppelmann (2014), McFarlane et al. (2002) establish the basis for defining smart/intelligent products in the thesis.

Since the authors from the SLR define smart/intelligent products differently depending on perspectives, application areas, or parts of the product lifecycle, there is also no uniform classification of when a product is considered intelligent. Table 13 shows that the classifications vary in the number of levels and the depth of content. For instance, W. J. Lee (2019) describes eight constructs, including autonomy, human-like touch, and learning functionality the other authors have not examined. Compared to that detailed analysis, Antons and Arlinghaus (2020) and Najlae et al. (2021) use the functionalities of intelligent products to classify smart/intelligent products into two levels. The classification of intelligent-product structures regarding their functionalities serves as the basis for the thesis and is examined in more detail in the following chapter.

2.2.4 Classification of smart/intelligent products

The chapter aims to present a transparent classification model, answering the question: "When is a product classified as intelligent?". The focus for classifying smart/intelligent products lies in the product functionalities in the application field of manufacturing.

The classification of smart/intelligent products started in 2002 with the authors McFarlane et al. (2002) and Wong et al. (2002), who introduced smart products in the manufacturing and supply chain. Both researchers clearly define two levels of product intelligence, which have been represented by Najlae et al. (2021) in the SLR. They characterised a smart/intelligent product as intelligent at Level 2 because it has all five characteristics at this stage. The characteristics can be summarised by having the ability to influence the product's function, communicate its status, and make its own decisions (Wong et al., 2002, p. 2). In 2008 and 2009, the smart/intelligent product was further characterised by an intelligent being and intelligent agent. The intelligent being is responsible for tracking and tracing the real-world entity, whereas the intelligent agent performs the decision-making and goal-oriented behaviour. Both product structures are required to define a product as smart/intelligent (Valckenaers et al., 2009, p. 220). Recently, the scope of smart/intelligent products continues to develop into smart systems and cyber-physical products/systems in the context of Industry 4.0 (Abramovici et al., 2016, p. 185).

In addition to the classification models of intelligent products, which describe the features of an intelligent product, Zbib et al. (2008) introduced a consolidating typology ranging from passive to intelligent products. It consists of the four functionalities: Processing, communication, memorisation, and sensor actuation, which helps to classify different deployment levels. In the first class, the product is assigned to a unique identification number, extended by reading and writing functionalities in the second class. In addition, products in the third class have a computing unit that makes it possible to process data and decide its destiny. Completion takes place in the fourth class with the help of the interaction and communication functionality to interact with the physical environment (Zbib et al., 2008, pp. 248–252). The classification of the different functionalities and classes is presented in 14.

Table 14: Different classes of intelligent products, based on (Zbib et al., 2008, p. 249)

Class 1	**Class 2**	**Class 3**	**Class 4**	**Functionalities**	
			X	**Sensor Actuation**	
		X	X	Decision making	**Processing**
X	X	X	X	Data processing	
		X	X	Service oriented	**Communication**
X	X	X	X	Data oriented	
Read	Read/Write	Read/Write	Read/Write	Data	**Memorisation**
intelligent data product		intelligent decisional product		**Classification**	

Table 14 uses "X" to indicate that the functionality exists in the classes of intelligent products. The complexity of the functionalities increases from the bottom line to the top line. For memorisation, reading functionality indicates that the product needs the ability to read data, for example, when the product can read data on a chip when it moves through the system. This functionality is expanded in Class 2 with writing data on a chip. Besides memorising data, the communication is separated into data-oriented and service-oriented parts. The product has data access capacity with reading and writing abilities for the data-oriented part. On the other side, service-oriented communication is similar to web services and provides advanced information services. The processing is also subdivided into data processing and decision-making. For the reading and storing of data in the first two classes, the processing is already required, which, however, requires lower computing unit functionalities than decision-making. For this reason, a distinction is made here. The last functionality describes the ability to interact with products and devices in the environment (Zbib et al., 2008, p. 250).

Furthermore, Zbib et al. (2008) distinguish between intelligent data products and intelligent decisional products. However, they do not indicate at what stage a product is classified as passive or intelligent. According to Zbib et al. (2008), an intelligent data product is constituted from the functionalities in the first two classes, whereas the last two constitute an intelligent decisional product. For the thesis, this distinction is accepted as a basis. An intelligent decisional product in class three has no ability of sensor actuation and therefore is not able to interact the decision with its environment to initiate an action. In addition, the definition of operational intelligence from Dörner (1986) includes solving a complex problem, which implies planning and executing the solution in the environment. Without action planning and sensor actuation, the products in Class three cannot be regarded as intelligent. Therefore, an intelligent product is specified to have all the functionalities of Class 4 to solve a complex problem comprehensively.

Another dimension of smart/intelligent product classification considers two different levels of aggregation. Many products are composed of components that can also be independent products. The example of a car illustrates the phenomenon, as it is assembled from components from different manufacturers, which can be composed of other parts (Meyer et al., 2009, p. 140). Therefore, the following distinction is made between intelligent products:

i. Product level: the product only manages information, messages, and decisions about itself; the components of the product cannot be distinguished as individual objects.
ii. Proxy level: In this case, the product not only manages information about itself as it also recognises the components of which it is composed and acts as a proxy.

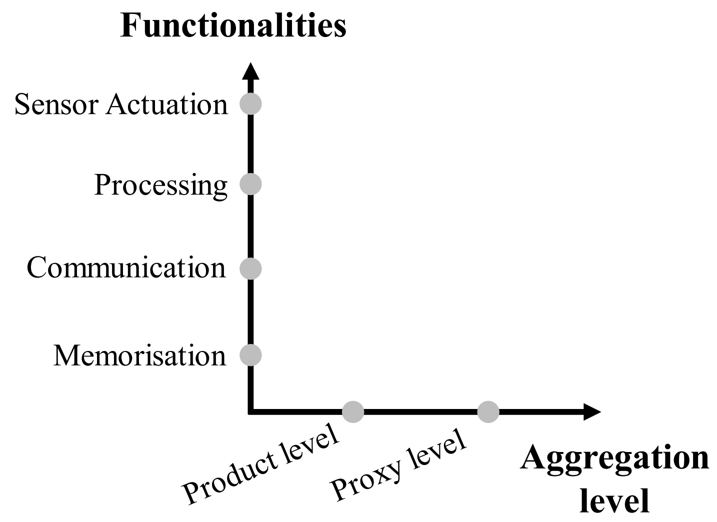

Figure 12: Expansion of the classification through the aggregation level based on (Meyer et al., 2009, p. 140)

The differentiation regarding the aggregation level is crucial for the design implementation of the intelligent or active product. The critical decision for an intelligent product is whether its product intelligence represents value-adding for the customer. If this is not the case, the entrepreneur should not senselessly upgrade the level of product intelligence and instead use a deputy to embody the smart/intelligent functionalities. Figure 12 shows the two dimensions of functionalities and aggregation level on a high level.

To summarise, various classification models have been observed in the SLR, but none of the authors provides a model applicable to the entire product life cycle. In addition, the models lack genericity and specifically focus on technology (Zbib et al., 2008, p. 247). Therefore, Zbib et al. (2008) developed the described typology to classify the product according to the four functionalities of memorisation, communication, processing, and sensor actuation. The dimension of aggregation level has been expanded because products in the manufacturing phase are often not intelligent by themselves but rather the carrier or pallet on which the product is transported. According to Zbib et al. (2008), the model provides a generic classification across the entire product lifecycle. Based on the arguments, the thesis uses typology as the basis for developing the conceptual framework.

2.3 Technologies for intelligent products

Zbib et al. (2008) defined the classification model of smart/intelligent products, which is technology-independent but easy to implement with current technology. However, implementing smart/intelligent products requires technologies that cover the functionality requirements of memorisation, communication, processing, and sensor actuation. Therefore, this section describes fundamental technologies for smart/intelligent products for each of the four functionalities.

2.3.1 Memorisation & communication

For smart/intelligent products, the focus lies on microcontrollers that control the system in which they are embedded. Therefore, a microcontroller's memory is explained, which stores the firmware code and the data generated during the code execution. Therefore, the bus system links the memory to the Central Processing Unit (CPU). If the internal data memory does not provide sufficient capacity, the buses in a microprocessor are bought out to pins to connect to external storage (Davies, 2008, pp. 11–12). There are two classes of memories:

i. Volatile memory requires a power supply to maintain the stored information. The application field of volatile memories includes primary storage and protection of sensitive data, as the data is lost on power-down. The reading and writing of data are done with equal ease. A typical example of volatile memories is data memory, such as random-access memories of a computer or microcontroller, which are used to store the data from sensors (Ibrahim, 2006, p. 8).
ii. Non-volatile memory is a type of memory that does not lose its content when the power of the memory is removed. The application field of non-volatile memories focuses on essential and consistent data such as identification and network addresses (Davies, 2008, p. 10). The program memory of a computer or microcontroller is usually a nonvolatile memory, such as electrically programmable read-only memories (EPROM) or flash memories. However, modern microcontrollers can write to their nonvolatile memory but use a slower speed threading (Ibrahim, 2006, p. 8).

There is an increasing spread of wireless communication applications using wireless technologies of radio frequencies, magnetic, optical, and acoustic (Haupt, 2019, p. 1). Therefore, some essential technologies in wireless communication are presented, which are required for designing smart/intelligent objects. The focus lies on automatic identification procedures such as barcodes, optical character recognition (OCR), biometric procedures, and RFID.

A barcode is a visual representation of information consisting of parallel lines and gaps of different widths, spacings, and sizes. In addition to lines, barcodes often consist of different combinations of alphanumeric characters, numbers, and symbols. Thus, various barcodes are used with considerable differences between the code layouts, such as Code 128, Code 39, or EAN. The European Article Number (EAN) is the most popular barcode by some margin and was designed for the grocery industry. The EAN barcode consists of 13 digits representing the country identifier, the company identifier, the manufacturer's item number, and a check digit (Finkenzeller & Müller, 2010, p. 4). The data representation is visible and readable for machines and can be scanned by special optical scanners and barcode readers. Barcodes are used for product identification and recognition to speed up the check-out processing and enable product tracking. The four barcode categories are numeric-only barcodes, alpha-numeric barcodes, 2D barcodes, and industry standards for barcodes and labels (Mohd Saad & Hashim, 2013, p. 278).

OCR defines the electronic or mechanical conversion of different document types such as images and handwritten or printed text into machine-encoded files. The significant advantage represents the high density of information and the possibility to read data visually, which are beneficial to several applications in production, service administration, and banks. However, the OCR procedure is expensive because of its complicated readers compared to other identification technologies (Finkenzeller & Müller, 2010, p. 4).

Biometric procedures include human beings and are the science of counting and measuring individual physical characteristics. The measured human characteristics are fingerprints, hand printings, voices, or iris. Fingerprinting procedure compares the papillae and dermal ridges of the fingertips. Therefore, the fingertip is often placed on a reader, which compares the record with a stored reference pattern. Voice identification requires a microphone linked to a computer that records spoken words and converts them into digital signals using specific software. Likewise, the process of iris recognition uses mathematic pattern-recognition on video images to identify an individual based on unique, stable iris characteristics (Finkenzeller & Müller, 2010, pp. 4–5).

RFID has gained increasing attention from academics and practitioners. All RFID systems have three main components: the tag, the reader, and the back-end database. The tag stores the data on non-volatile memory. The RFID tag consists of a microchip for storing and processing information, an antenna for receiving and transmitting the signal, and a substrate. There are three possible functions of the tags: active, passive, and semi-passive, which describes the level of battery assistance. Both active and semi-passive tags have an onboard battery, whereas the semi-passive tag is only activated in the presence of an RFID reader (Haupt, 2019, pp. 274–278). The reader can read data from and write data to the tag. The back-end database records the collected data from the readers. The data exchange between the tag and the reader is achieved using magnetic or electromagnetic fields.

First, the tag requires a unique identifier, such as an electronic product code attached to an item. Suppose the item moves into the reader's scanning range, and the reader's electromagnetic waves couple with the antenna on the tag. Based on the powered microchip in the tag, the tag can modulate the received signal to reflect a radio frequency signal, which the reader picks up. The reader can either store the information on the back-end database or communicate the information further (Haupt, 2019, p. 281). Compared to barcodes, RFID does not require a line of sight for the reader and can work in dirt, dust, and moisture conditions.

Furthermore, multiple tags are read simultaneously, and various information can be stored on the tag (S. Li et al., 2006, p. 194). Figure 13 shows the RFID system's principal and main components, where the RFÌD reader supplies energy to the tag and the operating cycle enabled by the clock. The two-way communication for data exchange between the reader is possible in the reception range of the reader.

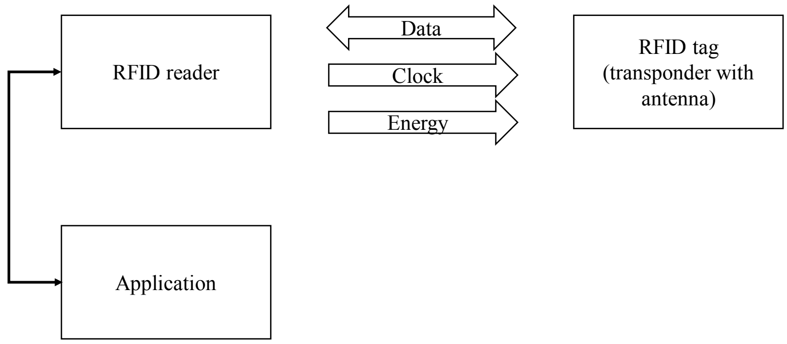

Figure 13: RFID system reproduced from (Finkenzeller & Müller, 2010, p. 10)

2.3.2 Processing

The functionality of data processing requires computer controlling power, which is often provided by microcontrollers nowadays. Microcontrollers have gained popularity in different industries such as communication, retail, and automotive. (Allied Market Research, 2022). There are also various use cases of microcontrollers in manufacturing to enable digital twin communication (Hinchy et al., 2019) or status monitoring for smart factory task planning applications (W.-L. Chen et al., 2021). Since single-chip microcontrollers are evolving and are mainly used for cyber-physical systems, the function and anatomy of a typical microcontroller are explained.

A microcontroller is a single-chip computer with build-in resources of input-output ports, data memory, program memory, central processing unit, and clock (see Figure 14). The input-output ports enable digital data to be read or output from the microcontroller. The data memory provides volatile data storing capacity with a random-access memory, whereas the program memory is non-volatile using a Read-Only Memory (ROM). The clock is used to synchronise the whole system and to run the control algorithm accurately. The data bus and the address bus link the subsystems and transfer the data and instructions. The connection to the outside world is enabled by input and output ports. For instance, the ports can read external memories(Davies, 2008, p. 9). Today’s microcontrollers are programmed by high-level languages such as BASIC, PASCAL, or C. According to Davies (2008), the most common choice is C, where a compiler translates C into machine code that is processable for the CPU.

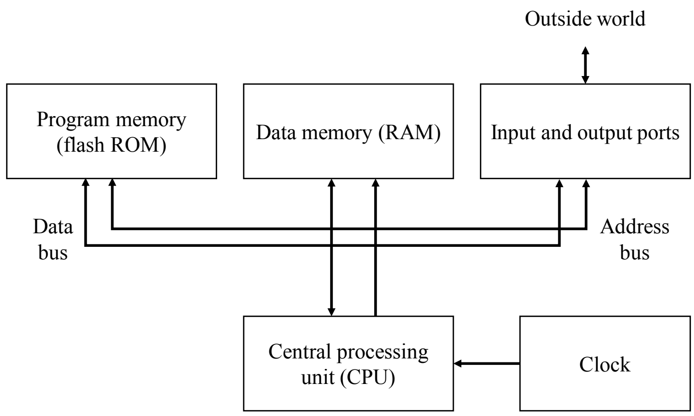

Figure 14: Essential components of a microcontroller reproduced from (Davies, 2008, p. 9)

2.3.3 Sensor actuation

Sensors measure some physical, chemical, or biological quantities of the environment and transmit a resulting electrical signal, either analogue voltage level or digital signal (Kaltenbacher, 2015, p. 2). Since microcontrollers require digital data input, an intermediate device of an analogue to digital converter (ADC) converts the analogue signals from the sensors to digital signals. However, most microcontrollers provide incorporate built-in converter circuits. The next step sends the digital signal to a computer controlling unit to process the information. Thus, the sensor output is the controller input. In a typical control system, the computer runs an algorithm to trigger the required actions by the actuator (Ibrahim, 2006, p. 3). The actuator operates in the reverse direction of a sensor and converts the electrical signal into any physical quantity. Figure 15 shows the typical computer or microcontroller-based control system.

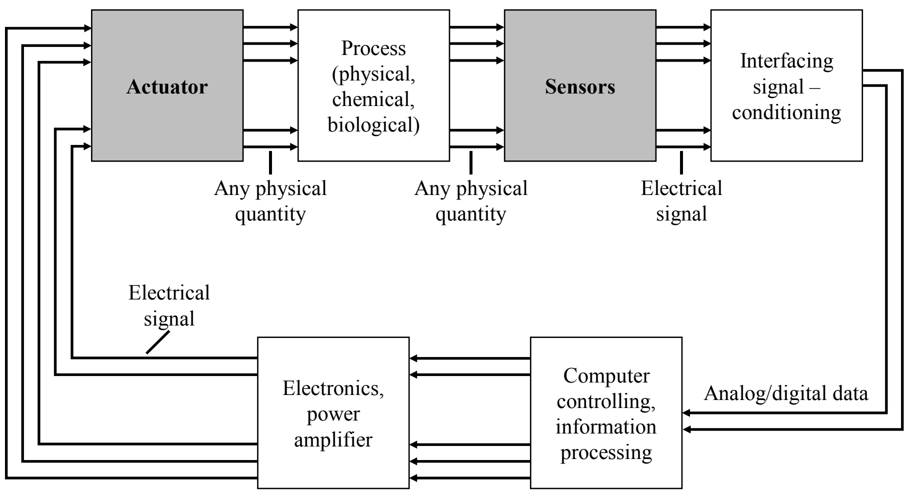

Figure 15: Typical control system reproduced from (Kaltenbacher, 2015, p. 2)

The classification into proprioceptive or exteroceptive sensors distinguishes whether the measurement is internal (proprioceptive) or external (exteroceptive) to the product. In addition, exteroceptive sensors are further classified as active or passive. An active sensor affects the environment and requires external energy to provide an output. Passive sensors do not need additional energy sources for directly generating an electrical signal (Ben-Ari & Mondada, 2018, p. 22).

Distance sensors are often used for robot applications to measure distances from the robot to an object. Distance sensors are usually classified as active because they pull a wave or signal and measure the time for receiving the reflection. The main transducing mechanisms for distance sensors are ultrasonic sound, infrared light, and laser light. However, each use case must individually select the distance type (Ben-Ari & Mondada, 2018, pp. 22–31).[7]

The measurement of a physical, chemical, or biological quantity can be characterised by its range, resolution, precision, accuracy, and linearity. Each term is explained and described by an example of distance sensors. However, the terms are generally valid and applicable to all other sensors.

The range represents the extent of the set values that can be measured for the sensor. For instance, a distance sensor can measure 5 to 400 mm values. Resolution describes the smallest change that a sensor can perceive. While a distance sensor with a lower resolution may detect displacements in centimetres (1cm, 2cm, 3cm, …), a sensor with a higher resolution can measure distance in millimetres (100 mm, 101mm, 102, …). Precision describes the reproducibility of a measurement. For instance, a distance sensor measures a steady state without any change. If the values are close or even the same, the degree of precision is high, whereas a wide range of values indicates low precision. The values do not have to be the actual, real-world value for determining the precision. However, accuracy describes how close the average of the measured values differs from the real-world value. In the case of a distance sensor, a high accuracy describes a small difference between the actual and measured values. Linearity describes the proportional ratio between sensor output and measured values. The ideal sensor is expected to have a linear transfer function, which is practically impossible, as all sensors have some nonlinearity (Ben-Ari & Mondada, 2018, pp. 32–33).

There is an increasing interest in IoT technologies in today's industry for monitoring, tracking, and connecting production, processes, people, and physical systems. Smart sensors are required to enable these functionalities, combining data memory, diagnostics, and communication functionalities to perform self-diagnosis. Smart sensors use onboard controllers to interpret data and communication units to pass the data to a digital data stream for transmission. Further onboard features of smart sensors are calibration, remote monitoring, and configuration (Gupta et al., 2021, pp. 40–42).

2.4 Conlusion: Literature review

In this chapter, a literature review has been focused on FMSs, intelligent products, and their technologies. For the definition and classification of flexibility, the multi-dimensional concept introduced by Browne et al. (1984) and the extension of Sethi and Sethi (1990) is considered. Even though there exists a linkage between intelligent products and flexibility dimensions, there are only four flexibility dimensions where intelligent products have a direct influence. The relevant flexibilities are Material handling flexibility, Process flexibility, Routing flexibility, and Program flexibility. Intelligent products use cases for each of the four flexibility dimensions. Intelligent products can manage and assist in production planning and control routing flexibility. QSC Audio Products serves as an example for tracking and controlling the movement of the product through the facility by optimising the routing of work (Meyer et al., 2009, p. 144). Compared to other operational objectives such as productivity, flexibility indicates potential behaviour rather than performance.

The second part of the literature review highlights manufacturing problems, which are classified according to the frameworks of Glouberman and Zimmerman (2002) and Snowden and Boone (2007). The top five problem fields in manufacturing from 2017-2020 are scheduling, control, planning, process, and environmental problems. Further, the thesis closely follows Dörner's definition of operational intelligence (Dörner, 1986). However, as elucidated through the systematic literature review on smart/intelligent products, various smart/intelligent product definitions focus on specific perspectives, application fields, and different parts of

[7] Further information about the mechanism of distance sensors is provided in Ben-Ari and Mondada (2018).

the product lifecycle. Two smart/intelligent product definitions provided by Porter and Heppelmann (2014) and McFarlane et al. (2003) directly address the scope of the research in manufacturing. For the smart/intelligent product classification, there exists a comprehensive model by Zbib et al. (2008), which provides a generic classification across the entire product lifecycle. Even though the classification model of Zbib et al. (2008) is technology-independent, intelligent products' implementation requires automatic identification procedures, microcontrollers, memories, and sensors to fulfil the functionality classes. Therefore, the final part of the literature review describes these fundamental technologies for smart/intelligent products for each of the four functionalities.

Chapter 3. Requirement specification for the framework

This chapter provides a set of requirements to develop a conceptual framework according to the present research gap.

3.1 Requirements set

Several requirements are proposed to support the development of an analysis and design method for intelligent-product structures in manufacturing. According to the work of van Aken and Berends (2018, p. 209), the design requirements can be divided into five requirement types, including:

i. **Functional requirements (FR):** The functional requirements refer to the framework specifications in terms of the performance demands. They represent the central components for the requirements specification.
ii. **User requirements (UR):** The user requirements focus on the users' point of view, which are set by the users and include the requirements in terms of usability, such as maintenance or operational specifications.
iii. **Boundary conditions (BC):** The boundary conditions denote the requirements and rules that must be met unconditionally. Examples are legislation, ethical habits, and code of conduct.
iv. **Design Restrictions (DR):** The design restrictions refer to limitations and exclusion of the design and function of the framework. Compared to the boundary conditions, the design restrictions are debatable, whereas boundary conditions are restricted.
v. **Attention points (AP):** Attention points are relevant to the conceptual framework, and define requirements that should be noted as desirable, even though they are not restrictions. However, these requirements do not have to be met or limit the design like restrictions.

3.2 Purpose of the framework

As highlighted in Section 1.3, a present research gap lies in improving the overall integration process of intelligent-product structures. Furthermore, managing mixed product-intelligence structures challenges FMSs (Bertelsmeier et al., 2016, p. 760).

The framework aims to guide the user through analysing, defining, and designing intelligent-product structures for a FMS. Based on the design science, developing a prescriptive knowledge framework should provide instructions for analysing and implementing intelligent-product structures. Thus, the conceptual framework is a solution concept that follows the empirical and learning cycle (van Aken & Berends, 2018, p. 37).

3.3 Functional requirements

The Functional Requirements (FRs) constitute the critical functionality of the framework in terms of performance demands on the integration process for intelligent-product structures. Table 15 shows the functional requirements, which are divided into three groups: (i) overarching functional requirements, (ii) conceptual functional requirements, and (iii) operational functional requirements. While overarching functional requirements exceed all functional requirements, the conceptual functional requirements are addressed by the conceptual framework. In addition, the operational requirements are managed by the guidelines for the operationalisation of the framework. It is essential to mention that even though there is a distinction between conceptual and operational functional requirements, there are points of contact between the two aspects.

The framework, as highlighted with FR1 & 5, aims to solve an existing business problem by defining and analysing the problem to derive designs of intelligent-product structures in manufacturing.

Table 15: Functional requirements

Requirement number	Requirements description
Overarching functional requirements	
FR1	The framework should contribute toward defining, analysing, and designing intelligent products or resources within the context of flexible manufacturing.
FR2	The framework should apply to various resources within the specified scope of manufacturing systems but needs to be extended for specific product analysis (such as robots or automated guided vehicles).
FR3	Although the framework is not aimed at prescribing specific methods, tools, or processes, some concepts should be provided to guide the users and simplify the framework's application.
FR4	The framework should consider integral activities to apply the framework to manufacturers successfully.
FR5	Realising the solution has the aim to solve a business problem, both from a technical as well as from an economic perspective.
Conceptual functional requirements	
FR6	The framework should consider product intelligence from a more dimensional perspective and is intended to avoid a narrow perspective, which is limited on the functionalities.
FR7	The framework should handle mixed product intelligence structures.
FR8	For both outcomes (value-adding or no value-adding of the intelligent product for a manufacturing system) of the feasibility analysis, the conceptual framework should define a procedure. A particular focus should be set on the case of value-adding of intelligent products.
FR9	The framework should support the design and information technology profile of intelligent products.
Operational functional requirements	
FR10	The framework should define a precise classification of passive and intelligent products within the scope of the manufacturing environment.
FR11	The framework should provide decision support in manufacturing systems regarding technology management within intelligent products. It should aid users in identifying and implementing flexibility potentials in their current manufacturing process.
FR12	The framework should be able to deliver a precise statement regarding the feasibility of intelligent products for the respective user.
FR13	The framework should support and enable the development process of intelligent products.

3.4 User requirements

The framework is intended to guide production planners and technical consultants who regard the role of intelligent-product structures as contributing to solving existing manufacturing problems. Therefore, the users of the developed framework can be associated with technical and / or management perspectives. Table 16 shows the User Requirements (URs).

Table 16: User requirements

Requirement number	Requirements description
User requirements	
UR1	The framework should be user-friendly and practicable, which indicates that it is easy to understand and adopt.
UR2	The framework should be designed so that the procedure and the interlinked concepts can be understood even without a thorough and deep understanding of the theoretical foundations. Therefore, the framework should provide a clear structure supported by precise requirements, definitions, and explanations.
UR3	The framework should facilitate repeated and continuous use.
UR4	The framework should enable users' input, guided by defined actions for the processing.

3.5 Boundary conditions

The Boundary Conditions (BCs) must be met unconditionally and are outlined in Table 17.

Table 17: Boundary conditions

Requirement number	Requirements description
Boundary conditions	
BC1	The framework must adhere to ethical, legal, and scientific requirements.
BC2	Risks and opportunities should be highlighted across the system, focusing on the desired solution and potential.
BC3	The framework has the goal and vision of demonstrating the potential of intelligent products. However, the potentials do not correspond to all forms of flexibility and are limited to defined fields.
BC4	The framework should provide value for all parties involved, e.g., the researcher or manufacturer. The exploitation of other parties should be avoided.

3.6 Design restrictions

Compared to BCs, the Design Restrictions (DRs) might be negotiable and include the preferred solution space by the principal. Therefore, Table 18 outlines the requirements for the desired solution.

Table 18: Design restrictions

Requirement number	Requirements description
Design restrictions	
DR1	The conceptual framework is not meant to consider the use phase of a product. However, it should be comprehensive enough to guide manufacturing systems defined by the functional requirements.
DR2	The framework should be developed for manufacturing but could also be applicable for other application fields such as logistics.
DR3	The framework does not guarantee a complete evaluation for all manifestations of an intelligent product, as not all of them can be covered due to many factors. The framework aims to provide a guideline to analyse the potential and the implementation.
DR4	The framework is intended for a decision-level analysis and implementation guideline but does not guarantee improved quality and performance changes.
DR5	The framework should be limited in the number of imperative tools and concepts.

3.7 Attention points

The Attention Points (APs) highlight the framework requirements that should be considered but do not constrain the framework's development (see Table 19).

Table 19: Attention points

Requirement number	Requirements description
Attention points	
AP1	Due to the nature of the framework, several opportunities for integration with other pre- and post-approaches and frameworks for analysing and designing intelligent products are considered. However, it is beyond the scope of this study to explicitly address such possibilities.
AP2	The high-level framework supports the analysis and implementation of intelligent products in manufacturing. However, the framework should also deal with the interlinked concepts in detail to provide the user with the best possible ease of use.
AP3	The framework should enable manufacturers to apply it in different ways, as they can use it to the extent they need. Therefore, the framework should allow the flexibility to adapt the application depth to the specific case, which should be adjustable by user input (as mentioned in UR4).

Chapter 4. IPIDS framework

This chapter contains the development of the conceptual framework – ***the intelligent-product initiation decision-support (IPIDS) framework***, which aims to integrate intelligent-product structures into a FMS. In Chapter 3, the framework's requirements are developed according to the five requirement types of van Aken and Berends (2018). Based on these requirements, the structure and content of the conceptual framework are proposed.

4.1 Features of the IPIDS framework

In addition, Jabareen (2009) distinguishes seven features of conceptual frameworks, including:

i. A conceptual framework should not be a collection of concepts. Instead, each of them has a core role.
ii. A conceptual framework represents an interpretative approach to social reality.
iii. A conceptual framework aims to provide understanding rather than "theoretical explanations".
iv. A conceptual framework provides a "soft interpretation of intentions".
v. A conceptual framework is indeterminist, implying preconditions unambiguously determine not all events. Causes do not unambiguously determine certain events.
vi. A conceptual framework is designed through a process of qualitative analysis.
vii. Discipline-oriented theories mainly define the source of a conceptual framework.

The conceptual framework is required to fulfil the seven requirements listed above. The guideline for developing the conceptual framework is also based on Jabareen (2009). The first and second step in the guideline consists of mapping, reading, and selecting data, which is addressed by the systematic and further literature review. In the reading phase, appropriate concepts are identified and categorised in steps 3 and 4. In phases 5 and 6, the concepts are iteratively grouped and categorised to reduce the number of concepts and develop a theoretical framework. Finally, the last two steps validate the theoretical framework by implementing external perspectives.

4.2 Structure of the conceptual framework

The structure of the conceptual framework is based on the functional requirements (defined in Section 3.3) to develop a holistic method for defining, analysing, and evaluating the potential for using intelligent products in the manufacturing environment. The object of investigation is a sub-area of manufacturing, such as a particular manufacturing cell or station, which may be connected to other production systems by a transport system. The guideline for the integration process of intelligent-product structures is divided into four stages: definition, execution, analysis and evaluation, and execution.

The first stage defines the production process and resources in the manufacturing environment. The product and additional resources are classified according to their existing functionalities. Besides defining the existing environmental conditions in the manufacturing system, the classification of the existing problems is examined at stage 1.

Stage 2 consists of analysing and evaluating the identified products and resources by considering further dimensions of autonomy and adaptivity. At this stage, the products' and resources' current intelligence level is extended by further dimensions for unmanned and robotic systems. The user of the IPIDS framework can elaborate on different scenarios by increasing the respective intelligence levels to identify potential benefits. Stage 2 aims to establish whether enhancing the product's intelligence level reduces the existing manufacturing problems. By analysing and evaluating different intelligent-product structures, a decision is required whether an increase in functionalities represents an improvement in the defined manufacturing problem. If the increased product functionality does not add value to the use case, the process should be discontinued at this stage.

In case the defined problem can be improved or even eliminated, the third stage examines the design and technical requirements of the intelligent-product structure. A list of requirements is established based on the selected intelligent-product levels and the mixture of levels. The design requirements of the intelligent-product structure contain a flow diagram, a data model, and a definition of flexibility or adaptivity objectives.

The final stage involves designing and developing the intelligent-product structures in the manufacturing environment. At this stage, the hardware and software for the implementation are selected, and attention points are highlighted.

Figure 16 summarises the four stages and the seven steps to conduct the IPIDS framework in manufacturing systems. Even though the application of the IPIDS framework is linear, there are potential iteration loops possible, which will be examined in the detailed explanation of the framework steps.

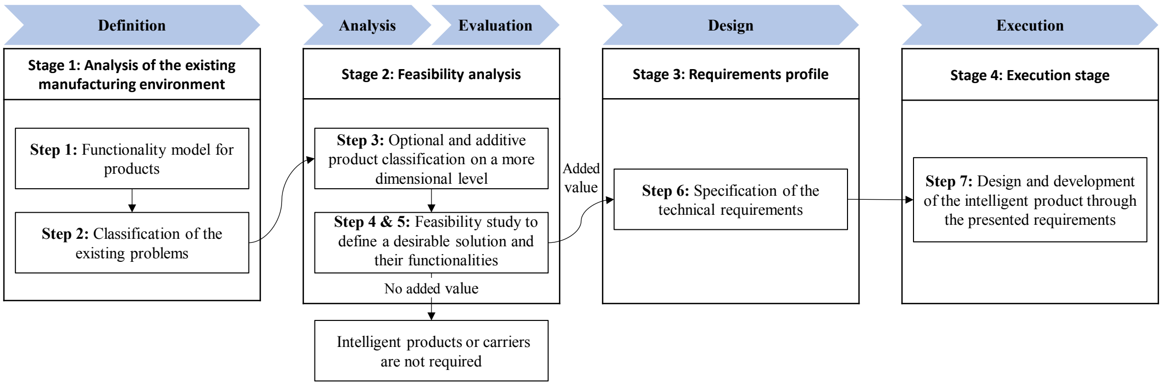

Figure 16: IPIDS framework

4.3 Definition stage

The definition stage is divided into two steps the functionality model for products and resources and the problem classification in manufacturing systems. The first step of the definition stage includes the typology of products ranging from passive to intelligent products. Therefore the classification model of Zbib et al. (2008) is selected to define the product's level of intelligence. A more detailed explanation of the model is provided in Section 2.2.4. The second step of problem classification refers to the problem types of Glouberman and Zimmerman (2002) and Snowden (2010). In addition, the intelligent functionalities are linked with Dörner's solving process of problems. The foundations of problem classification and intelligence definition have already been covered in the literature review in Sections 2.2.1 and 2.2.3.

4.3.1 Step 1: Functionality model for products

A customised questionnaire is developed, guiding the user through the functionality model. In context of the thesis, functionality is defined as an operation performed by a piece of equipment or software. Thus, a function defines the operation that the product must be able to perform (M. Glinz, 2007, p. 21). It is essential to mention that the execution of the questionnaire and, therefore, the classification of the intelligence level is conducted independently per product or resource. The manufacturing system represents a mixed product-intelligence structure if there is more than one product or resources with different functionality classes. Thus, the functionality model presents a listing of the current functionalities in the selected field of manufacturing, showing the respective functionalities and the resulting class for each product and resource. Table 20 provides a question-based guideline to the user to facilitate the selection of the intelligence level.

Table 20: Questionnaire for the functionality model

Functionalities		Questions
Sensor Actuation		Does the product/resource interact with the physical and/or informational resources to control, adjust, or intervene parameters in the manufacturing environment?
Decision making Data processing	**Processing**	Does the product/resource deal with basic data-oriented processing or more sophisticated decision-making?
Service-oriented Data-oriented	**Communication**	Does the product/resource only have reading and writing functionalities to communicate available data/measures (data-oriented), or does the product/resource communicate information-oriented services, which require processing?
Data	**Memorisation**	Can the product/resource only read or read / write data on a memory?

A decision is provided to define the product's characteristics for each of the four main functionalities. Therefore, the memorisation concerns whether the product/resource deals with static "read-only" or dynamic "read/write" data storage. The "read/write" functionality indicates the permission of remote reading and writing data on a carrier. In contrast "read" functionality stores the information permanently, such as a unique identifier. The functionality of communication distinguishes between "data-oriented" and "service-oriented" communication. If the product/resource can read and write information, it has data access functionality. For "service-oriented" communication, the product/resource provides advanced informational services. The functionality of processing distinguishes between "data processing" and "decision making", which can be differentiated by the following question of whether the product/resource deals with basic "information-oriented" data processing or more sophisticated "decision-making". In "data processing", the product collects or synthesizes information to ensure product traceability or provides the basis for the decision making. If the product/resource can decide independently, more symbolic actions such as dynamic resource allocation or best-path learning are conducted. Finally, the question regarding the sensor actuation queries whether the product/resource can interact with the physical world to control, intervene, or adjust the environment (Zbib et al., 2008, p. 249).

The second dimension of intelligent products considers the aggregation level of intelligence, which has already been defined in Section 2.2.4. The user of the IPIDS framework needs to answer whether the product or resource manages information, notifications, and decisions about itself on a product level or also about components. In case a product does not exist of independent, intelligent components or cannot be distinguished into own individual objects, a product/resource is classified as product level. A proxy level is characterized as a product/resource consisting of sub-components that can continue as intelligent containers by themselves. For instance, an intelligent workpiece carrier in a manufacturing environment or an intelligent shelve in a supply chain domain represent proxy devices. The intelligent workpiece carrier can provide process information to the operating system, and the intelligent shelve can notify its owners when a product is out of stock.

Both dimensions of product/resource functionalities and aggregation level are combined in the functionality concept in Figure 17, which represents the product/resource definition stage. The orange fields require user input by selecting the appropriate answer from the drop-down list. The functionality or aggregation fields remain empty if the IPIDS framework user cannot answer the question. The functionality table autonomously visualises the intelligence level based on the user's input.

Resource:		
Functionalities per Resource		**Questionnaire**
Memorisation		Can the product/resource only read or read / write data on a memory/storage?
Communication		Does the product/resource only have reading and writing functionalities to communicate available data/measures (data-oriented), or does the product/resource communicate information-oriented services, which require processing?
Processing		Does the product/resource deal with basic data-oriented processing or more sophisticated decision-making?
Sensor actuation		Does the product/resource interact with the physical world to control, adjust, or intervene in the environment?
Aggregation level		Does the product/resource interact with the physical and/or informational resources to control, adjust, or intervene parameters in the manufacturing environment?

Class 1	**Class 2**	**Class 3**	**Class 4**	**Functionalities**	
					Sensor actuation
				Decision making	**Processing**
				Data processing	
				Service-oriented	**Communication**
				Data-oriented	
				Data	**Memorisation**

Figure 17: Functionality concept to identify the product's functionality and aggregation level

The functionality levels are expressed by Class 1 to 4, ranging from data products (Class 1 and 2) to decisional products (Class 3 and 4). A decisional product in Class 3 has no sensor actuation ability and therefore cannot interact the decision with its environment to initiate an action. Thus, an intelligent product needs all functionalities. The functionality levels represent a stepwise structure completed at Level 4 and fulfilled by 100%. Figure 18 represents this logic through a level diagram from Class 1 to Class 4. There are seven different modes of operation along with the four functionalities because there are two options except for sensor actuation.

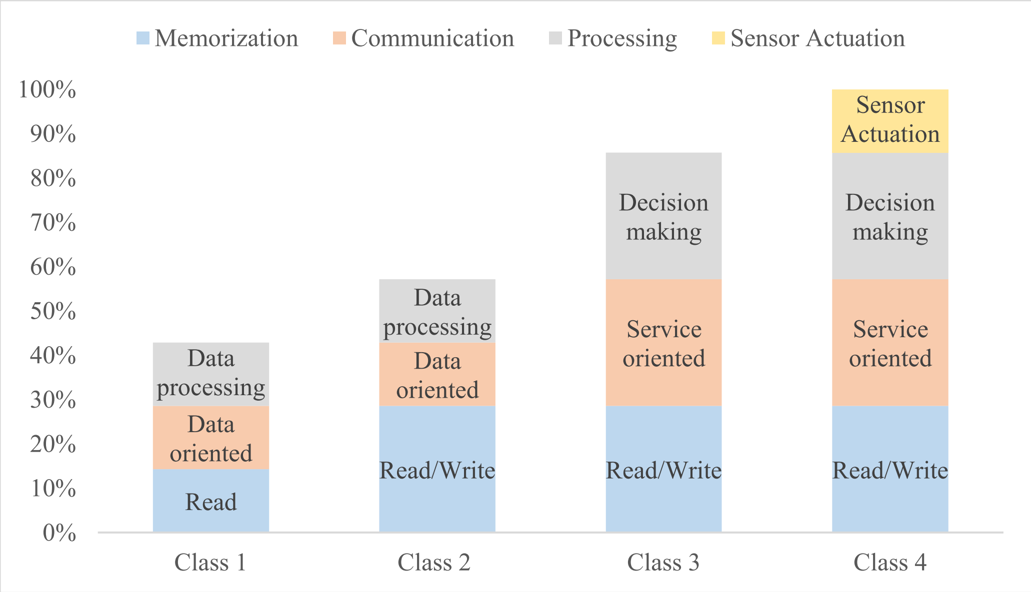

Figure 18: Level diagram of the functionality model

4.3.2 Step 2: Problem classification

The second step of the definition stage consists of classifying the existing problem in the manufacturing system. Therefore, a comprehensive understanding of the Cynefin Framework and the three types of problems by Snowden (2010) and Glouberman and Zimmerman (2002) is provided in Section 2.2.1. This chapter also provides a classification of identified problems in manufacturing according to their problem type. The bibliometric literature outcome shows that the assembly's selected use case belongs to the category of complicated problems.

Before categorizing the problem according to the three types of simple, complicated, and complex, a problem description is required. The problem description is divided into five categories. First, a brief problem statement is required, focusing on the five W-questions: What, Who, Where, When, and Why. The formulation of the problem statement should be chosen so that even people without a thorough and deep knowledge of the topic can understand the facts. The required data for the questionnaire can be gathered through historical data, personal knowledge, or expert interviews. The second category of urgency describes when a particular problem should be solved. The lower the period to eliminate or reduce the problem, the higher the urgency level. In case there is more than one problem identified in the manufacturing system, the urgency level influences the rank order. In addition, the visibility category requires a statement of whether the visibility is low, medium, or high. High visibility indicates that the problem is easy to identify. For instance, a power failure is straightforward to detect as the lights or machinery in the manufacturing turn off. Logically, low visibility of the problem indicates a problematic identification of the problem. The case of low visibility is more critical, as these problems are below the surface and may increase without notice. The last category of preliminary analysis or proposed solution provides a more detailed answer to why the problem occurs and serves as a starting point for reducing and solving the problem.

After defining the problem statement, the problem characteristics need to be examined. Therefore, a list of characteristics is provided to distinguish between the problem types. The criteria for selecting the characteristics are based on research from Glouberman and Zimmerman (2002) and Snowden (2010). Table 21 presents the selection tool for categorizing the identified manufacturing problem. The tool provides a distinction between simple, complicated, and complex problems. The fourth domain of chaotic problems from Kurtz and Snowden (2003) is not covered by the IPIDS framework, as there is no response time to investigate and probe the situation in chaotic problems. The IPIDS framework cannot provide quick actions to mitigate the turbulences since there are no visible cause and effect relationships.

Table 21: Selection tool to categorise the identified manufacturing problem

Type	Characteristics		Moving factors	Solution Approach
Simple	**Rules** and **recipes** exist to solve the problem.	☐	Simple problems can be automated.	Sense Categorise Respond (SCR) Application of best practice
	Rules and recipes are proved to provide **replication (Reproducible).**	☐		
	Low level of **details.**	☐		
	No expertise is required.	☐		
	Providing **clear**, **standardised**, and **predictable solutions.**	☐		
	Clear **cause-and-effect relationship.**	☐		
Complicated	**Recipes, rules, and formulae** are critical and necessary.	☐	Lean Management and standardisation.	Sense Analyse Respond (SAR) Application of good practice
	A high level of **expert diagnosis** is required.	☐		
	Unanticipated difficulties are a frequent but **high degree** of **outcome certainty.**	☐		
	There might be **more than one correct answer** possible.	☐		
	There is **no straightforward** and **standardised rule** or **recipe.**	☐		
	High level of **detail.**	☐		
	Entirely predictable if the solution is known.	☐		
Complex	**Recipes, rules, and formulae** have **limited application.**	☐	Understanding the problem through agile frameworks.	Probe Sense Respond (PSR) Application of emergent practice
	A problem-solving approach is **not reproducible.**	☐		
	Expertise is valuable but **may not apply**, as it is **no success factor.**	☐		
	Outcomes remain **highly uncertain.**	☐		
	High level of **detail.**	☐		
	Emergent instructive patterns.	☐		
	Many competing ideas.	☐		

According to D. Snowden (2010), a solution approach is defined for each problem type. Applying the solution approaches has the chance to shift a situation from complex to complicated or from complicated to simple. Certain moving factors support shifting from one problem type to a lower level. According to Snowden (2010), clear or straightforward problems can be controlled by automatization. For complicated problems, lean management and standardisation can reduce the handling difficulties and increase the certainty of outcome. These learning factors can positively influence the development of a simple problem over time. Agile frameworks can assist in understanding the problem and reduce the complexity level in the last problem type.

The final category provides approaches to adequately present ways of proceeding. In the case of a simple problem, the approach is to sense, categorise, and respond. For instance, Snowden and Boone (2007) mention an example of loan-payment processing, where the employee senses the problem (borrower has paid less than required) and categorises the problem (reviews the loan documents) and responds (follows the terms of the loan). The approach for a complicated problem is to sense, analyse, and respond. It includes assessing the facts and analysing and applying fair practice by a rational approach. In the complex domain, the approach is to probe, sense, and respond and then allow the emergent practice. Due to high outcome uncertainty and that own actions change the situation in unpredictable ways, the approach take-it-apart-and-see-how-it-works is used here. The solution approach requires creative and innovative approaches to make patterns visible and stabilize them.

In addition to the functionality and the problem classification model, Dörner (1984) defines the problem-solving process. The problem-solving process starts with a problem statement based on several possible motives. After the problem has been recognized, a search is conducted on the problem-relevant material in the memory. This process can be completed quickly if the search in the memory already provides the necessary solution, or it can take longer if the memory structure needs to be built or rebuilt. If the existing memory does not provide information to solve the problem, the search process is unsuccessful, and any additional information collection and exploration phase is required. Once the search for problem-relevant material is completed, a goal-directed action can be constructed. Before the problem is mastered with defined actions, an iteration loop can search for additional problem-relevant material, including a self-reflection (Dörner, 1984, p. 11).

The problem management process is shown in a flow chart in Figure 19, which contains the link between Dörner's operational intelligence to solve problems and the functionalities of an intelligent product, according to Zbib et al. (2008). The flow chart allocates the functionalities with the phases of problem-solving. The first step of defining the problem statement requires the functionalities of memorisation by reading and writing information. The product must gather information to enable data-oriented communication and data processing. The second step of searching for problem-relevant information requires a processing unit with service-oriented communication and decision-making functionalities. According to Zbib et al. (2008), this characterizes a Class 3 product. Through the interaction ability in the fourth step, the product can interact with the physical environment to plan and realize an action. In principle, only a product or resource with the functionalities of all four classes can solve a problem because the product manages all phases of the problem-solving process. In addition, the linkage of Dörner’s problem-solving process and the intelligent product functionalities do not support the allocation of the problem types, as the problem-solving process is type-independent. However, the search process for simple problems will likely involve less time, effort, and iteration loops than for complicated or complex problems. The statement of type-dependent resolution time of a problem is supported by the solution approaches of Snowden and Boone (2007), as complicated problems require analysing functionalities, whereas simple problems only categorize the problem.

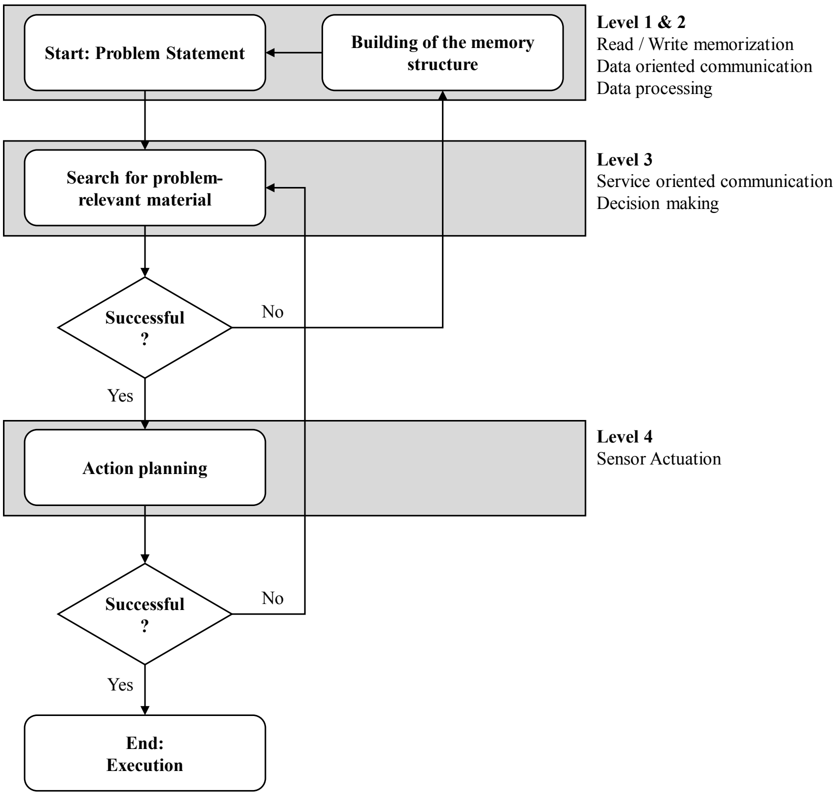

Figure 19: Managing problems with intelligent products author's own representation based on (Dörner, 1984, p. 11; Zbib et al., 2008, p. 249)

4.4 Analysis and evaluation stage

The analysis and evaluation stage consists of more dimensional product classification and demonstrating potential benefits through improved product functionalities. The outcome of the analysis and evaluation stage contains a decision on whether an improvement of the product functionalities causes a reduction or solution to the existing problem. The first step of a more dimensional product classification expands the already examined dimensions of problem type, functionality class, and aggregation level by autonomy and adaptivity. The second step consists of a feasibility analysis to fundamentally justify the outcome regarding the intelligent-product structure.

4.4.1 Step 3: More dimensional product-classification

Besides the three generic dimensions of problem type, functionality class, and aggregation level, the dimensions of autonomy and adaptivity can be extended for specific products or resources. The autonomy addresses intelligent Unmanned Systems (UMSs) and, more particular, the subcategory of Unmanned Ground Vehicles (UGVs). In contrast, adaptivity is based on findings from robotics. However, the extended product classification is an optional and additive variant for unmanned ground systems and robotic systems, which needs to be separated from the mandatory basic categories and is only applicable to specific resources. The user of the IPIDS framework needs to decide whether the resources in manufacturing are classified into unmanned ground systems and robotic systems and thus apply to the more dimensional product classification.

In the literature, various methodologies assess the autonomy level of the unmanned ground system and robotic system domains. For instance, the autonomy levels for unmanned systems (ALFUS) framework uses several test metrics to generate an autonomy level. The framework consists of a three-aspect model: mission complexity, environmental complexity, and human independence (Huang, 2007, p. 48). In addition, the non-contextual autonomy potential (NCAP) provides another robust and simple assessment tool. Since the autonomy level is measured outside a mission and environment-specific setting, the framework is termed the NCAP. Compared to the ALFUS framework, the measures of the NCAP framework can be calculated without first performing extensive operational-level testing (Durst & Gray, 2014, p. 15). Therefore, the NCAP method is selected to classify the product's autonomy level.

The NCAP framework defines four autonomy levels, ranging from non-autonomous to fully autonomous. The first level describes a product/resource, which is externally controlled and only collect data about the environment without using the data. For instance, products such as LIDAR or camera sensors that are externally controlled by teleoperation would be non-autonomous. The second level is semi-autonomous if the product or resource generates a world model or retains internal knowledge. At this level, the product is analysing and interpreting the sensor data. Suppose the product processes the incoming data from the camera or LIDAR sensor and generates a world map but still requires external control to move in the environment. In that case, Level 2 of semi-autonomous is assigned. A product or resource at Level 3 that uses the generated data to perform a plan or action based on internal knowledge is called autonomous. An example of an autonomous guided vehicle is planning the best path in the production environment but still relies on the user's input to select the best alternative. In case no user input is required, the last level of autonomy is reached and is consequently fully autonomous. The structure of the autonomy scaling follows the same principle as the previous concepts and uses a questionnaire to guide the user through the process (Durst & Gray, 2014, pp. 17–20). Table 22 shows the autonomy classification concept for one resource in the IPIDS framework.

Table 22: Autonomy scale

Autonomy scale		**Questionnaire**
Level 1	☐	Is the product/resource externally controlled and detect the environment by sensors?
Level 2	☐	Does the product/resource generate some sort of world model or retain internal knowledge based on sensor data of its surroundings?
Level 3	☐	Does the product/resource use the generated world model to form a plan of action based on internal knowledge?
Level 4	☐	Does the product/resource perform the best action without operator input?

Compared to the functionality model explained in stage one, the autonomy scale focuses on managing sensor data with little attention to memorisation and communication. For instance, autonomy Level 3 does not explicitly require communication, as the product/resource generates a world model to develop an action plan based on internal knowledge. Even though user input is required at this stage, the communication functionality does not characterize autonomy. The same phenomenon is observed for full autonomy, as no operator input is required. The comparison between the functionality model and the autonomy scale shows that they examine different domains.

Adaptivity is based on human-robot collaboration, representing the robot's ability to accomplish a given task despite unexpected situations. In robotics, adaptivity refers to the dynamic behaviour to respond to situations and environmental changes. It is essential to achieve high adaptivity by changing one's actions based on a particular situation, which leads to a high level of collaboration (Krüger et al., 2017, p. 289). The differentiation between adaptability and adaptivity is examined in the next step. According to VDI (2017, p. 6), a production system is defined as adaptable if it represents the ability to change to counter dynamic changes in the environment actively. Therefore, it is described by comparing specific indicators before and after the structural change (VDI, 2017, p. 6). Adaptivity instead indicates the ability of a system to adapt autonomously (Gervasi et al., 2020, p. 848). Thus, an object changes its parameters without requiring environmental influence. For evaluating the product/resource adaptivity, the four-level scale from Krüger et al. (2017) is consulted as a basis (see Table 23).

Table 23: Adaptivity scale

Adaptivity scale		**Questionnaire**
Level 1	☐	Does the product/resource execute the pre-fixed operations in a known task without reactive behaviours?
Level 2	☐	Does the product/resource operate on a fixed underlining model for its actions to enable a flexible, reactive behaviour? (Note: The model is fixed and does not represent flexibility.)
Level 3	☐	Can the product/resource change its parameters according to environmental stimuli to complete the task and learn from the experience?
Level 4	☐	Can the product/resource consider the behaviour of another agent in the context of a goal and its actions and functionalities?

The provided questionnaire for defining the adaptivity level of the product/resource guides the user through the process. Task execution characterizes the first level of adaptivity by pre-fixed operations without reactive behaviour. At this level, the product/resource does not have any form of adaptivity. A product/resource at Level 2 is based on the pre-fixed underlining model from Level 1 to perform the actions, yet the product/resource can act and behave flexibly. For instance, a changing product is a predefined procedure based on a specific trigger. Krüger et al. (2017) mention the example of a cleaning robot that bumps into a wall to understand that this is not the right path to follow and therefore changes the path. Level 3 of adaptivity describes the product's ability to change its parameters according to environmental stimuli to complete the task. In comparison to Level 2, the product or resource learns from experience. In the case of the cleaning robot, the robot remembers the position of the wall by creating a world model, which prevents the robot from bumping into the wall. Finally, the highest level of adaptivity considers the behaviour of another agent in the system and its actions and functionalities. In the provided example of the cleaning robot, the robot takes a priority decision to decide which room to clean first, based on human habits. The adaptivity classification model is only applicable for unmanned and robotic systems and thus expresses the fifth dimension for classifying the products and resources in the manufacturing system.

In addition, a summary of the classification model lists the product dimensions, classification, and the related evaluation method (see Table 24). It is essential to mention that the evaluation methods are based on models and frameworks from the scientific literature. However, some of them are adopted in the manufacturing environment, which leads to partial adjustments to the frameworks.

Table 24: Summary of the holistic product classification

Usage	Product dimension	Classification	Evaluation method
Generic basic	**Problem type**	Simple, complicated, complex	(Glouberman & Zimmerman, 2002; Snowden & Boone, 2007)
	Functionality class	Memorisation, communication, processing, sensor actuation	(Ostgathe, 2012; Zbib et al., 2008)
	Aggregation level	Product level, proxy level	(Meyer et al., 2009)
Specific and additive	**Autonomy**	No autonomy, semi-autonomy, autonomy, full autonomy	(Huang, 2007)
	Adaptivity	No adaptivity, flexible reactions, learning from experience, goal-oriented adaptivity,	(Krüger et al., 2017)

The main goal of the holistic product classification is to analyze and compare various intelligent-product structures. The proposed classification model brings together different viewpoints on intelligent product levels and provides a meeting point for experts from production planning, engineering, and cognitive science.

4.4.2 Step 4: Feasibility analysis

The previous stages and sub-steps of the conceptual framework include the actual state of the manufacturing system. Therefore, the problem statement and the more-dimensional classification of the resources are examined for the comprehensive actual state analysis. The next feasibility analysis step is investigating whether the manufacturing problem can be improved by increasing the resource functionalities. The problem description from step 2 and the resource classification from step 1 and 3 is used to define a desirable solution. The design of the feasibility study is inspired by the knowledge meta-process for developing ontologies (Sure-Vetter et al., 2009, p. 139).

First, the problem statement needs to be observed, whether the level of detail and possible solutions are comprehensively provided. It is helpful to break down the problem into subproblems. In addition, the principle of problem fragmentation has the positive effect of dissolving the emotional component to a spontaneous preference for a potential solution, which leads to a rational discussion. The user needs to define sub-problems, opportunity areas, and potential solutions to complete the analysis. Since there could be many problems and sub-problems when establishing an individual field of manufacturing, a focus area is required. The focus only considers a limited area, which can be handled by intelligent products and resources and does not require additional knowledge. For instance, if a complex problem has been identified in the problem classification in step 2, it is advisable to break it down further to a feasible subproblem. In addition, goals for the selected focus area need to be defined. The goals should be quantifiable and measurable in this context to check whether the potential solution enables system improvement. Therefore, the methodology of writing SMART objectives from Doran et al. (1981) is used to define meaningful objectives. Defining the timing and economic objectives determines the technical requirements and development framework. Thus, the SMART objectives represent the user's budget in terms of time, money, and infrastructure. The goals can be used after the execution phase to verify that the targets have been achieved. Finally, the listed possible solutions for the perceived problems and opportunities are filtered to receive a desirable solution. Additional evaluation criteria for selecting the desirable solution could be the available IT infrastructure, identification and processing technology, knowledge, and costs. Some factors contribute to FMS changes. At the top of these factors, the measurable indicators such as process technology, facility layout, job design, and production and material planning are ranked. The characteristics of the manufacturer's initial situation determine how far and how easily a system can change. In addition, soft factors influence a system's flexibility behaviour. If the focus lies on flexibility improvements, the IPIDS framework user describes the maturity level in the six factors described by Slack (1983).

Based on the selection of the desired solution, the questionnaire of step 1 and step 3 needs to be filled in again, but at this step, for the desired solution. In the end, two product classifications per source will be available. The first classification considers the actual state of the manufacturing system, whereas the second represents the product's functionalities in the desired solution. Table 25 shows the feasibility study of the focus area, goals, and desirable solution, which requires user input in the orange fields.

Table 25: Feasibility study

Focus area
Establish subproblems based on the overall problem classification.
Goals
SMART Goals (**S**pecific, **M**easurable, **A**ssignable, **R**ealistic, **T**ime related)
Desired solution
Possible iteration loop to step 2, to redefine the subproblem if the solution is not achievable by the functionalities and requires additional knowledge.

The conceptual framework for integrating intelligent-product structures into a FMS consists of potential iteration loops. Conducting the feasibility study could refine the subproblem if the desired solution is not achievable by the functionalities of intelligent products. The problem could be too comprehensive or complex to manage by intelligent-product functionalities. Therefore, observation is required to determine whether the problem statement can be further subdivided. For instance, intelligent products may break a complex problem into several complicated problems manageable. Besides creating subproblems, the focus area can also be reduced by considering, for instance, not the entire manufacturing line but focusing on a sub-manufacturing or specific manufacturing station.

Numerous use cases of intelligent products in the industry point out their economic and process benefit (Bertelsmeier et al., 2016; J. Barbosa et al., 2016; Neal et al., 2019). Bertelsmeier et al. (2016) developed an intelligent workpiece carrier in candle manufacturing to produce customized candles with variable shapes, colours, and lot sizes. The focus lies on developing the intelligent workpiece carrier in the use case of process and resource allocation. Furthermore, J. Barbosa et al. (2016) investigated the cross-benefits of CPS and intelligent products for future innovative industries. In particular, the strengths of intelligent product functionalities lie in product monitoring, tracking of data, and real-time adaption of routing. Neal et al. (2019) developed a cyber-physical intelligent container for the manufacturing environment. The container monitors its environmental parameters as well as its components. The material and tool tracking of containers reduces setup times and improves change-over management. The three use cases of intelligent products represent only an excerpt in industrial scenarios for the framework user. However, frequently stated benefits are summarised as:

i. Traceability of the product allows the owners and users to access the product's location, condition, and physical state at any time. Data-centric manufacturing can increase product quality and provide transparent product history.
ii. Sensing the product's condition enables to stop or intervention in a process in case of an "out-of-condition" situation. Product sensing has the potential to decrease the production-down-times and enable immediate adjustments by triggering actors.
iii. Self-awareness of the product allows postponing decisions to the last moment to provide an adequate reaction to disturbances. The product's decision-making can adjust the product planning to real-time business needs.

4.4.3 Step 5: Definition of target functionalities for the desired solution

After the problem classification and the desired solution are established, steps 1 and 3 need to be completed again, but at this step, for the desired target solution. Based on the comprehensive description of the target solution, its product functionalities need to be defined. Finally, the initial situation and the target solution can be compared in terms of their functionalities. To fulfil the desired solution and thus solve the manufacturing problem, various scenarios of differently distributed functionalities among the products and resources are possible. In most cases, mixed product-intelligence structure classes satisfy the problem, as not all products and resources need to be on the same intelligence level. Depending on the use case, equal functionality levels among the products and resources can reduce barriers to communication or interaction, as all entities are on the same level. Economic, technical, or future strategical factors influence the selection of the appropriate scenario.

Besides the fact that the problem can be reduced or solved by intelligent-product functionalities, there exists the case of no value-adding of intelligent products to the problem statement. There is no value-adding if the identified problem cannot be simplified and therefore cannot be reduced or solved by the intelligent-product structures even after several iteration loops. The process should be aborted here, as intelligent-product structures do not offer a solution.

4.5 Design stage

The third stage is necessary if the problem can be improved or even eliminated and involves the requirements profile for the intelligent-product functionalities. First, the listing of the design requirements is inspired by the 5C architecture for implementing the CPS of J. Lee et al. (2015) and (Vogel-Heuser et al., 2015, p. 779) are supplemented by the intelligent-product-aspect. Since CPS is a combination of an intelligent and adaptive control system, only a few requirements of the 5C architecture are considered. In addition, the technical requirements of intelligent products are linked with the generic functionalities.

4.5.1 Step 6: Specification of the technical requirements

In addition to the already identified functionality levels of the products or resources, different designs and technical requirements are needed to establish a holistic picture of the FMS. The specification of the design requirements is threefold. First, a flow diagram is required to identify the resources' logical interfaces, which is extended by a data model in the second step. Finally, the flexibility or adaptivity objective needs to be defined.

Design requirement DR_1: To successfully integrate intelligent-product structures into manufacturing, additional knowledge about the products or resources are required regarding their physical and logical interfaces to other resources and the existing product variances. Therefore, a flow diagram or interface diagram of the desirable solution displays the relationship between the products or resources in the use case. The flow diagram displays all entities and their relationship to achieve the desired solution.

Design requirement DR_2: This requirement is based on DR_1 and considers the identification and organisation of the required data and converted information needed for processing and decision making. A data model can show the logic of the elements of data and their relationship to one another.

Design requirement DR_3: Identification of the flexibility or adaptivity objective in the FMS, which needs to be achieved by intelligent products. This represents the objective of the desired solution to be a part of the flexible, controlled manufacturing system. The intelligent product or carrier needs to be flexible and adaptable. Parker and Wirth (1999) and Sethi and Sethi (1990) provide knowledge for the manufacturing environment for selecting the flexibility dimensions and their measurements. The definition, metrics, and measurement procedure of adaptability are based on VDI (2017).

In addition to the design requirements, Table 26 links each of the functionalities with the technical requirements. The functionality of memorisation specifies two access rights: read or read-only and read and write. The ROM stores data permanently according to a specific pattern or mask. It applies to storing data that will never require modifications or changes, such as a unique product, production ID, or serial number (Butterfield & Ngondi, 2016, p. 474). In other words, the device can only record once but can be read many times from other devices. This category includes ROM chips or ROM optical disks and is therefore used for a broad range of storage devices. However, there are many applications where there is the requirement to write, erase, and rewrite the information in the memory. With read and write memory, it is possible to add information to individual storage locations within the device or write over existing information. In this case, the technical requirement needs read and write memory that is flexible to applications by updating the data. RAM devices typically read and write memories (Butterfield & Ngondi, 2016, p. 457). However, the functionality of reading and writing also has the option to be locked to prevent overwriting of data or tag tampering. A product may have both read-only and read-and-write memory.

The means of communication is an essential ingredient of intelligence, as, without it, the device cannot participate in a network. The functionality of communication distinguishes between data-oriented and service-oriented communication. According to Zbib et al. (2008), the technical requirement for data-oriented communication is defined as data access capacity and reading and writing ability. The memorisation has already addressed the reading and writing functionalities. The application of an RFID system represents an example of data-oriented communication, as the system consists of a reader, an antenna, and a tag.

Compared to the simple data access capacity of reading and writing functionalities, service-oriented communication aims to broker and utilise services and therefore uses services instead of protocols. It enables communication through a service-oriented architecture. The basic approach consists of a service negotiation between a service user and a service provider, which a broker performs. (Reuther & Henrici, 2008, p. 596). According to Reuther and Henrici (2008), the technology that supports the building of a service-oriented architecture model requires the following three functionalities:

i. Specification of services.
ii. Matchmaking of the services.
iii. The service-oriented interface between service users and providers.

In other words, service-oriented communications aim to convert communications and communication channels into software for better integration and collaboration among devices or people. In addition, bidirectional communication is provided, as the service user is sending a request to the service provider and the service provider performs the request action.

For the processing functionality, the technical requirements are based on IoT sensor data processing, fusion, and analysis techniques (Krishnamurthi et al., 2020, p. 3). In the first step, the data processing definition of

Zbib et al. (2008) considers only the gathering and synthesizing of data, which is already covered by reading and writing data from a storage device. The data processing functionality considers cleaning, further data management, and checking the input data's completeness to enable decision making and knowledge generation. According to Krishnamurthi et al. (2020), data processing includes different functions of data denoising, data outlier detection, missing data imputation and data aggregation, which are required to control the improper data transmission from the sensors. These data processing steps are required to handle the sensor data and generate knowledge and decision-making in the next step (Krishnamurthi et al., 2020, p. 5). After gathering, cleaning and managing the data, the knowledge discovery or decision-making requires data mining models and analysis techniques to interpret the data (Krishnamurthi et al., 2020, p. 15).

Finally, the technical requirements of sensor actuation are considered, which requires sensors and actuators to enable interaction between the intelligent entities in the informational or physical environment. There are two types of interaction, namely proprioceptive and exteroceptive. Proprioceptive interaction describes an internal form of perception and interaction, where the focus lies on the product's physical state (such as temperature, vibration, or light irradiation), controlled by an augmentation module. In comparison, the exteroceptive interaction considers the physical or informational interaction with the external resource environment. The physical interaction controls the distance to an external object, whereas the informational interaction considers the communication with resources in the environment (Zbib et al., 2008, p. 249). Both types of interaction require sensors and actuators to measure and control the internal product or environmental state.

Table 26: Technical requirements for basic functionalities

Functionalities	Characteristics	Conditions	Technical requirements
Memorisation	Read	Static information (unique production ID)	"Read-only" memory (data permanently stored)
	Read/Write	Dynamic information (work-in-progress information)	"Read/write" memory (data temporary stored)
Communication	Data-oriented	Bidirectional communication	Data access functionality and reading and writing
	Service-oriented	Bidirectional communication	Specification & matching of services and interface between users and providers
Processing	Data processing	Information-oriented data processing	Collecting, synthesizing, and data management
	Decision making	Data analysis and solution approaches	Data mining models and analysis techniques
Sensor actuation		Interaction	Proprioceptive and exteroceptive sensors and actuators

4.6 Execution stage

The execution stage consists of implementing the intelligent product according to the technical requirements from stage three. At this stage, a decision is required whether the functionalities of the intelligent product are on the product itself or the intelligent carrier. The decision of the product's aggregation level is threefold. The first aspect considers the value-adding factor of intelligent products for the customer in the product's use phase.

Secondly, the product's level of completion in manufacturing is investigated, as the product cannot be equipped with the functionalities in the early phases of production. Furthermore, the third aspect describes the varying intelligent functionalities during the product's life cycle.

4.6.1 Step 7: Design and development of the intelligent product or carrier

At this stage, a crucial decision about the aggregation level is needed to define whether the desired product solution requires its product intelligence to manage information and decisions about itself or if a product proxy is suitable. Therefore, two significant aspects need to be investigated. The first aspect is about the value-adding factor for the customer. If the onboard intelligence indicates no value-adding for the customer, the level of product intelligence should not be increased but decreased to a minimum level. The value-adding factor of the customer can be measured by conducting market surveys or analysing future trends. However, suppose the market research results in an application field and therefore predicts a value-adding of an intelligent onboard product for the customer. In that case, intelligent functionalities should be provided on the product. The second aspect considers the product's level of completion in manufacturing. A product in the early production phase does not have the functionalities to participate in the decision-making about its own life. In the early manufacturing phase, an intelligent carrier that acts as a proxy can provide intelligent functionalities. The third aspect considers the different intelligent functionalities of products during the product's life cycle. The life cycle is simplified and divided into manufacturing, usage, and recycling phases. Since the intelligence in manufacturing is designed for particular use cases, such as dynamically defining the resource allocation according to their availability or other scenarios, the intelligence is not needed during the product's use phase. The former intelligence can be removed and instead retained by abilities such as self-monitoring and self-diagnosis in the product use phase. In addition, the recycling phase of the product requires different abilities, such as analysing the product's life history during the use phase to decide which parts of the product are reusable and which need to be recycled. The abilities for the use cases in the product life cycle must be implemented in the product manufacturing phase or adjusted at each stage. In general, intelligent products provide powerful functionalities to actively control the different use cases in the product life cycle.

After the aggregation level of each resource is defined, the implementation of the intelligent product or carrier is conducted based on the defined requirements. A bill of material assists the development of the hardware components and provides matchmaking between the technical requirements and hardware components. In addition, the development phase must select an electric circuit diagram, a server structure diagram, or software-related tools. If further requirements arise during the development of the intelligent carrier to solve the manufacturing problem, the user of the IPIDS framework needs to derive the additional resources. If additional resources cannot solve the requirement, an iteration to step 6 of the IPIDS framework is suggested to respecify the design and technical requirements. If the repeated specification of requirements is not successful and does not enable the development of the intelligent-product structure, an iteration to step 2 and 4 of the IPIDS framework is required to classify the problem and define an adjusted problem statement. Consequently, this narrows the scope by addressing less complicated problems or dividing the problem into simple subproblems. In general, a backwards iteration implies that steps that have already been completed must be executed again.

4.7 Conclusion: Framework development

This chapter presents the development of the IPIDS framework, which addresses the requirement specification, proposed in Chapter 3. The framework development consequently follows these conceptual requirements. Thus, the IPIDS framework provides a systematic and holistic approach for assessing the manufacturer's resource functionalities and deriving intelligent-product structures to enhance communication and decision-making of the manufacturing resources. The user of the IPIDS framework is guided through the seven steps by tools, methods, and processes covered in Chapter 4.

Chapter 5. Evaluation of the IPIDS framework

This chapter evaluates the developed conceptual framework, structured into verification and validation. The verification of the framework is based on five requirement types that were established in Chapter 3. Therefore, the requirements are individually verified according to their satisfaction level and assigned phase in the IPIDS framework. For validation purposes, a prototype implementation is performed in the learning factory in Reutlingen to provide confidence in the applicability, practicability, and usability of the developed framework.

5.1 Verification - Evaluation of the requirement specification

The verification process examines whether the framework has been developed according to established requirements and assesses whether the system has been developed correctly. Verification is described by the question, "Am I building the product right?". In comparison to verification, the validation establishes whether the correct product has been built. Validation involves testing the framework at the end of the development to ensure it does what it is supposed to. However, both evaluation principles aim to identify and resolve problems and risk issues to secure the correct performance of its intended functions (Boehm, 1984, p. 75).

The requirements for developing the conceptual framework are categorised according to van Aken and Berends (2018). Chapter 3 is the requirement specification of the five categories and includes functional requirements, user requirements, boundary conditions, design restrictions, and attention points. For each of these categories, an individual requirement verification is conducted to consider whether the conceptual framework achieves them and whether they are addressed by a specific step across the IPIDS framework. The outcome of the verification process is displayed in the following tables by evaluating how the framework stages address the requirements. It is essential to mention that some of the requirements are related to the framework generically and conceptually and therefore cannot be linked to a specific phase.

Table 27: Functional requirements verification

<table>
<tr><th rowspan="3">REQUIREMENT NUMBER</th><th rowspan="3">REQUIREMENTS</th><th colspan="7">STEPS OF THE CONCEPTUAL FRAMEWORK</th></tr>
<tr><th colspan="2">DEFINITION</th><th colspan="3">ANALYSIS / EVALUATION</th><th>DESIGN</th><th>EXECUTION</th></tr>
<tr><th>01. FUNCTIONALITY MODEL FOR PRODUCTS</th><th>02. CLASSIFICATION OF THE EXISTING PROBLEMS</th><th>03. MORE DIMENSIONAL CLASSIFICATION</th><th>04. FEASIBILITY STUDY</th><th>05. FUNCTIONALITIES FOR THE DESIRED SOLUTION</th><th>06. DESIGN AND TECHNICAL REQUIREMENTS</th><th>07. DESIGN AND DEVELOPMENT OF REQUIREMENTS</th></tr>
<tr><td colspan="9">Overarching functional requirements</td></tr>
<tr><td>FR1</td><td>The framework should contribute toward defining, analysing, and designing intelligent products or resources within the context of flexible manufacturing.</td><td>✓</td><td></td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td></tr>
<tr><td>FR2</td><td>The framework should apply to various resources within the specified scope of manufacturing systems but needs to be extended for specific product analysis (such as robots or automated guided vehicles).</td><td colspan="7">✓</td></tr>
<tr><td>FR3</td><td>Although the framework is not aimed at prescribing specific methods, tools, or processes, some concepts should be provided to guide the users and simplify the framework's application.</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td>✓</td><td></td></tr>
<tr><td>FR4</td><td>The framework should consider integral activities to apply the framework to manufacturers successfully.</td><td></td><td>✓</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>FR5</td><td>The realisation of the solution has the aim to solve a business problem, both from a technical as well as from an economic perspective.</td><td></td><td></td><td></td><td>✓</td><td>✓</td><td></td><td></td></tr>
</table>

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Conceptual functional requirements								
FR6	The framework should consider product intelligence from a more dimensional perspective and is intended to avoid a narrow perspective, which is limited on the functionalities.	✓		✓				
FR7	The framework should handle mixed product-intelligence structures	✓			✓	✓		
FR8	For both outcomes (value-adding or no value-adding of the intelligent product for a manufacturing system) of the feasibility analysis, the conceptual framework should define a procedure. A particular focus should be set on the case of value-adding of intelligent products.				✓	✓	✓	✓
FR9	The framework should support the design and information technology profile of intelligent products.	✓		✓			✓	
Operational functional requirements								
FR10	The framework should define a precise classification of passive and intelligent products within the scope of the manufacturing environment.	✓						
FR11	The framework should provide decision support in manufacturing systems regarding technology management within intelligent products. It should aid users in identifying and implementing flexibility potentials in their current manufacturing process.				✓	✓		✓
FR12	The framework should be able to deliver a precise statement regarding the feasibility of intelligent products for the respective user.				✓	✓		
FR13	The framework should support and enable the development process of intelligent products.						✓	✓

Table 28: User requirements verification

		STEPS OF THE CONCEPTUAL FRAMEWORK						
		DEFINITION		ANALYSIS / EVALUATION			DESIGN	EXECUTION
REQUIREMENT NUMBER	REQUIREMENTS	01. FUNCTIONALITY MODEL FOR PRODUCTS	02. CLASSIFICATION OF THE EXISTING PROBLEMS	03. MORE DIMENSIONAL CLASSIFICATION	04. FEASIBILITY STUDY	05. FUNCTIONALITIES FOR THE DESIRED SOLUTION	06. DESIGN AND TECHNICAL REQUIREMENTS	07. DESIGN AND DEVELOPMENT OF REQUIREMENTS
User requirements								
UR1	The framework should be user-friendly and practicable, which indicates that it is easy to understand and adopt.	✓						
UR2	The framework should be designed so that the procedure and the interlinked concepts can be understood even without a thorough and deep understanding of the theoretical foundations. Therefore, the framework should provide a clear structure supported by precise requirements, definitions, and explanations.	The developed constructs of the conceptual framework appeal to academically inclined and practically oriented audiences. At the same time, the stages of definition and analysis appeal more to the academically inclined audience and the design and execution target practitioners. For the realisation of intelligent products, all stages are required.						
UR3	The frame should facilitate repeated and continuous use.	✓						
UR4	The framework should enable users' input, guided by defined actions for the processing.	✓	✓	✓	✓	✓		✓

Table 29: Design restrictions verification

<table>
<tr><th rowspan="3">REQUIREMENT NUMBER</th><th rowspan="3">REQUIREMENTS</th><th colspan="7">STEPS OF THE CONCEPTUAL FRAMEWORK</th></tr>
<tr><th colspan="2">DEFINITION</th><th colspan="3">ANALYSIS / EVALUATION</th><th>DESIGN</th><th>EXECUTION</th></tr>
<tr><th>01. FUNCTIONALITY MODEL FOR PRODUCTS</th><th>02. CLASSIFICATION OF THE EXISTING PROBLEMS</th><th>03. MORE DIMENSIONAL CLASSIFICATION</th><th>04. FEASIBILITY STUDY</th><th>05. FUNCTIONALITIES FOR THE DESIRED SOLUTION</th><th>06. DESIGN AND TECHNICAL REQUIREMENTS</th><th>07. DESIGN AND DEVELOPMENT OF REQUIREMENTS</th></tr>
<tr><td colspan="9">Design restrictions</td></tr>
<tr><td>DR1</td><td>The conceptual framework is not meant to consider the use phase of a product. However, it should be comprehensive enough to guide manufacturing systems defined by the functional requirements.</td><td colspan="7">Each step of the conceptual framework provides comprehensive tools, methods, and processes to illuminate considerations for intelligent products. Thereby, the template approach does not manipulate or target specific issues.</td></tr>
<tr><td>DR2</td><td>The framework should be developed for manufacturing but could also be applicable for other application fields such as logistics.</td><td colspan="7">The conceptual framework delivers tools and approaches applicable to problem scenarios in logistics or supply chain management, which has not been validated and suggested for further research.</td></tr>
<tr><td>DR3</td><td>The framework does not guarantee a complete evaluation for all manifestations of an intelligent product, as not all of them can be covered due to many factors. The framework aims to provide a guideline to analyse the potential and the implementation.</td><td colspan="7">The conceptual framework's templates aim to provide a generic viewpoint on intelligent products and their functionalities. However, there are could also individual factors such as autonomy and adaptivity for unmanned ground systems and robotics be necessary for a complete evaluation.</td></tr>
<tr><td>DR4</td><td>The framework is intended for a decision-level analysis and implementation guideline but does not guarantee improved quality and performance changes.</td><td colspan="7">The critical element of the decision analysis is provided by the feasibility study, which combines the manufacturing problem and the desired solution in the context of intelligent products. However, the insights gained from the framework highlight the potential of flexible and intelligent products in manufacturing.</td></tr>
<tr><td>DR5</td><td>The framework should be limited by the number of imperative tools and concepts.</td><td colspan="7">An optional additive product classification in unmanned ground systems and robotics is provided in step 4 of the conceptual framework. However, this is not mandatory and does not constitute a crucial part.</td></tr>
</table>

Table 30: Attention points verification

<table>
<tr><th rowspan="3">REQUIREMENT NUMBER</th><th rowspan="3">REQUIREMENTS</th><th colspan="7">STEPS OF THE CONCEPTUAL FRAMEWORK</th></tr>
<tr><th colspan="2">DEFINITION</th><th colspan="3">ANALYSIS / EVALUATION</th><th>DESIGN</th><th>EXECUTION</th></tr>
<tr><th>01. FUNCTIONALITY MODEL FOR PRODUCTS</th><th>02. CLASSIFICATION OF THE EXISTING PROBLEMS</th><th>03. MORE DIMENSIONAL CLASSIFICATION</th><th>04. FEASIBILITY STUDY</th><th>05. FUNCTIONALITIES FOR THE DESIRED SOLUTION</th><th>06. DESIGN AND TECHNICAL REQUIREMENTS</th><th>07. DESIGN AND DEVELOPMENT OF REQUIREMENTS</th></tr>
<tr><td colspan="9">Attention points</td></tr>
<tr><td>AP1</td><td>Due to the nature of the framework, several opportunities for integration with other pre- and post-approaches and frameworks for analysing and designing intelligent products are considered. However, it is beyond the scope of this study to explicitly address such possibilities.</td><td>✓</td><td></td><td>✓</td><td></td><td></td><td>✓</td><td></td></tr>
<tr><td>AP2</td><td>The high-level framework supports the analysis and implementation of intelligent products in manufacturing. However, the framework should also deal with the interlinked concepts in detail to provide the user with the best possible ease of use.</td><td colspan="7">✓</td></tr>
<tr><td>AP3</td><td>The framework should enable manufacturers to apply it in different ways, as they can use it to the extent they need. Therefore, the framework should allow the flexibility to adapt the application depth to the specific case, which should be adjustable by user input (as mentioned in UR4).</td><td>✓</td><td></td><td>✓</td><td></td><td></td><td></td><td></td></tr>
</table>

Table 31: Boundary conditions verification

		STEPS OF THE CONCEPTUAL FRAMEWORK						
		DEFINITION		ANALYSIS / EVALUATION			DESIGN	EXECUTION
REQUIREMENT NUMBER	REQUIREMENTS	01. FUNCTIONALITY MODEL FOR PRODUCTS	02. CLASSIFICATION OF THE EXISTING PROBLEMS	03. MORE DIMENSIONAL CLASSIFICATION	04. FEASIBILITY STUDY	05. FUNCTIONALITIES FOR THE DESIRED SOLUTION	06. DESIGN AND TECHNICAL REQUIREMENTS	07. DESIGN AND DEVELOPMENT OF REQUIREMENTS
Boundary conditions								
BC1	The framework must adhere to ethical, legal, and scientific requirements.	The conceptual framework highlights considerations to support intelligent-product structure analysis, evaluation, and design. Therefore, it should be used for its intended purpose, where it does not stand in contention with other approaches.						
BC2	Risks and opportunities should be highlighted across the system, focusing on the desired solution and potential.	For the design and development of intelligent products, technical resources of IT infrastructure, processing and sensor technology are required. Therefore, the framework implicitly aims to facilitate a detailed analysis of the desired solution to not master the problems only through expensive technology.						
BC3	The framework has the goal and vision of demonstrating the potential of intelligent products. However, the potentials do not correspond to all forms of flexibility and are limited to defined areas.	The potential of intelligent products is demonstrated by an extensive literature review on the topic, which addresses various use-cases for the assembly and other areas, with different forms of flexibility.						
BC4	The framework should provide value for all parties involved, e.g., the researcher or manufacturer. The exploitation of other parties should be avoided.	The value-adding of the conceptual framework is described by solving an existing manufacturing problem. In addition, the value of insights regarding requirements, risks, and opportunities for intelligent products is provided to support the decision-making process.						

The presented tables outline the requirements of the IPIDS framework. The IPIDS fulfils the functional requirement of defining, analysing, and designing intelligent-product structures in the context of FMS by a template approach and providing comprehensive tools, methods, and processes for each stage. Thus, the framework consists of integral activities without prescribing any approach for manufacturers. Furthermore, the feasibility analysis of the IPIDS framework solves business problems from a technical and economic perspective. Smart objectives represent the user's budget in terms of time, money, and existing infrastructure, and a short description of use cases highlights use cases with economic and technical benefits. The assessment of composite product-intelligence structures is covered in step 1, the functionality model and step 5, the selection of the target functionalities. Each product or resource functionality is individually analysed to define the initial status and provide different solution scenarios. In addition to the five requirement types of van Aken and Berends (2018), the development guideline of the IPIDS framework is based on the seven features from Jabareen (2009). Since the features are related to the framework generically and conceptually, they are linked to all steps. The verification of the features is displayed in Table 32.

Table 32: Features for developing conceptual frameworks

		STEPS OF THE CONCEPTUAL FRAMEWORK						
		DEFINITION		ANALYSIS / EVALUATION			DESIGN	EXECUTION
REQUIREMENT NUMBER	REQUIREMENTS	01. FUNCTIONALITY MODEL FOR PRODUCTS	02. CLASSIFICATION OF THE EXISTING PROBLEMS	03. MORE DIMENSIONAL CLASSIFICATION	04. FEASIBILITY STUDY	05. FUNCTIONALITIES FOR THE DESIRED SOLUTION	06. DESIGN AND TECHNICAL REQUIREMENTS	07. DESIGN AND DEVELOPMENT OF REQUIREMENTS
Features of conceptual frameworks								
F1	A conceptual framework should not be a collection of concepts. Instead, each of them has a core role.	The templates of the IPIDS framework have the common goal of defining, analysing, and designing intelligent-product structures in the context of flexible manufacturing systems. In addition, the IPIDS framework presumes relationships among the concepts. For instance, problem-solving is linked with the functionality classes of intelligent products.						
F2	A conceptual framework represents an interpretative approach to social reality.	The application of the IPIDS framework is possible in various ways and has the flexibility to adapt the application depth to the specific use case. It covers use cases in FMS and the framework user can utilize to the extent they need.						
F3	A conceptual framework aims to provide understanding rather than "theoretical explanations".	The IPIDS framework consists of theoretical definitions and classifications to understand the product's functionalities. In addition, the template approach of the IPIDS framework supports practical understanding and thinking.						

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F4	A conceptual framework provides a "soft interpretation of intentions".	The IPIDS framework has the intention to enhance the product and resource functionalities. Self-aware products and resources can communicate their status and perform tasks independently of the human operators.
F5	A conceptual framework is indeterminist, implying preconditions unambiguously determine not all events. Causes do not unambiguously determine certain events.	Preconditions determine most steps of the IPIDS framework. The aim is to analyse the initial situation in a manufacturing system and its problems to develop a desirable solution of intelligent products and resources. However, the design stage is not entirely determined by preconditions, as additional factors play a role besides problem-solving.
F6	A conceptual framework is designed through a process of qualitative analysis.	The IPIDS framework is developed based on the research problem and objectives of overall system integration and evaluation tool for manufacturing systems, focusing on mixed product-intelligence. Therefore, qualitative and systematic literature reviews are conducted.
F7	Discipline-oriented theories mainly define the source of a conceptual framework.	The IPIDS framework aims to produce concepts to analyse, define, and design intelligent products. The data source is multifaced, as product intelligence is based on psychological and industrial perspectives. The discipline-oriented theories become the empirical data collected by the systematic literature review. However, the conceptual framework of IPIDS is based on multidisciplinary bodies of knowledge and a systematic synthesis of findings from qualitative studies.

5.2 Validation - Prototype implementation

For the validation of the IPIDS framework, the technique of practical implementation is applied to evaluate the applicability, usefulness, and practicability. Using the framework in a real-world phenomenon is intended to show that the IPIDS framework is feasible to apply promptly. Therefore, a use case in the learning factory in Reutlingen follows the framework's guideline of analysing and implementing intelligent-product structures step by step, which provides a practical example. Each of the provided steps from the IPIDS framework is conducted for the use case-specific situation in the learning factory, which will be summarised and reviewed at the end of this chapter.

5.2.1 The initial situation at Werk150

The Werk150 in Reutlingen provides innovative infrastructure for developing and evaluating application-oriented solutions in the context of Industry 4.0. It represents a learning factory that offers students and professionals from industry the opportunity to experience innovative technologies and learn and develop system and interface skills. These competencies are explained using a pedal scooter assembly. There are three different scooter models assembled at Werk150. Some allow individualisation in terms of personalised add-on components such as mobile phone mount in various colours or a mirror with the customer's initials engraved. The assembly is classified as a multi model assembly line, as three different scooter models are produced on the same assembly line. However, the current assembly line requires set-ups to change from one scooter model to the other, which belongs to batch model mix assembly. The classification of flexible assembly lines is illustrated in Figure 20. A distinction is destined between single and multi-model assembly, determining if only one or more products are assembled on the same line. In addition, the multi model assembly is subdivided into batch model assembly and serial model assembly. For batch model assembly, identical products are bundled into one batch, and one batch is produced after the other. Changing from one batch size to the next always requires a setup process.

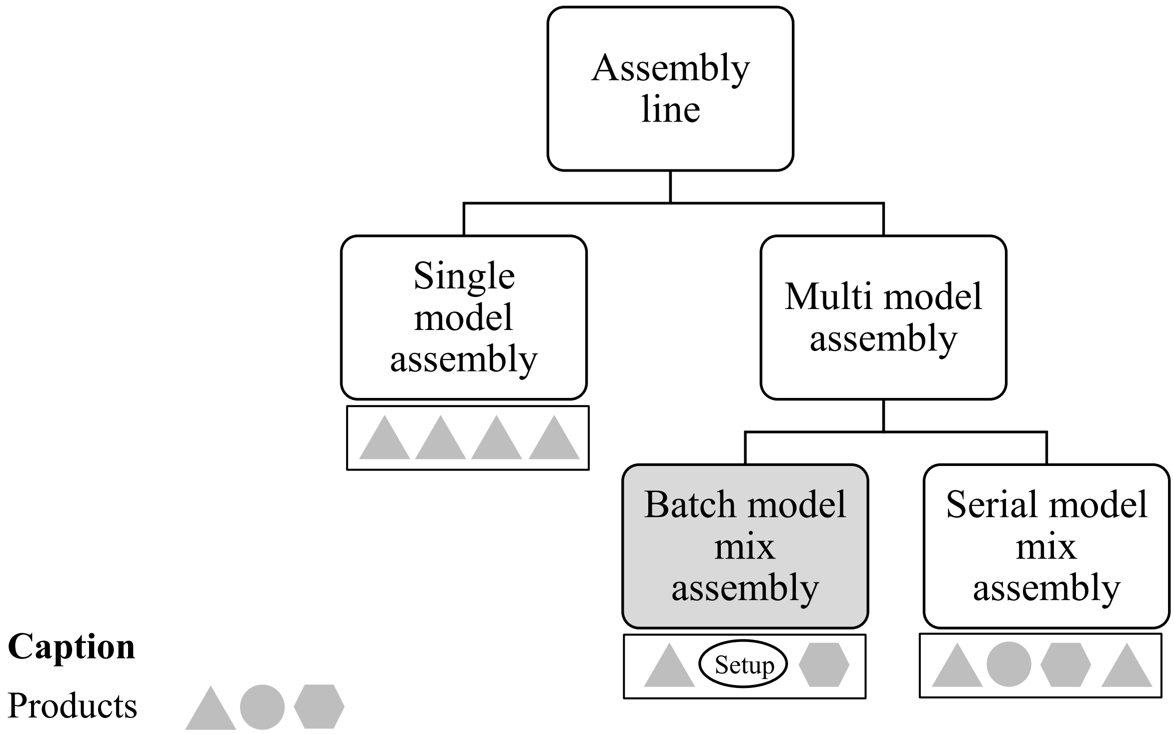

Figure 20: Classification of assembly lines based on (Pröpster, 2015, p. 12)

In contrast to batch model mix assembly, the serial model mix assembly does not require setup processes. However, sometimes serial model mix assembly lines have little setup processes, which is about the processing time very little and does not disturb the one-piece flow in batch size one. The multi model assembly lines intend to cope with the changes in global demand by improving flexibility. Increasing numbers of variants in small batches show a predominant need for multi model assembly lines (Lotter, 2006, p. 4).

The pedal scooter production involves many logistics and assembly processes with different material flow between the individual assembly stations. Therefore, the assembly process is divided into three workstations for assembling the footboard, the handlebars, and the final assembly. The primary process in the pedal scooter assembly is the permanent joining of two or more parts to produce a product of higher complexity (VDI, 1990). In addition to joining, other sub-processes such as putting together, filling, and forming operations are used for assembling the pedal scooter.[8]

At the assembly stations, human operators and assisted robots perform most of the activities manually. Only some processes, such as commissioning parts on a workpiece carrier, run fully automatic by a robot. Semi-automatic systems are often called hybrid systems, consisting of automatic devices such as robots with manual work in one system (Misra & Saran, 2021, p. 283). In addition, each workstation is indirectly connected to a conveyor system, as the employee needs to lift the workpiece carrier from the conveyor system for assembly and place it on an adjacent table or workbench. A particular assembly station is considered for validating the IPIDS framework, where assembly steps for the footboard are executed.

5.2.2 Step 1: Functionality model for resources at the assembly station

Before analysing the existing resource functionalities, the assembly station and its resources are described comprehensively. For the prototypical validation of the IPIDS framework, the sub-processes of picking and placing screws on the footboard are considered. Other pre- and post-processes are irrelevant, as potential intelligent structures are only investigated on this station. The operator initially takes the workpiece carrier from the conveyor system and places it on the workbench. The workpiece carrier must be placed between two fixed brackets on the workbench, ensuring the same position every time. The collaborative robot UR10e conducts the process of picking and placing screws. At the same time, the human carries out further joining processes on the workpiece in parallel, which is not relevant in this context and therefore is not further explained. The workstation is displayed in Figure 21 and consists of the collaborative robot UR10e and a workbench.

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[8] The joining processes are defined in (DIN, 2003).

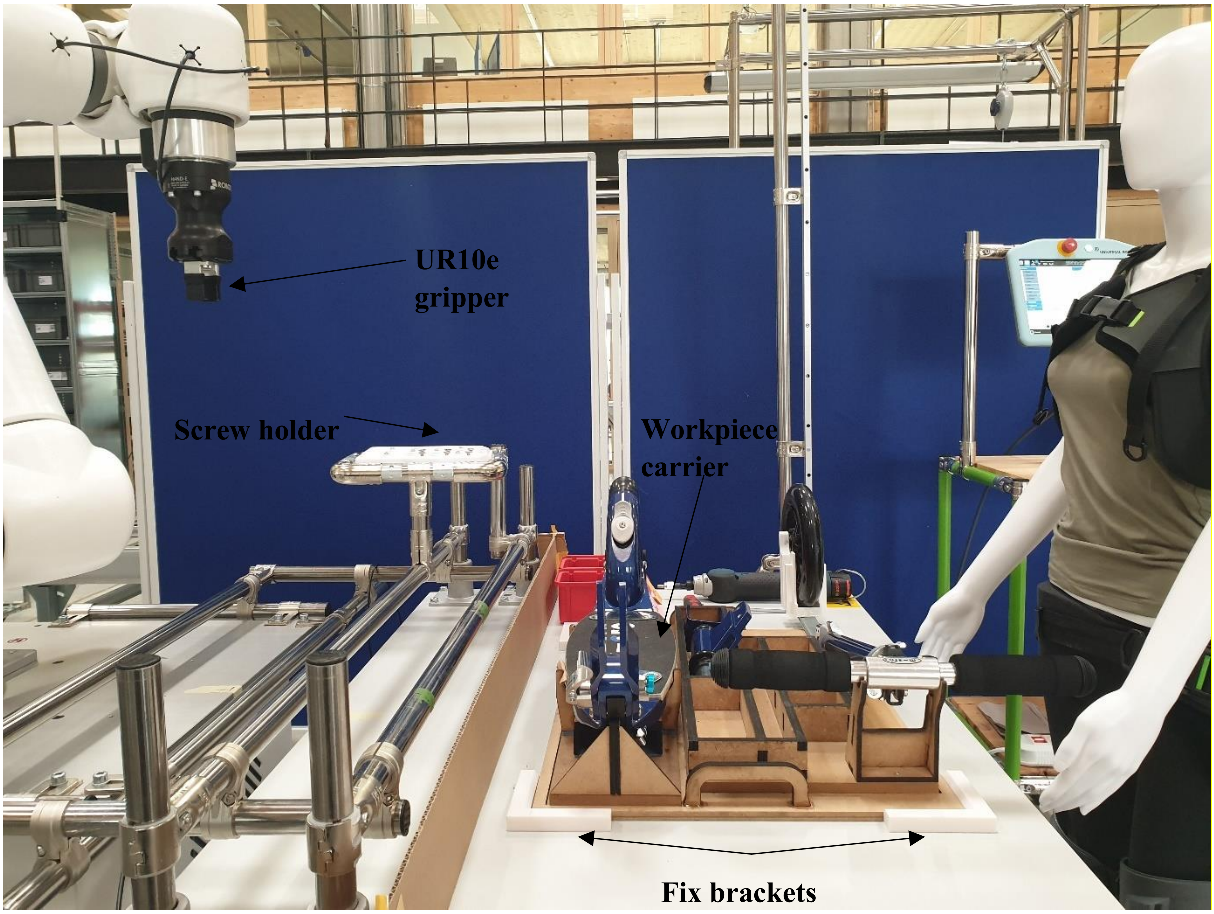

Figure 21: Initial situation of the assembly station at Werk150

The UR10e is connected to the internet by using its ethernet connection. There are rigid tube connections between the frame of the UR10e and the workbench to keep a constant distance, ensuring the robot program's correct execution. In addition, there is a screw holder where the UR10e gripper picks the screws to place them on the footboard. The upstream material supply of the screws on the bracket is not considered here.

After describing the existing production process, the current resources are classified. Therefore, the resources workpiece carrier and UR10e are classified according to the functionality classes of Zbib et al. (2008), which are presented in Figure 22.

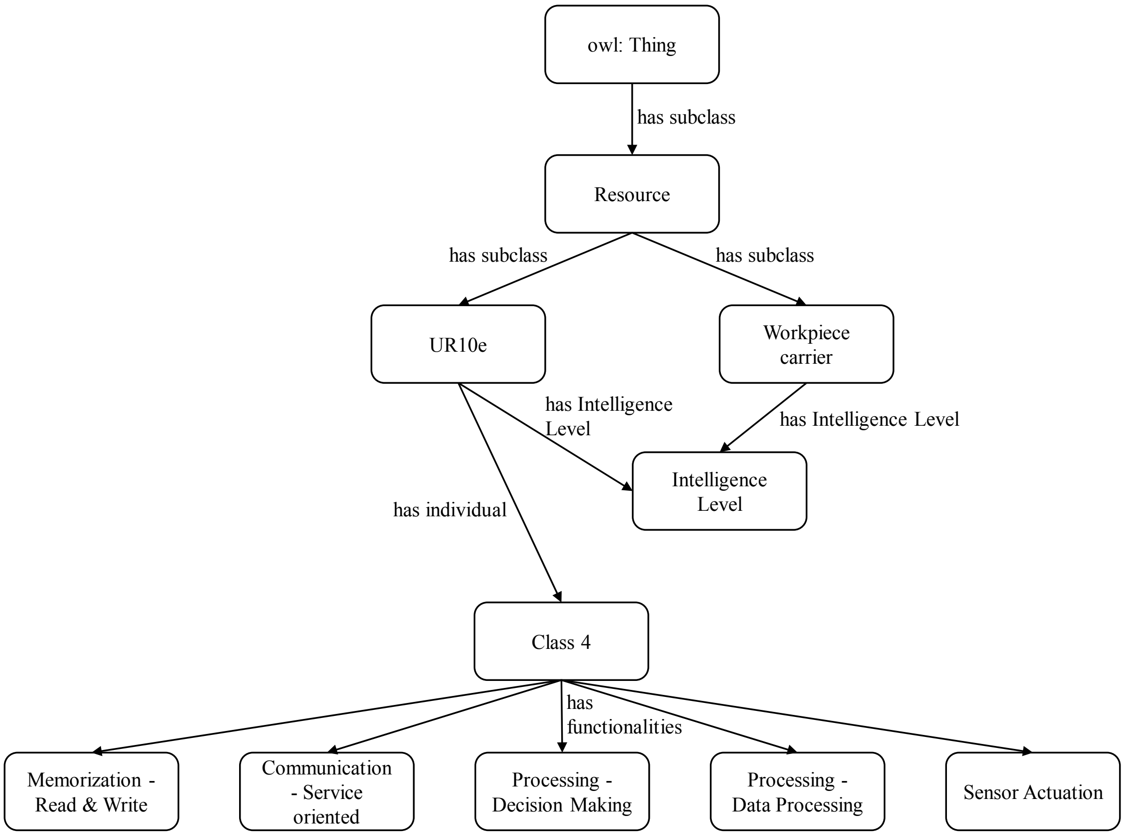

Figure 22: Functionality classification of the UR10e and workpiece carrier

The collaborative robot UR10e is grouped into Class 4, representing all characteristics of the functionality model. Regarding memorisation, the UR10e can read and write information from external USB drives or internal memory. Thus, the UR10e has internal storage to save robot programmes. For programming, the robot uses PolyScope, which runs on the graphical user interface on the 12" touchscreen. The communication requirements are provided by several interfaces such as USB, RS-422/RS-485 and SPI, which enable data-oriented communication. In addition, there is an ethernet socket on the UR10e to enable a connection to the network. It uses one of the standard communication protocols, commonly known as TCP/IP (Universal Robots, 2022). By providing an interface to the network, the UR10e can answer questions to users, such as how long a particular process will take or how long the product will stay in its system. To fulfil the requirement of decision making, the UR10e is not only collecting and synthesising process information about force, power, speed, or momentum. It also takes decisions on its own. The UR10e has an add-on safety solution called AIRSKIN with pressure-sensitive sensors, which detect all collisions with the robot. The UR10e decides a protective stop detected by the AIRSKIN pad. The AIRSKIN pad is a soft, thin, airtight skin for industrial robots such as the UR10e. The sensors inside the hull detect the pressure changes when a contact on the pad surface deforms the pad. The activation of the AIRSKIN requires 5 Newton. In this case, physical interaction for sensor actuation is provided as the sensors detect any collision between the UR10e and a third party (AIRSKIN technology, 2022).

The current workpiece carrier at Werk150 acts as a transport aid, which carries components from one processing station to the other. In addition, it has individual inserts that can be exchanged for the respective pedal scooter. Thus, it has no additional functionalities such as memorisation, communication, processing, or sensor actuation and is not classifiable to any of the four functionality classes.

5.2.3 Step 2: Problem classification

Table 33 lists the current problems facing the described assembly station. It is essential to mention that it only considers the assembly process of picking and placing screws with the resources of the UR10e and the workpiece carrier, as explained in Section 5.2.1.

Table 33: Problem description

Brief problem statement (What?, Who?, Where?, When?, Why?)	Urgency	Visibility	Rank order	Proposed solution
The workpiece carrier cannot be assembled by the collaborative robot on the conveyor system, as its position is inconsistent and varies. It requires additional manual handling to a workbench with the ensured consistent position.	Medium urgent as the current process is unstable.	Medium	1	Position determination of the workpiece carrier.
Inflexible workbench, as there are brackets on the workbench for a predefined position of the workpiece carrier.	Less urgent as the workbench is currently only required for one process.	High	2	Position determination of the workpiece carrier.
No information regarding the workpiece carrier's current state or position during the assembly. No interaction with other resources.	Less urgent as the current process is stable.	Medium	3	Self-awareness of the workpiece carrier.

The problem description, consisting of three brief problem statements, highlights that the current situation is inflexible and requires additional manual handling activity of the operator. In addition, a workpiece carrier is a passive object that does not gather or share information with other environmental resources. Categorising the identified problems according to the frameworks of Snowden and Boone (2007) and Glouberman and Zimmerman (2002) causes complicated problems. The assembly situation is complicated because there is more than one correct answer. There are several scenarios to determine the workpiece carrier's position since the functionalities could be on the pedal scooter itself, the workpiece carrier, or even the workbench.

The mentioned issues require a self-aware workpiece carrier with the ability to determine its current position on the workbench and interact with other resources. The nature of a complicated problem needs to be solved using formulae and recipes as well as a certain level of expertise. In addition, many details are involved in finding one right solution for the position determination of the product. An inflexible assembly system's problem-solving process includes three steps: sensing, analysing and responding to a situation (Kurtz & Snowden, 2003, p. 468).

5.2.4 Step 3: Product classification of the collaborative robot

Step 3 of additive more-dimensional product classification is only executed for the collaborative robot UR10e, as it is a kind of UMS. Therefore, the current adaptivity and autonomy level are assessed. The adaptivity of the UR10e indicates characteristics of Level 2 because the UR10e operates on a fixed underlining model, which the operator programs. However, the AIRSKIN of the UR10e enables a perception of external behaviours such as collision detection to other systems and shows flexible, reactive behaviour. The robot program itself is fixed and does not represent any flexibility. Regarding autonomy, the UR10e is classified as Class 1, as the collaborative robot is externally controlled and does not collect the environmental data to generate a world model.

5.2.5 Step 4: A feasibility study

Step 4 considers the feasibility study, which is represented in Table 34.

Table 34: Feasibility study

Focus area
The additional manual handling from the conveyor system to the workbench requires much process time. In addition, it is a potential source of error as the workpiece carrier can be damaged. It is also a physical strain for the operator, as parts and subassemblies of the footboard and handlebar are already on it.
SMART Goals (Specific, Measurable, Assignable, Realistic, Time related)
S: Dynamic TCP-positioning of the UR10e to adjust its placing waypoints depending on the actual position of the workpiece carrier on the workbench. M: Position difference between the workpiece carrier's current position and the initial position in the x and y-direction. A: The TCP-positioning method's measurement of distances and calculation is executed on the intelligent workpiece carrier. R: The design and implementation of the prototypical system should be cost-efficient, below 100 euros per workpiece carrier. T: The design and implementation time is roughly about two to four weeks for one employee.
Desirable solution
The TCP-positioning method should use precise distance sensors mounted on the workpiece carrier. The raw input data of the sensors are processed on the workpiece carrier itself, and the placing adjustment is communicated to the UR10e. Other sensors such as LIDAR sensors fulfil the technical requirements, but they are too expensive. An additional low-cost solution could also be achieved by using ultrasonic sensors. However, the sensors are too inaccurate and do not meet the technical requirements.

As mentioned in the problem classification in Section 5.2.3, several scenarios exist to achieve the dynamic TCP-positioning method. Furthermore, three scenarios are examined. The first scenario investigates an intelligent pedal scooter with Level 2 functionalities. They consider the manufactured product intelligent and require a local integration of the functionalities into the product. In the case of the pedal scooter, own product intelligence is characterized as non-value adding for the customer. There is no use of distance sensors for the customer. In scenario 2, the intelligent functionalities are on the workbench to determine and communicate the actual position of the workpiece carrier. This alternative is rejected because the solution should also be practicable for additional use cases on the conveyor system. To constantly determine the workpiece carrier's position on the conveyor system, there are lots of distance sensors required, which involves high costs. The desired solution in Table 34 equips the workpiece carrier with the required functionalities, which means that the pedal scooter has no or low product intelligence after manufacturing. Besides the goal of multiple applications, the workpiece carrier's self-awareness supports the manufacturing system's adaptability, defined as the ability to adapt a system with low effort to unknown changes (VDI, 2017). Compared to the position determination on the workbench, the method on the workpiece carrier has mobility and universality, as it can be used in other manufacturing stations.

5.2.6 Step 5: Target functionalities

Step 5 defines the required target functionalities to achieve the desired position determination. The focus is on the workpiece carrier, as the UR10e has already functionalities of Class 4. For measuring and storing the distances from the workpiece carrier to the side rails of the workbench or conveyor system, the workpiece carrier requires memorisation functionalities of reading and writing. The position adjustment in terms of rotation and translation between the initial and target positions requires the workpiece carrier's data processing functionalities. The initial position describes the position of the workpiece carrier that is known to the UR10e and is required for the inflexible robot program to run successfully. The data processing is based on certain formulae. The communication of the adjusted picking position to the UR10e needs data-oriented communication functionalities. Regarding the aggregation level of the workpiece carrier, the passive workpiece carrier in the initial situation has already been classified at the proxy level, as the carrier also considers its components. The functionalities of the target solution represent a functionality upgrade to Level 2. Figure 23 represents the functionality upgrade of the workpiece carrier as well as the unchanged functionality levels of the UR10e.

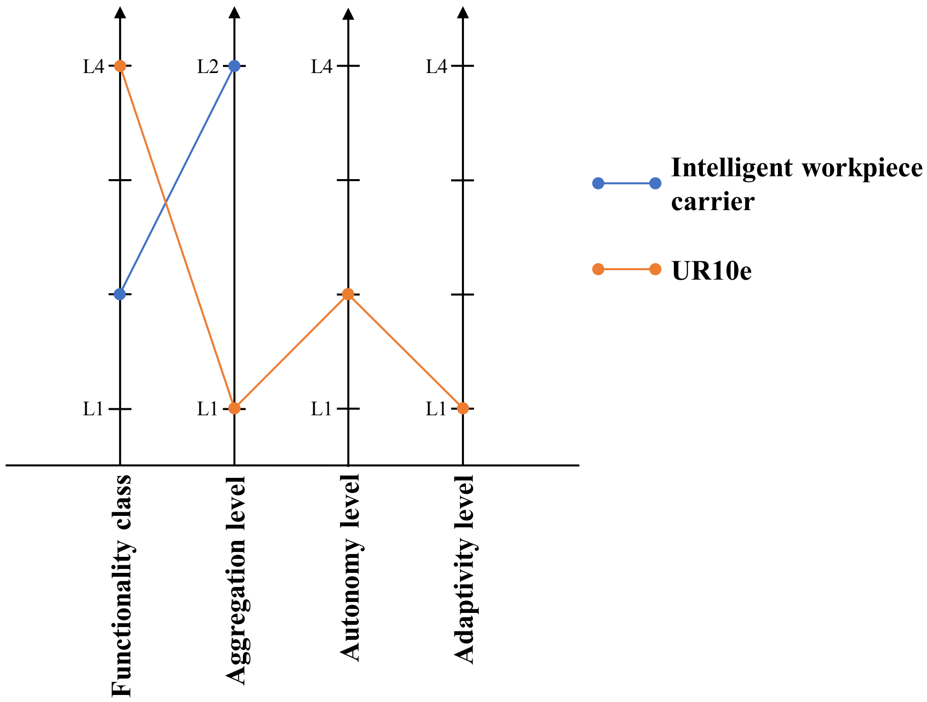

Figure 23: Target functionalities of the intelligent workpiece carrier and UR10e

5.2.7 Step 6: Design and technical requirements

Step 6 consists of the design and the technical requirements to upgrade the workpiece carrier to Level 2. The first aspect of the design requirements includes the flow diagram and its ten steps, which are displayed in Figure 24. It contains the workpiece carrier, the microservice as calculation unit, the local server, and the UR10e and their interfaces. The process start is triggered by the operator, who approves the touch panel of the UR10e to start the assembly and thus the dynamic TCP-positioning method. For calculating the adjusted waypoints, the microservice requires the sensor data of the workpiece carrier and the initial waypoints of the UR10e. The sensor data consists of distances between the side rails of the workbench and the workpiece carrier. The initial waypoints of the UR10e define the target picking and placing positions, which are initially programmed. These waypoints are based on the fixed position of the workpiece carrier, which was achieved by the position brackets. After calculating the new waypoints, the values are published to the UR10e to update the initial waypoints. In the next step, the picking and placing process of the screws with the updated waypoints is performed.

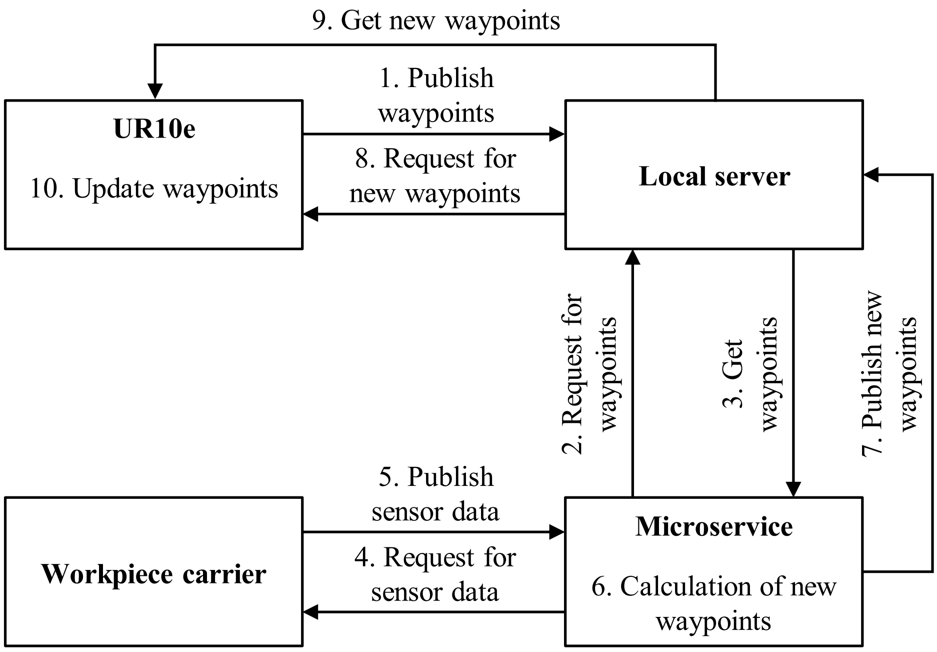

Figure 24: Flow diagram for position determination of the workpiece carrier

The second design requirement is based on the flow diagram and shows the organisation of the required data and converted information required for calculating the new waypoints. The data model in Figure 25 shows the logic of the data units and their relationship to one another. The focus is on the microservice, which requires the raw data input of the sensors and the initial waypoints to calculate and publish the adjusted waypoints to the UR10e. The relationship between the microservice and the workpiece carrier is 1:n, as one microservice operates several workpiece carriers. On the other side, only one calculation unit for the workpiece carrier is required. The relationship to the UR10e follows the same logic, as the microservice can serve several collaborative robots.

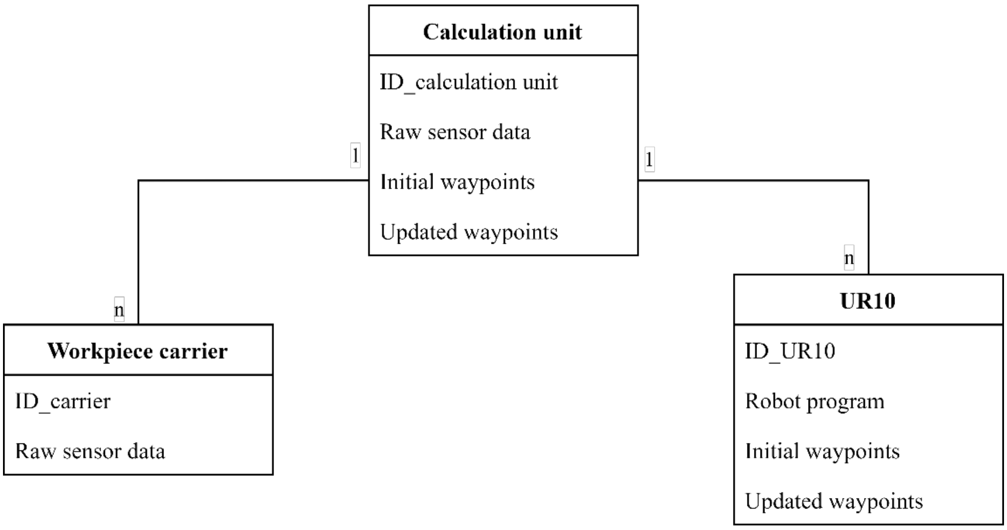

Figure 25: The data model for calculation of updated waypoints

The third design requirement identifies the flexibility or adaptivity objective, which must be achieved by upgrading the workpiece carrier. Equipping the workpiece carrier with sensors and processing power enables the self-awareness of the carrier and communication functionality. Therefore, the dynamic TCP-positioning method and the intelligent workpiece carrier aim to improve the process and material handling flexibility.

In the initial situation, there are fixed brackets on the workbench to position the workpiece carrier, which ensures the same position for each assembly procedure of the UR10e. Without the brackets on the workbench, the assembly station can be more flexible. In addition, changes in the dimensions of the workpiece carrier require movements of the brackets, as the position is only valid for one size. Especially in a multi model assembly line, which assembles different products, the dimension of the workpiece carrier can vary among the different products. Nevertheless, the intelligent workpiece carrier requires hardware and software installation. Compared to the initial situation of fixed brackets, the intelligent workpiece carrier does not require any changeovers or set-ups after the initial installation. According to Slack (1983), the crucial factors for process flexibility are the job design and the process technology, which enable the potential to share the assembly station with UR10e across different processes with no need for machine duplicates.

The dynamic TCP-positioning method is also applicable to the conveyor system. The principal is equal to the examined use case on the workbench. The main difference is that the intelligent workpiece carrier measures the distances to the side rails of the conveyor system and not to the side rails on the workbench. It communicates the adjusted waypoints to UR10e, which performs its picking and placing activities directly on the conveyor system. The assembly on the conveyor system does not require the manual handling of the workpiece carrier to a workbench. Thus, implementing the TCP-positioning method and the intelligent workpiece carrier on the conveyor system enables improved material handling flexibility through efficient production. Furthermore, the intelligent workpiece carrier can potentially improve the UR10e utilization, as the transport from one machine to the other is more efficient. Considering the factors for FMS of Slack (1983), the facilities layout and the production and material planning are improved by the dynamic TCP-positioning methods, as manual handling is no longer required, and the workstation can be used independently of the product variant.

The process and material handling flexibility improve the characteristics of the assembly system. Lotter (2006) defines three characteristics of flexible assembly systems, which need to be fulfilled by the dynamic TCP-positioning method. The characteristic of assembling all variants of a product family in any sequence is provided, as the intelligent functionalities apply to all workpiece carriers. In addition, The TCP-positioning method reduces the set-up times of the batch model mix assembly since there is no chance of the required positioning brackets on the workbench. The intelligent workpiece carrier knows its position on the workbench independent of the product variant. Furthermore, the intelligent functionalities are provided by standard modules, which are reusable for future product variants. Thus, the pedal scooter assembly detach itself from the product life cycle and focuses on the life cycle of the assembly system (Lotter, 2006, p. 309).

Based on the design requirements, the technical requirements are developed. The functionalities of Level 2 require read and write memorisation, data-oriented communication, and data processing. A microcontroller fulfils all these requirements, as it reads the firmware code from the nonvolatile program memory and writes the generated data to volatile data memory during the code execution. Providing the functionalities of reading and writing already achieves the data-oriented communication requirements. In the case of the TCP-positioning method, the microcontroller also needs to be equipped with a WIFI module to communicate the data from the distance sensors and send data to the local server.

Furthermore, the microcontroller provides a microprocessor for collecting, synthesizing, and managing the data. The powering of the microcontroller on the workpiece carrier requires a battery. Figure 26 summarises the technical parts of communicating with the informational and physical environment.

5.2.8 Step 7: Development of the intelligent workpiece carrier

Step 7 is about the execution and design of the intelligent workpiece carrier through the presented design and technical requirements. First, the logic of the TCP-positioning method is presented, which focuses on the mathematical calculation of the adapted waypoints and the technical implementation of the communication. Furthermore, the functionality and interaction of the hardware components are established. In conclusion, the target requirements defined in step 5 and the design and technical requirements of step 6 are compared with the developed hardware and software.

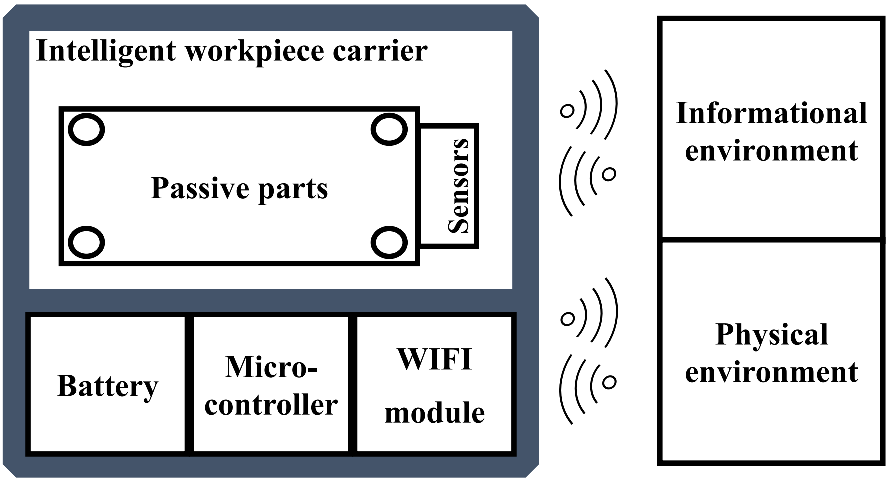

Figure 26: Functional units of an intelligent workpiece carrier

The development of a dynamic TCP-positioning method of the UR10e uses the intelligent workpiece carrier with its distance sensors and microcontroller as a part of the solution. The dynamic TCP-positioning method aims to adjust the predefined waypoints of the UR10e for all workpiece carrier positions on the assembly station. Therefore, the dynamic TCP-positioning method allows the UR10e's placement activities to operate not only for a predefined workpiece carrier position, but in fact for all positions on the assembly station. Figure 27 shows the principle of the TCP-positioning method at the assembly station. The station consists of the UR10e, a workbench for the assembly operations, and the intelligent workpiece carrier, consisting of four Time of Flight (ToF) sensors. The ToF sensors measure the distances to side rails, which are mounted on the workbench.

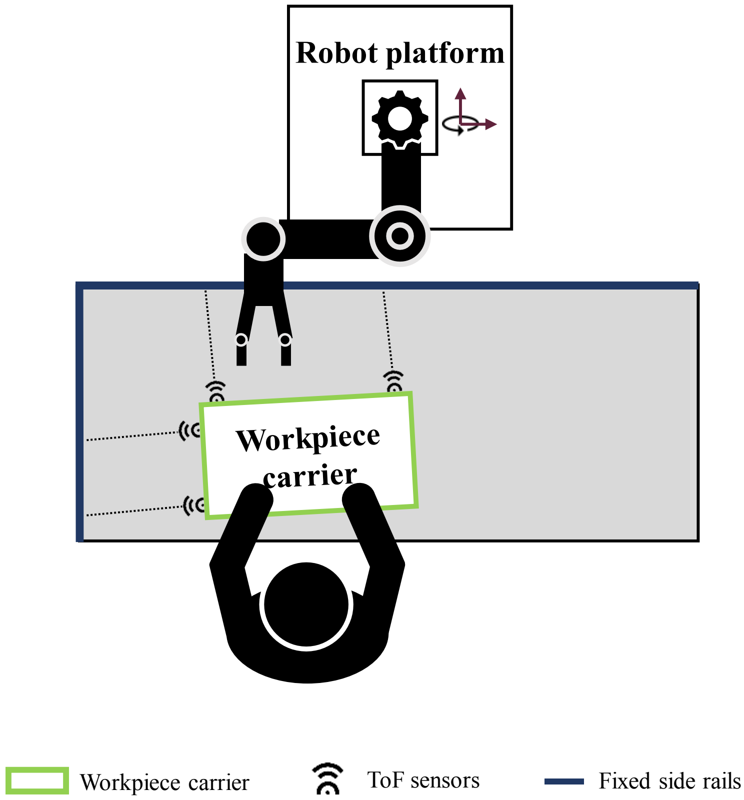

Figure 27: Assembly station

The following section aims to answer the question of how the dynamic adjustment of the predefined waypoints of the UR10e is performed. The flow diagram of the TCP-positioning method (see Figure 24) illustrates two input parameters consisting of predefined waypoints from the UR10e and the four distances from the ToF sensors. Both input parameters are required to perform the calculation conducted in the microservice. The calculation is based on coordinate transformation composed of translation and rotation. The translation is described by a vector $T = (t_x, t_y)$, which expresses a straight-line displacement in the x and y direction (Papula, 2018, p. 165). The Cartesian x,y -coordinate system change into the rectangular u, v -coordinate system by a parallel shift of the coordinate axes. Besides translation, a Cartesian coordinate system's rotation describes an object's rotation concerning a fixed point by an angle, which lies in origin. Translation and rotation of a Cartesian coordinate system and its objects are displayed in Figure 28.

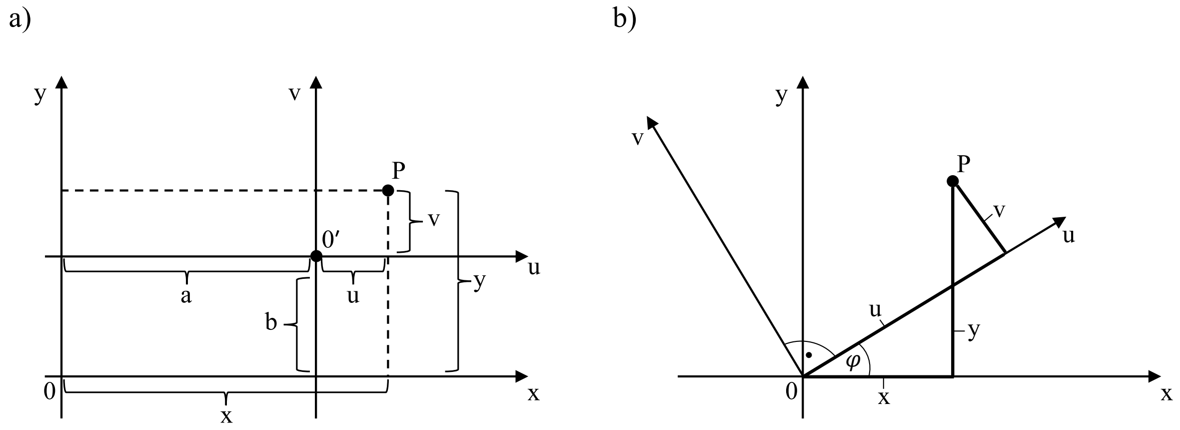

Figure 28: a) Parallel displacement and b) Rotation of a Cartesian coordinate system

For the rotation of a Cartesian coordinate system by the angle φ, the following equation applies to any point P (Papula, 2015, p. 61).

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} \cos(\beta) & \sin(\beta) \\ -\sin(\beta) & \cos(\beta) \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \tag{1}$$

As already mentioned, the dynamic TCP-position method starts with the automatic input of the initial waypoints from the UR10e and the distances from the ToF sensors. In addition, there is manual input required to run the calculation program. The manual input of parameters includes:

- Individual dimensions of the workpiece carrier (width, length, and position of the ToF sensors).
- The initial position of the workpiece carrier is expressed by its cornerstones in the Cartesian coordinate system of the robot (The initial position describes the position of the workpiece carrier that is known to the UR10e and is required for the inflexible robot program to run successfully. There are fixed brackets to position the workpiece carrier on the workbench.).
- Desired distances to the side rails in x and y directions (based on the initial waypoints).

No adjustments must be applied to the input parameters if the environmental conditions do not change. However, the first step of the TCP-positioning method uses the initial coordinates of the workpiece carrier to express the carrier's rotation with the robot coordinate system. The rotation between the coordinate system of the workpiece carrier and the UR10e is further applied to express the initial waypoint in the workpiece carrier's coordinate system. For this expression, equation (1) calculates the waypoint in the rotated coordinate system.

The next step considers calculating the rotation angle between the workpiece carrier's actual and initial positions.[9] Therefore, the workpiece carrier's distances to the side rails and the fixed position of the ToF sensors on the carrier are required. The rotation angle calculation is expressed in equation (2), and variables are displayed in Figure 29.

[9] In the further course of the thesis, the explanation listed under input parameters will be used for the initial position.

$$\varepsilon = cos^{-1}\left(\frac{(d_1{}^2 + p_2{}^2 - f^2)}{2 \times d_1 \times p_2}\right) \tag{2}$$

Figure 29 schematically represents one possible situation of the intelligent workpiece carrier on the workbench. The red rectangle symbolises a random position of the workpiece carrier on the workbench. Since the dynamic TCP-positioning method relies on a compound transformation, the blue rectangle represents the object's rotation. In contrast, the green rectangle is translation-adjusted and represents the position known to the robot in an inflexible environment. According to the schematic illustration, the calculations of the TCP-positioning method are explained.

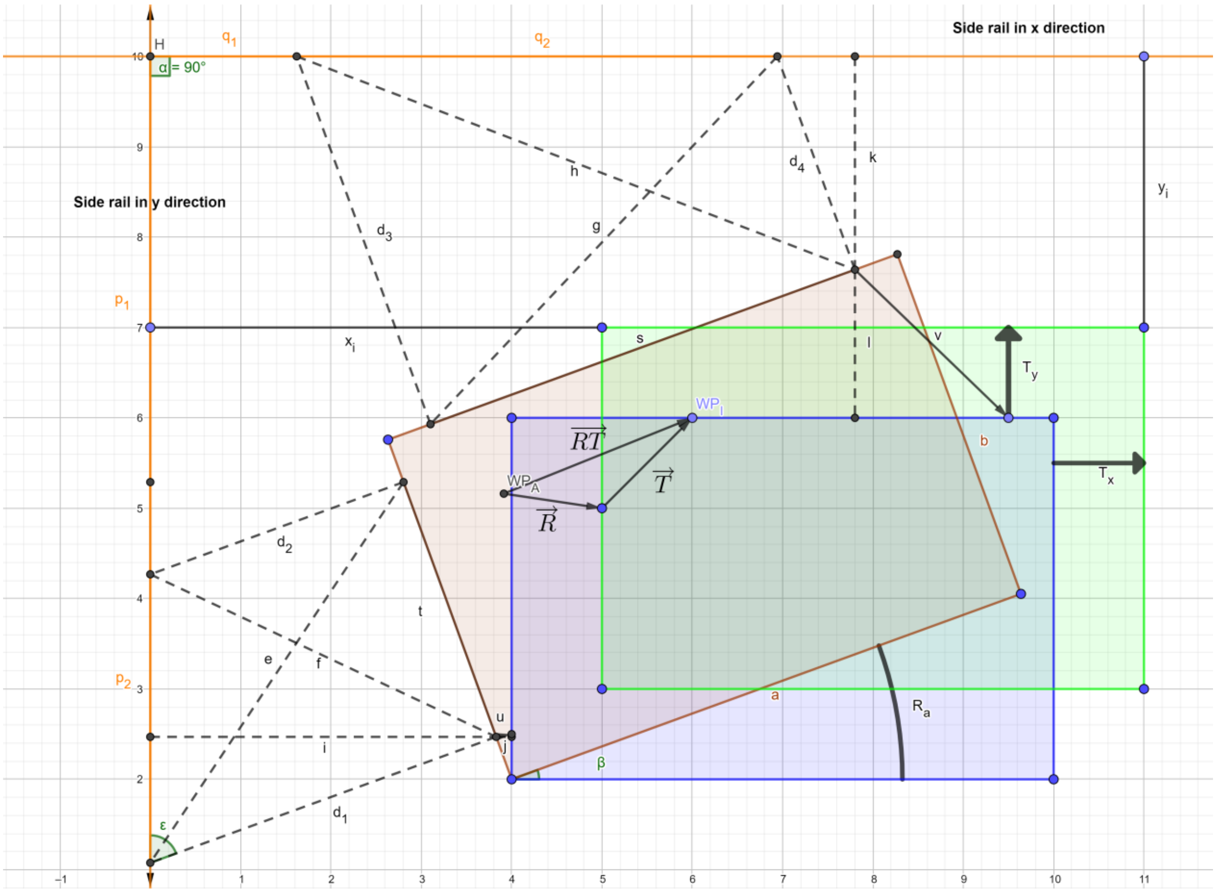

Figure 29: TCP positioning method

The focus of the TCP-positioning method lies on the transformation vector $\overrightarrow{RT}$, which combines the rotation expressed by $\vec{R}$ and the translation expressed by $\vec{T}$ of one waypoint. Thus, the transformation vector represents the x and y direction adjustment to correctly process the robot program according to the workpiece carrier's position. This exemplary adjustment of one waypoint presented is calculated and performed individually for all waypoints of the UR10e.

The rotation vector $\vec{R}$ of the waypoint is based on the principle explained in equation (1). For the rotation-adjusted waypoint, the calculation requires the previously calculated waypoint coordinate in the coordinate system of the workpiece carrier and the rotation angle β, which is used for the coordinate transformation. Figure 29, the rotation of the workpiece carrier is shown by the blue rectangle. The second component of the $\overrightarrow{RT}$ vector consists of the translation vector $\vec{T}$, which describes the straight-line displacement of $\vec{T}_x$ and $\vec{T}_y$ to the initial position of the workpiece carrier (represented by the green rectangle). The calculation of $\vec{T}_x$ and $\vec{T}_y$ is based on the initial distances of the workpiece carrier to the side rails (x_i and y_i), the rotation angle (β), the distance measurements of the ToF sensors (d_1 and d_4) as well as the x or y rotation coordinate of the respective ToF sensor (u_x and v_y), which is expressed in equation (3).

$$T_x = x_i - (cos(\beta) \times d_1 + u_x)$$
$$T_y = y_i - \left(\cos(\beta) \times d_4 + v_y\right) \quad \textbf{(3)}$$

In addition, Figure 30 highlights the translation in the x and y direction and visualizes how the translation vector $\vec{T}$ composes.

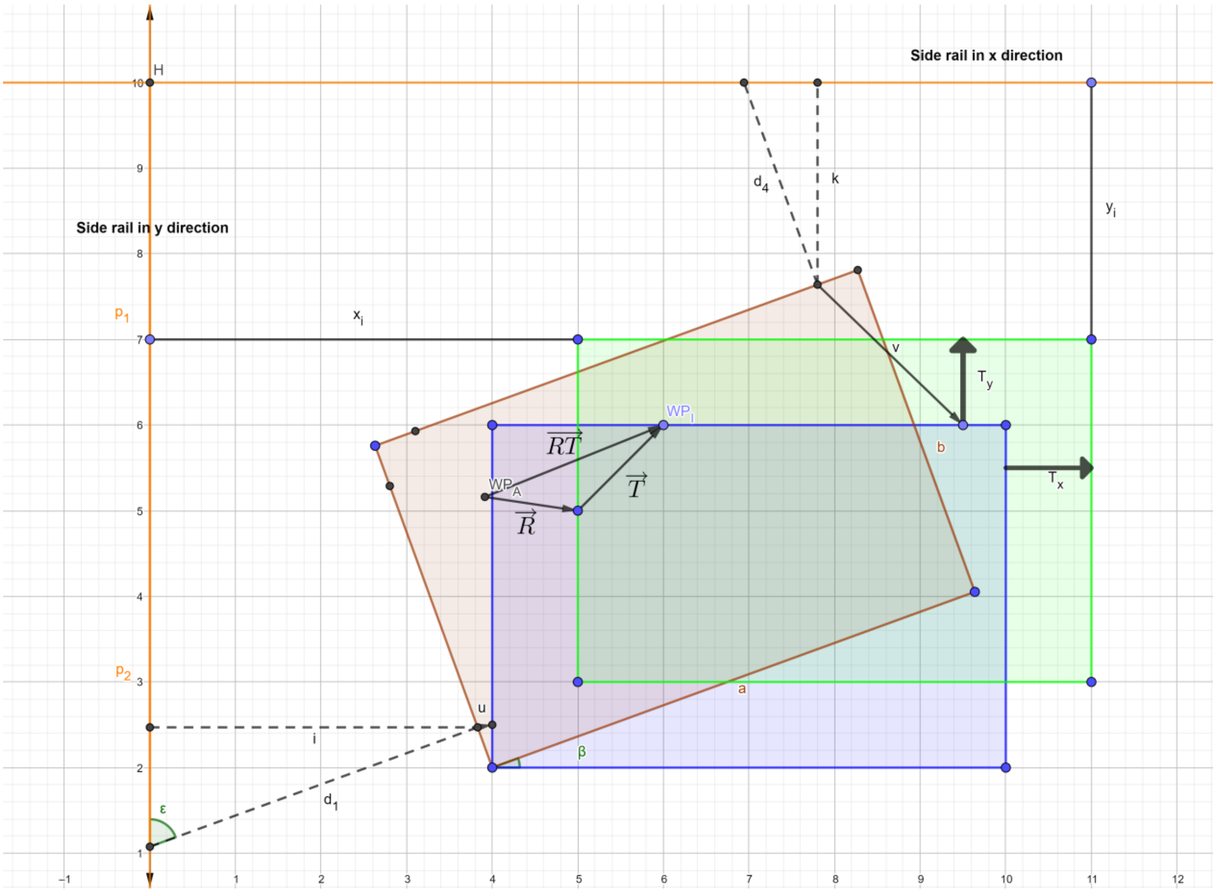

Figure 30: Translation in x and y direction

In summary, the calculation of the adapted waypoint WP_A uses the transformation vector $\overrightarrow{RT}$ to adjust the initial waypoint WP_I. In addition, the dynamic adjustment of the UR10e requires manual and automated input parameters, which are processed in supporting calculations such as calculating the rotation angle or conversion of the coordinates from the workpiece carrier coordinate system into the coordinate system of the UR10e, and vice versa. The dynamic TCP-positioning is generally equal for all waypoints and would already work with only three ToF sensors. However, four sensors are used to compensate for a possible technical failure. The structure of the microservice, which has been mentioned in Figure 25, consists of three functions. There is one function for reading the initial waypoints, which are permanently published by a thread in the UR10e script. In addition, there is another Phyton function to get the distances from the ToF sensors. Therefore, a socket connection has been established, in which the microcontroller represents the client to contact the microservice (socket service). In addition, the calculation of the adjusted waypoint uses the incoming data from these two functions and publishes the adjusted waypoints to the local server. While the UR10e script is running, it permanently calls the adjusted waypoints in the tread function to adjust its placing waypoints. Likewise, the calculation of the dynamic TCP-positioning method permanently publishes the adjusted waypoints. It thus detects changes in the workpiece carrier's position even if the assembly process has already been started. The communication follows the flow diagram for position determination of the workpiece carrier, presented in Figure 24).

In addition to the explained software and communication interfaces, the development of the intelligent workpiece carrier requires the hardware and electronics to comply with the requirements. Accordingly, Figure 31 displays the CAD model and the intelligent workpiece carrier with electronics. Both illustrations present the workpiece carrier without the two inlays for the pedal scooter handlebar and footboard.

a) b)

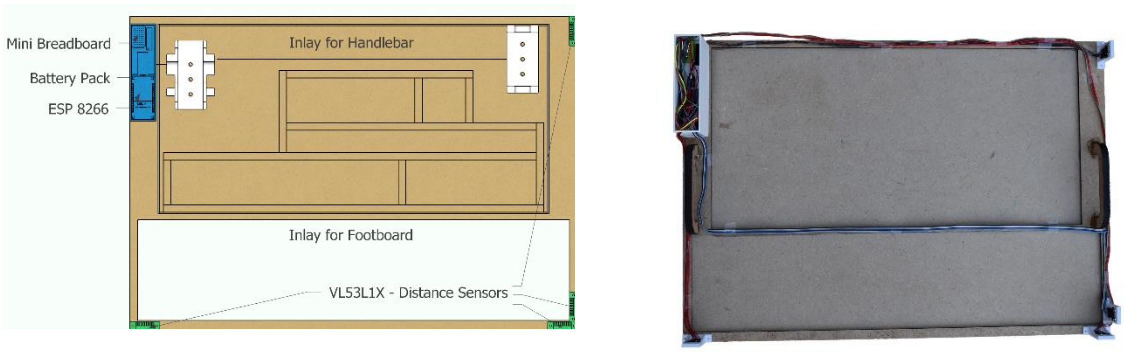

Figure 31:Intelligent workpiece carrier: a) CAD model b) carrier with electronics

The requirements for the intelligent functionality classes of the workpiece carrier are mainly realised by the ESP8266 microcontroller board and the four VL53L1X distance sensors. The ESP8266 enables the functionality of data processing and decision making. Furthermore, the ESP8266 is equipped with a WIFI module, enabling the ability to communicate and interact with local controllers and manufacturing cells. Besides, there are 16 general-purpose input-output pins on the ESP8266 board to wire the four distance sensors to the board. The electronic circuit between the ESP8266 and the distance sensors uses a mini breadboard. In addition, a 2.200 mAh battery pack powers the ESP8266 through the USB port. Except for the sensors, all components are installed in one housing, coloured blue in Figure 31.

A detailed overview of the wiring and communication logic of the distance sensors and the ESP8266 is provided in a breadboard design in Figure 32. Firstly, the red wire provides regulated 3.3V output to each of the four distance sensors. In addition, the black wire grounds the distance sensors with a connection to the negative terminal of the power supply. The blue and the purple wire enable the Inter-Integrated Circuit (I2C) protocol communication by using the Serial Clock Pin (SCL) for synchronising all data transfers and the Serial Data Pin (SDA) to receive and send data. Each of the four VL53L1X distance sensors requires an individual configuration by setting the sensor address, defining the distance mode, setting the timing budget, and the interval for requesting the measurement. Furthermore, each of the XSHUT pins of the distance sensor is wired up to one general input-output pin on the ESP8226, which is represented by the brown, green, orange, and grey wire. The working principle of the XSHUT pin is comparable to an on/off switch. Setting the XSHUT pin to high turns the sensor on, while low mode sets the sensor into shutdown or reset mode.

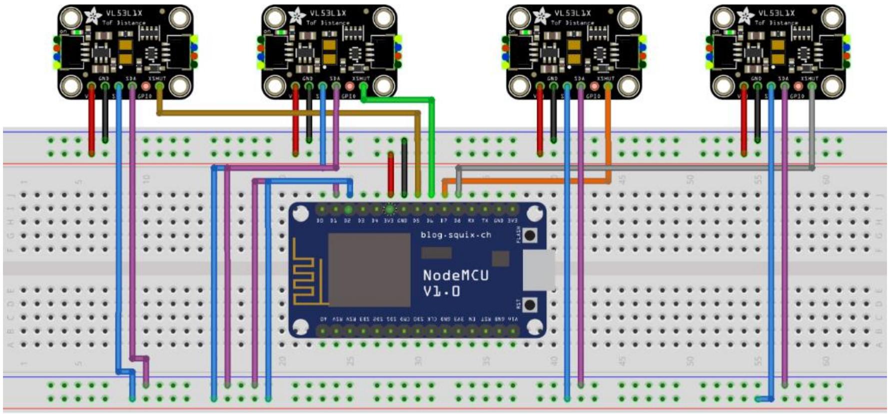

Figure 32: Breadboard design

The TCP-positioning method on the workpiece carrier is based on the absolute distances between the workpiece carrier and fixed side rails. Therefore, four time of light VL531X distance sensors are mounted on two adjacent sides of the workpiece carrier. The sensors work according to the Time-of-Flight (ToF) principle, which is based on the speed of light. An emitter sends photons, which are reflected by one or more objects and detected by the receiver. The distance between the emitter and object represents the difference between the emission and the reception. In case the signal's propagation velocity (c) and the recorded travel time (ΔT) between emitter and detector are known, the distance to the surface (d) can be calculated according to the following equation (Lewellen, 1998, p. 269).

$$d = \frac{\Delta T \ \times c}{2} \tag{4}$$

The application of ToF sensors is recommended for treating only a single point at a time. The sensor needs to mechanical sweep its signal across the scene to provide a full range of information. For instance, a 3d scanner requires the sensor to be mounted on a servo motor, which enables measuring in various directions. However, the development of the TCP-positioning method works with a single point at a time, as each sensor measures a single distance to the side walls at a time, and no complete range information is necessary. The VL53L1X measures values in a range of 4 to 400cm. However, objects closer than 4 cm are detected, but the measurement is highly inaccurate. In general, there are three possible distance modes available short (up to 130cm), medium (up to 300cm), and long-range (up to 400cm), which can be called in the sensor configuration. The calculation of the TCP-position of the UR10e uses the short-range mode since most of the measurements are less than 130cm, and the distance mode has the best ambient light immunity. The distance sensor VL53L1X has a high resolution, as the measurements are in millimetres. The manufacturer does not provide official values for precision, accuracy, and linearity. In the use case scenario, the measured values slightly differ from the actual values by 2-3% in a positive and negative direction, corresponding to a deviation of +/- 3% (Ewald, 2019). [10]

The total costs for one ESP8266, four VL53L1X distance sensors, mini breadboard, power bank, jumper connector cables, and 3D printed parts are 79,34€, below the target of 100€.[11] The price calculation is based on the actual purchasing costs of the components and a cost simulation of the 3D printed parts. The cost simulation considers the weight of the components, provided by SolidEdge and standard

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[10] The user manual of ST life.augmented describes all technical functionalities of the VL53L1X.

[11] Appendix C shows a detailed bill of material for the functionality upgrade of the workpiece carrier.

parameters for defining the printing conditions. In addition, developing the dynamic TCP-positioning method followed a time-related goal (see feasibility study in Figure 23) of implementing the intelligent workpiece carrier at the assembly station in roughly two to four weeks. In summary, the time specification of four weeks is realistic for one employee and can be reduced using several employees.

The intelligent workpiece carrier's development and the assembly station's set-up almost fulfil all the target functionalities. The hardware and software components have directly implemented the technical requirements of memorisation, data-oriented communication, and data processing. Therefore, the implementation has been guided by the flow diagram and data model, which are central to the design requirements. However, the additional manual handling of carrying the workpiece carrier from the conveyor system to the workbench can only be solved by processing the assembly steps directly on the conveyor system. A detailed solution to the problem has already been examined in Section 5.2.6. In addition, the development of the dynamic TCP-positioning method for the UR10e and the intelligent workpiece carrier represents an example of mixed product-intelligence structures in manufacturing, as the workpiece carrier has been upgraded to Level 2.

In contrast, the collaborative robot UR10e has functionality Level 4. In the use case scenario, an upgrade of the workpiece carrier to Level 3 or 4 is not recommended by the IPIDS framework because the input data is processed by a dedicated logic, which does not require the functionalities of decision making or sensor actuation. Therefore, the use case exemplifies that mixed intelligence levels are practicable and reasonable. However, if the manufacturer wants to provide the functionalities for future scenarios with more complicated problems, upgrading the workpiece carrier to Level 4 can be reasonable. Nevertheless, if the focus area of the feasibility analysis includes a future awareness of more complicated problems, equal functionality levels are possible.

5.2.9 Analysis of the intelligent workpiece carrier

The initial dataset examines how often the UR10e places the three screws correctly in the screw holes. Therefore, it consists of four features displayed in Table 35. The ID feature is used to identify and trace the UR10e runs. It is classified as numerical – absolute because it indicates values from 0 to 84 to describe the UR10e run distinctly. There are three individual features for placing screws in the holes of the datatype categorical – nominal, as they express a yes or no statement. These features are discrete-valued and have no order relation. In total, the dataset consists of 85 records and four features.

Table 35: Data types

Feature	Data Type	Data attribute
ID	Numerical – Absolute	Natural numbers
Screw 1	Categorial – Nominal	0 or 1
Screw 2	Categorial – Nominal	0 or 1
Screw 3	Categorial – Nominal	0 or 1

The data quality report in Table 36 describes the characteristics of the categorical features using standard statistical measures of central tendency and variation. The standard measure of central tendency is the mode and the standard deviation for the variation. The standard deviation is not considered, as it is not value-adding. In addition, there are no missing instances in the measurement of the positional accuracy of the two different systems, so the data set is 100% valid.

Table 36: Categorical features of the initial situation

Feature	Count	% Miss.	Card.	Mode	Mode Freq.	Mode %	2nd Mode	2nd Mode Freq.	2nd Mode %
Screw 1	85	0.0	2	1	77	90.6	0	8	9.4
Screw 2	85	0.0	2	1	84	98.9	0	1	1.1
Screw 3	85	0.0	2	1	83	97.6	0	2	2.4

The second dataset uses the same features as in the initial situation, displayed in Table 37. Compared to the initial situation, case 2 uses intelligent functionalities to determine the actual position of the workpiece carrier to dynamically adapt the waypoints and thus the TCP-position of the UR10e. The sample size for placing screws is 333, which is equally shared among the three features.

Table 37: Categorial features using the intelligent workpiece carrier

Feature	Count	% Miss.	Card.	Mode	Mode Freq.	Mode %	2nd Mode	2nd Mode Freq.	2nd Mode %
Screw 1	111	0.0	2	1	102	91.8	0	9	8.2
Screw 2	111	0.0	2	1	95	85.6	0	16	14.4
Screw 3	111	0.0	2	1	106	95.5	0	5	4.5

Bar plots illustrate the total distribution and density of the categorical features. Figure 33, Figure 34, Figure 35, and Figure 36 show the relative comparison of the initial (left side) and the situation using the dynamic TCP-positioning method (right side) on the intelligent workpiece carrier.

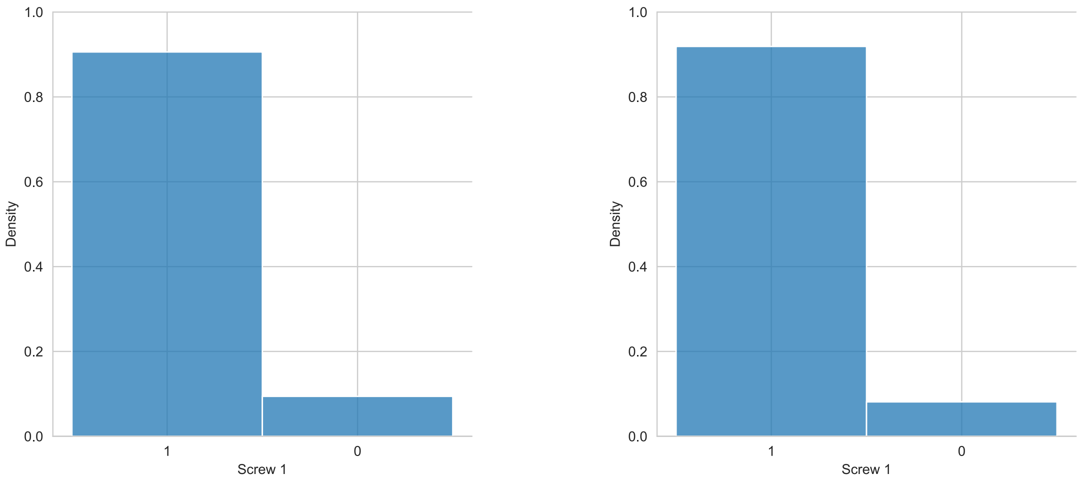

Figure 33: Distribution of the feature Screw 1 between the initial and changed situation

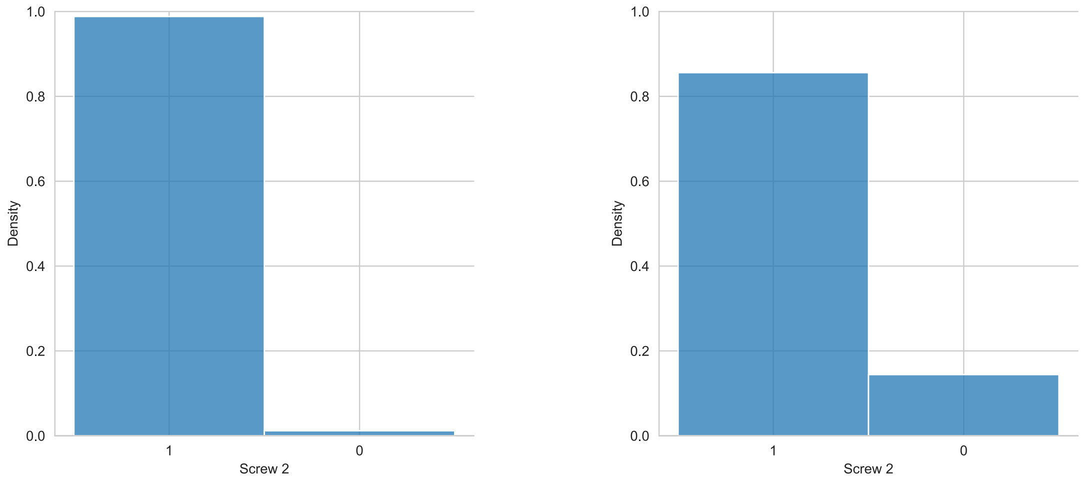

Figure 34: Distribution of the feature Screw 2 between the initial and changed situation

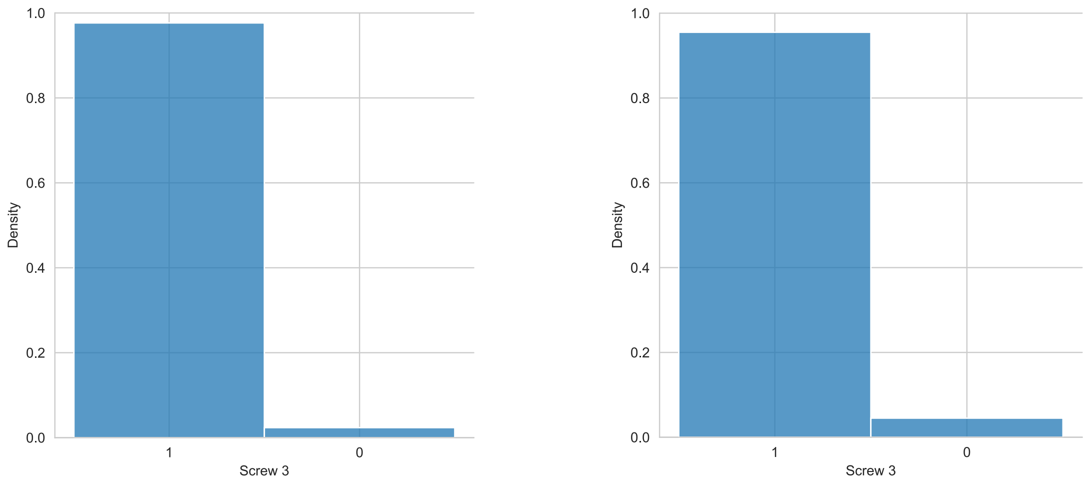

Figure 35: Distribution of the feature Screw 3 between the initial and changed situation

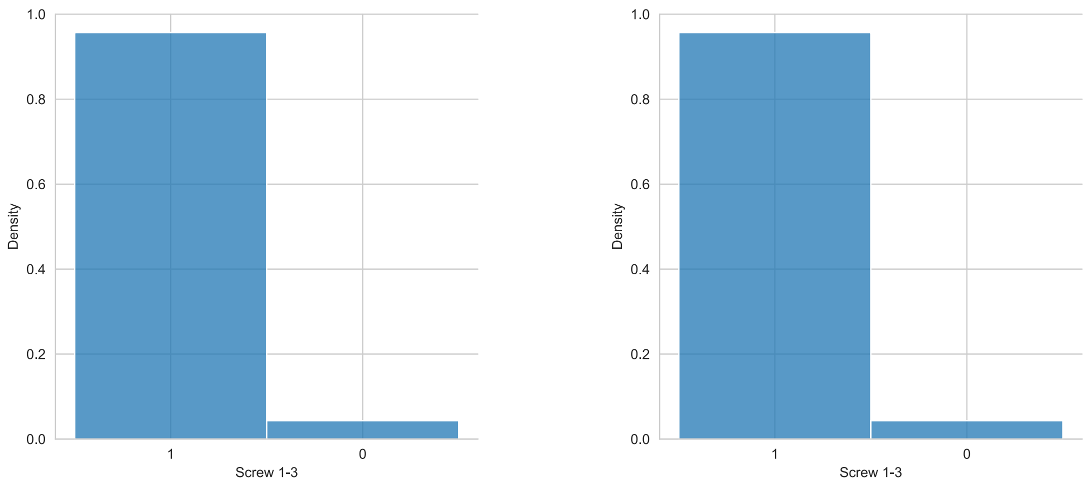

Figure 36: Distribution of the accumulated features between the initial and changed situation

The illustrations above show that the initial situation performs a higher placing accuracy for all three screws compared to the dynamic TCP-positioning of the intelligent workpiece carrier. However, in the accumulated version, the total deviation of 4.7% is minor, as the initial situation shows a placing accuracy of the UR10e of 95.7% compared to 91% using the position determination (see Figure 36). A detailed analysis of Screw 1 indicates a slightly lower placing accuracy of 90.6% in the initial situation, compared to 91.8% for the dynamic TCP-positioning method. Comparing the placing accuracy of Screw 2 displays that the dynamic TCP-positioning method has a significantly lower placing accuracy of 85.6% compared to the initial situation of 98.9%, which is the highest accuracy measured. Likewise, the placing accuracy of the dynamic TCP-positioning method for Screw 3 is slightly lower than in the initial situation. It is essential to mention that the sample size differs between the two situations. For the initial situation, the sample size is 85, while for the position determination, 111 runs are recorded (see Table 36 & Table 37).

Several factors influence the selection of statistical methods, such as the study's aim, the dataset's type and distribution, and the nature of the observations. When considering the aim of the study, there is a differential questioning of the two test cases with or without intelligence functionalities. Therefore, there are two scenarios: the initial situation without intelligent functionalities and the dynamic TCP-positioning method using intelligent functionalities on the product level. For both cases, the placing accuracy of the UR10e is documented and compared. Different statistical tests are suitable for the same object, and the selection differs depending on the data type. In the use case, two categorical features exist of nominal data, which belongs to nonparametric methods. The first feature consists of a distinction between non-intelligent and intelligent functionalities, whereas feature two measures whether the screw has been placed correctly on the workpiece carrier using yes or no statements. For the nature of observations, the data is unpaired, as it compares the placing accuracy from two independent scenarios (Mishra et al., 2019, p. 297). In addition, the groups must be independent of each other. Considering the selection criteria and the fact that marginal probability is unknown, the χ^2 (Chi)-square test of independence is selected. The following listing summaries the required conditions for a Chi-Square test:

i. The study aims to investigate a differential question of whether there is a difference between the two situations.
ii. The two categorical features are at the nominal level in the use case. The data in the cells of the contingency table counts frequencies of whether the screw is correctly placed.
iii. The expected frequency count for each contingency table cell is a minimum of 5 in at least 80% of the cells.
iv. The study groups are independent, ensuring that there are two different situations. The measured values of situation A are independent of situation B.

Table 38 and Table 39 show the observed values and the expected values in a 2x2 contingency table, where the calculation rule for the expected values is the following:

$$m_{ij} = \frac{n_{i\cdot} \times n_{\cdot j}}{N} \tag{5}$$

For calculating the expected values (m_{ij}), it refers to the sum of the frequencies per row ($n_{i\cdot}$), the frequencies in the corresponding column ($n_{\cdot j}$) as well as the sample size N. Comparing the observed values with the expected values for the position determination shows that there are fewer correctly placed screws than expected and more incorrectly placed screws than expected. For the functionality of no position determination, the phenomenon is vice versa. In this case, more correctly placed screws are observed than expected.

Table 38: 2x2 Contingency table analysis of observed values

	0	1	Σ
No Position determination	11	244	255
Position determination	30	303	333
Σ	41	547	588

Table 39: 2x2 Contingency table analysis of expected values based on (Bortz & Schuster, 2016, p. 139)

	0	1	Σ
No Position determination	17.8	237.2	255
Position determination	23.2	309.8	333
Σ	41	547	588

According to Bortz and Schuster (2016, p. 138), the statistical χ^2test compares how much the observed frequencies (O_i) deviate from the expected ones (E_i), which is expressed in the following formula. In case of the prototype, the χ^2test is used to estimate whether the variables functionality level and placing accuracy are independent. The format of the individual variables needs to be binary, which is expressed by 1 (“yes”) and 0 (“no”). A further main prerequisite for conducting a χ^2 test is the appropriate scale level. The variables under consideration should therefore have a nominal or ordinal scale level.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

The results of the χ^2test is summarised in Table 40.

Table 40: Statistical analysis based on (Bortz & Schuster, 2016, pp. 137–140)

Notion	Symbol	Value
Null hypothesis	H_0	The features of functionality level and placing accuracy are independent.
Alternative hypothesis	H_1	The features of functionality level and placing accuracy are dependent.
Significance level	α	0.05
Critical value	$\chi^2_{1;95\%}$	3.84
Degree of freedom	df	1
Chi-Square value	χ^2	4.91
Probability value	p	0.027

The contingency table of the expected values (see Table 39) shows no cells with an expected frequency below five, as the minimum expected frequency is 17.8. It meets the requirement that at least 80% of the cells have expected values of five or more, which does not require the maximum likelihood ratio method (McHugh, 2013, p. 147). Fisher's exact test is rejected for the same reason since none of the expected cell frequencies is below five. The chi-square test, according to Pearson, is therefore selected without any correction.

The chi-square test of independence shows a score of 4.91 with a p-value of 0.027. The null hypothesis is rejected because the p-value of 0.027 is smaller than the significance level of $\alpha = 0.05$. In addition, the rejection is supported by the higher Chi-square value of 4.91 compared to the critical Chi-Square value of 3.84, with $\alpha = 0.05$ and $df = 1$. It is essential to mention that the result is significant and close to the significance level of $\alpha = 0.025$. Therefore, the null hypothesis is unlikely, and the alternative hypothesis is assumed. There is evidence of an association between functionality level and the placing accuracy of the UR10e at a 5% significance level.

The Chi-square test provides information on whether the null hypothesis can be rejected or not but does not provide information on the strength of the association. The association's strength depends on the effect sizes and shows how strong the relationship between the variables is. The phi-coefficient is a measure of association between two binary variables introduced by Karl Pearson and relates to the chi-squared statistics of a 2x2 contingency table. The phi-coefficient (φ) and Cramér's V are measures of the strength of the association of two nominally scaled variables. The phi-coefficient (φ) requires a 2×2 contingency table and two dichotomous variables provided by the dataset. It is essential to mention that the phi-coefficient is identical to Cramér's V when there is a 2×2 cross-tabulation. According to Cohen (2013), both effect size measures can be interpreted similarly to a correlation. The range of values for effect size index (w) for contingency tables and goodness of fit consists of small, medium, and large. In this case, the effect size index for the provided data set is 0.091, ranked as small, below 0.1.

In conclusion, the statistical chi-square test of independence shows a relationship between the two categorial features of functionality level and correctly placed screws. However, the relationship is small, according to its effect size index of 0.091. The descriptive analysis of the results shows that the probability of correctly placed screws of the UR10e slightly differs between the two situations. For the initial situation with no intelligent functionalities on the workpiece carrier, the placing process is more stable as in 95.6% of the cases, and the screw was correctly placed. In comparison, the workpiece carrier with the functionality of the TCP-positioning method for the UR10e has placed the screw correctly in 90.6% of the cases. The 4.7% less correctly placed screws is accepted, as the placing process is more flexible regarding changes in the assembly environment. The statistical comparison shows that the practicability of the TCP-positioning method is provided due to the minor placing deviation.

5.3 Conclusion: Framework evaluation

The chapter evaluated the IPIDS framework through verification and validation. The verification considers the evaluation of the requirement specifications, whereas the validation is based on a comprehensive application of the IPIDS framework. In addition, the prototypical implementation of a dynamic TCP-positioning method in a learning factory is validated by statistical analysis, comparing the initial situation with the developed solution. The validity and applicability of the IPIDS framework provide a premise for intelligent-product structures in FMSs.

Chapter 6. Summary and conclusion

In Chapter 6, a summary of the study is provided, the attainment of the research objectives stated in Chapter 1 is evaluated, and contributions are highlighted. Subsequently, the limitations and delimitations of the study are examined with a focus on the applicability of the IPIDS framework in South Africa and Germany. The chapter concludes by establishing opportunities for future research.

6.1 Research summary

This thesis addresses the problem of missing overall system integration and evaluation processes for mixed product-intelligence structures in FMSs. The motivation of the thesis is based on the research gap and the fact that intelligent products have already been identified as promising enablers to increase flexibility in manufacturing.

The IPIDS framework suggests a comprehensive approach for defining, analysing, and designing intelligent products or resources within FMSs that can manage mixed product-intelligence structures. The research outputs contribute toward developing increasingly comprehensive and flexible assessments helpful to decision-makers and practitioners.

Table 41 links the research objectives (ROs) and their sub-research questions with a research summary to provide an overview of how they are addressed in this thesis. In addition, it shows the allocation of the thesis chapters and the research objectives.

Table 41: Evaluation of the attainment of research objectives

Sub-research objectives	Chapter section	Chapter summary and evaluation of the objectives attained
R01: To contextualise flexibility, intelligent products, and their required technologies from a theoretical and practical perspective to support the rationale of this research.		
RO1.1: Review the purpose and definition of flexibilities in manufacturing and measuring approaches.	2.1	The linkage analysis of smart/intelligent products and flexibility dimensions highlighted that the products only influence the four dimensions of Material handling, process, routing, and Program flexibility. The flexibility dimensions and their measurements are based on Browne et al. (1984) and Sethi and Sethi (1990).
RO1.2: Explore the factors that lead to complex problems and intelligence in psychology. Investigating and comparing smart/intelligent products in literature through a bibliometric analysis to define and classify the term and provide application fields.	2.2	Manufacturing problems of scheduling, control, planning, process, and environmental issues have been highlighted by conducting a SLR on problems in manufacturing. According to Glouberman and Zimmerman (2002) and Snowden and Boone (2007), the manufacturing problems have been classified as complicated. The thesis closely follows the intelligence definition of Dörner (1984) to solve complicated and complex problems. The definitions and classifications of smart/intelligent products differ in varying perspectives, application fields and parts of the product lifecycle. For defining smart/intelligent products in manufacturing, the definitions of Porter and Heppelmann (2014) and McFarlane et al. (2003) are selected since they directly address the scope of research and have the highest frequency rank among the SLR studies. Similar, the SLR did not yield a uniform classification model. Additional research led to the model of Zbib et al. (2008), which provides a generic classification across the entire product lifecycle.
RO1.3: Review the required technologies for the functionalities of intelligent products.	2.3	Based on the smart/intelligent product functionalities of Zbib et al. (2008), the key technologies of memorisation, communication, processing, and sensor actuation have been examined. The functionality classes require technologies of automatic identification procedures, microcontrollers, memories, and sensors.
RO2: Develop and evaluate a conceptual framework that analyses the existing manufacturing environment and derives intelligent-product structures.		
RO2.1: Define the requirement specification for the conceptual framework.	3	A set of requirements defined the premise for integrating intelligent-product structures into a FMS. The requirement specification contains 13 functional requirements, four user requirements, five design restrictions, three attention points and four boundary conditions. The requirement specifications showcased the development strategy of the IPIDS framework.

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RO2.2: Develop the conceptual framework for integrating intelligent-product structures.	4	The IPIDS framework is proposed as the result of the requirement analysis presented in Chapter 3. The framework consists of the four key stages, namely: (i) Definition, (ii) Analysis/Evaluation, (iii) Design, and (iv) Execution, that collectively provide the premise for the integration of intelligent-product structures. Each stage has sub-steps with processes, methods, and tools. The key decision for the user is the value-adding provided in the feasibility study.
RO2.3: Verify and validate the developed framework to identify whether it is feasible and fits its intended purpose.	5	The evaluation (i.e., verification and validation) of the developed framework is presented in Chapter 5. The verification of the IPIDS framework is based on predefined requirements. The requirements include the five requirements of van Aken and Berends (2018) and the seven features from Jabareen (2009). A prototype implementation is executed for validation to provide confidence in the developed framework's applicability, usefulness, and practicability. Each framework step has been performed for an actual use case scenario. The prototypical implementation showcased that the IPIDS framework provides a classification model for products and resources and manufacturing problems to analyse feasible solutions. The validation of the IPIDS framework highlighted the premise for integrating intelligent products in manufacturing with a focus on mixed product-intelligence structures.

6.2 Contributions

The primary contribution of the thesis is the IPIDS framework, which provides the integration method for intelligent-product structures in flexible assembly. The integration approach focuses on defining, analysing, and designing intelligent products or resources. The presented framework addresses the research gap of incomplete integration and evaluation approach for mixed product-intelligence structures in FMSs, presented in Section 2.1.

The IPIDS framework goes beyond the general definition and classification of intelligent products to provide a set of guideline approaches to assess the initial situation (i.e., products, resources, and problems), analyse and evaluate potential solutions, and design and develop the intelligent products in manufacturing. Thus, the four stages of the IPIDS system demonstrate a comprehensive integration and evaluation approach of intelligent products based on assessing the initial functionality situation in manufacturing. The assessment of the initial functionality situation of the products and resources in stage one of the IPIDS framework enables the investigation of multiple products and resources in the manufacturing field, which can lead to a mixed functionality structure. Along with the entire framework, the mixed product-intelligence structure is considered, and the definition of the desired solution does not require equal functionality levels for the products and resources. Providing processes, methods, and tools for each stage of the IPIDS framework facilitates the execution of the framework for the user. The IPIDS framework contributes insights regarding the potential of taking a nuanced view on intelligent-product structures by considering various domains of product functionalities, aggregation levels, adaptivity, and autonomy for innovative solution practices of the problem, due to a comprehensive and cross-domain assessment. Moreover, the IPIDS framework clarifies the activities and actions by providing a seven-step guideline to define, analyse, and design intelligent-product structures.

As mentioned in the thesis, various researchers have raised concerns about the lack of a comprehensive integration and evaluation procedure for intelligent products and resources and the applicability of developed concepts. Applying the developed framework to a manufacturing problem in the learning factory in Reutlingen highlights the applicability, usefulness, and practicability of FMS. Furthermore, a noteworthy observation from the prototypical implementation of the dynamic TCP-positioning method for a collaborative robot using an intelligent workpiece carrier presents the consideration of mixed product-intelligence structures, as the desired solution contains different functionality levels for the products and resources.

6.3 Limitations and delimitations

The research consists of parameters, which are distinguished into limitations and delimitations. Limitations are characteristics of the research design that are outside the researcher's control but influence the research outcomes. For instance, selecting the type of methodology includes limitations in terms of generalizability (Theofanidis & Fountouki, 2019, p. 156). On the other side, the delimitations of research are characteristics that arise from limitations, which define the boundaries. The delimitations result from specific choices by the researcher, which include the choice of objectives, questions, variables of interest and others (Theofanidis & Fountouki, 2019, p. 157). The limitations and delimitations of the research are set out below.

Limitations

i. The IPIDS framework does not guarantee improved quality and performance changes for the users – but it is intended as a management practice tool in terms of a decision-level analysis as well as an implementation guideline, which structures the implementation process of intelligent-product structures.
ii. The IPIDS framework does not mean to include a wide range of tools and methods for each step in the framework to elucidate the definition, analysis, evaluation, design, and implementation of mixed product-intelligence structures. However, one method or tool for each process step of the conceptual framework is provided.
iii. The conceptual framework is validated in the learning factory in Reutlingen, representing a compact application scope. Therefore, the applicability and practicability of the results cannot be generalised.
iv. Several design restrictions for the conceptual framework highlighted in Section 3.6 also serve as limitations.

Delimitations

i. The focus and scope of this research lie on the product manufacturing phase. Due to a higher product variety, shorter product life cycle, and resulting manufacturing challenges, the design of future manufacturing facilities needs to be more flexible and adaptable (Bertelsmeier et al., 2016, p. 755). Thus, the research focuses on certain forms of FMSs.
ii. The research is limited to the product manufacturing phase, not the product use phase with intelligent products for everyday life.
iii. The research does not cover a general point of view. The aim is to develop a conceptual framework for manufacturing enterprises that contributes to defining, analysing, and designing intelligent products and resources.

Even though there are some limitations and delimitations to the IPIDS framework, there are no country-specific peculiarities to applying the framework in the research environment of German and South African manufacturing. In particular, Gasparetto et al. (2018) highlighted that intelligent-product structures, such as an intelligent workpiece carrier, can be beneficial for order picking and process optimization for SMEs with a lower level of automation. However, the IPIDS framework provides an individual assessment of intelligent product potentials, guided by processes, methods, and tools that apply to all automation levels in the initial situation. Suppose the application of the IPIDS framework indicates the value-adding of intelligent products in a specific manufacturing environment. In that case, potential improvements to smart manufacturing can be effective operations, fast response to customer demand, and real-time operations optimization (Shai et al., 2020).

6.4 Opportunities for future research

The thesis provided the foundational integration approach for intelligent-product structures in manufacturing systems but left room for additional and complementary research within the following three focus areas: (i) application of the IPIDS framework inside and outside of the initial research scope, (ii) evaluation of the framework outcome in a productivity environment, (iii) challenges of mixed product-intelligence structures.

The framework proposes a system integration and evaluation method for intelligent-product structures in manufacturing to provide an assessment and guideline for implementation. The practical implementation is conducted in the limited research environment of a learning factory to provide applicability, usefulness, and practicability. In the manufacturing research environment, the applicability of mixed product-intelligence structures for the IPIDS framework is validated in one use case. Implementing different use cases of mixed product-intelligence structures in the IPIDS framework will assist in validating the framework. Since the IPIDS framework represents a generic concept of implementing intelligent-product structures, it should be feasible outside manufacturing. Further research is required to prove the feasibility in additional application fields, such as logistics and digital supply chain management. The informational connection of logistic- and manufacturing execution systems by intelligent products enables more transparent and efficient supply chain management, thus enhancing the fulfilment of the demands and customer satisfaction.

After implementing the prototype of an intelligent workpiece carrier, the next step shall be integrating it into a productivity environment. Even though the intelligent workpiece carrier design intends to meet the requirements of a productivity environment, the dynamic TCP-positioning method has not been tested with a runtime of several working days or weeks. Since the VL53L1X time of flight distance sensor represents a key component in the dynamic TCP-positioning method, the deviations in precision and accuracy of the distance measurements in a productivity environment are an opportunity for further research. A further optimization opportunity of the dynamic TCP-positioning method represents the transmission rate of the measurement data to the robot. Applying the TCP-positioning method to further manufacturing systems requires adjustments and individualisation. In case there are protruding parts on the workpiece carrier, or the geometrical shape of the workpiece carrier varies, this needs to be considered for further applications to avoid crashes between the collaborative robot and the product. Besides the technical feasibility in a productivity environment, further research is recommended in the profitability of the TCP-positioning method. The prototypical implementation of the intelligent workpiece carrier yielded material costs of 79,34 €, which is not reflected in any measurable and beneficial key figure. Thus, a return-on-investment calculation is essential before commissioning the dynamic TCP-positioning method in a productivity environment.

As mentioned above, the prototypical implementation of the dynamic TCP-positioning method exemplifies the applicability of mixed product-intelligence structures in manufacturing for a concrete use case. In addition, the IPIDS framework assesses the functionality levels of the resources, representing the degree of intelligence. However, intelligent manufacturing requires similar technologies and functionalities among the resources to enable machines or devices to vary their behaviours in response to diverse situations. If a machine is not participating in the communication and decision-making, the flexibility and adaptability enhancements are difficult to reach due to minor functionalities compared to the other resources. For instance, routing flexibility relies on real-time data of the machines and products to improve reliability and utilisation of the production resources. Thus, routing flexibility requires similar product intelligence structures for communication and decision-making. Further research needs to focus on a minimum level of product intelligence to apply in FMSs. In addition, the impact and limits of mixed product-intelligence structures in manufacturing need to be further analysed, as the IPIDS framework only assesses the initial situation.

6.5 Final reflection

The presented research provides a holistic concept to assess the existing manufacturing environment, identifying value-adding factors through intelligent products and deriving design and implementation concepts. Methods, tools and processes are provided for each step of the IPIDS framework to guide the user through implementing intelligent-product structures in flexible manufacturing. In addition, the research contributes toward mixed product-intelligence structures.

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Appendix

Appendix A: Classification of identified problems in manufacturing

Classes	Occurrences	Relevance
Scheduling problem	1110	1.14
Flexible job shop scheduling problem	206	1.60
job shop scheduling problem	173	1.44
Control problem	164	0.88
Planning problem	158	0.69
Process problem	156	0.66
Environmental problem	131	0.75
Cell formation problem	108	1.60
Inverse problem	104	0.61
Benchmark problem	100	0.83
Np hard problem	98	1.08
Test problem	96	0.94
Facility layout problem	93	1.39
Flow shop scheduling problem	91	1.15
Optimisation problem	89	0.65
Layout problem	74	1.34
Salesman problem	69	0.78
Multi objective optimization problem	69	0.29
Classification problem	66	0.60
Decision making problem	63	0.70
Combinatorial optimization problem	54	1.15
Parallel machine scheduling problem	53	1.37
Production scheduling problem	49	1.35
Hybrid flow shop scheduling problem	43	1.34
Multi objective problem	41	0.54
Large scale problem	33	0.99
Production problem	33	0.57
Permutation flow shop scheduling problem	32	1.48
Single machine scheduling problem	32	1.34
Original problem	26	0.69
Large sized problem	25	1.43

Appendix B: Synopsis of selected studies on perspective and respective definition approach

Article	Definition Perspective	Own definition	Based on established definition	Based on combined definitions
(Alcayaga et al., 2019)	Product		(Whitmore et al., 2015)	
(Antons & Arlinghaus, 2020)	Manufacturing		(Bertelsmeier et al., 2015; McFarlane et al., 2013)	x
(Attajer et al., 2019)	Product User		(Porter & Heppelmann, 2014)	
(Frank et al., 2019)	Product User		(Porter & Heppelmann, 2014)	
(Henkens et al., 2021)	Product User		(Anke, 2019; Porter & Heppelmann, 2014),	x
(Kahle et al., 2020)	Product User		(Meyer et al., 2009; Porter & Heppelmann, 2014)	x
(Kondoh et al., 2021)	Product User		(Pagoropoulos et al., 2017; Stock & Seliger, 2016)	x
(Kovalenko et al., 2019)	Manufacturing		(McFarlane et al., 2013; W. Lepuschitz et al., 2011)	
(Lenz, MacDonald, et al., 2020)	Product		(McFarlane et al., 2003)	
(Lenz, Pelosi, et al., 2020)	Product		(Porter & Heppelmann, 2014)	
(Meindl et al., 2021)	Product User		(Kahle et al., 2020; Porter & Heppelmann, 2014)	x
(Miranda et al., 2019)	Product User		(Porter & Heppelmann, 2014)	
(Najlae et al., 2021)	Manufacturing		(Cardin & Chové, 2013)	
(Pardo et al., 2020)	Product		(Abramovici et al., 2016)	
(Riedelsheimer et al., 2021)	Product		(Abramovici et al., 2016)	

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(Romero et al., 2020)	Product		(McFarlane et al., 2013)	
(Schuh et al., 2019)	Product		(Porter & Heppelmann, 2014)	
(D. Thomas et al., 2019)	Product User		(Mühlhäuser et al., 2008)	
(Tomiyama et al., 2019)	Product	x		
(Wan et al., 2021)	Product		(Kubler et al., 2010)	
(Zapata et al., 2020)	Product User		(Porter & Heppelmann, 2014)	
(Gentner et al., 2018)	Product User		(Gutierrez et al., 2013)	
(Ahmed et al., 2019)	Product User	x		
(Cao et al., 2021)	Product		(Z. Wang et al., 2019)	
(Dehnert & Burkle, 2020)	Product		(Beverungen et al., 2019)	
(Dong et al., 2022)	Product User		(Raff et al., 2020)	
(Holst et al., 2020)	Product User		(Porter & Heppelmann, 2014), (Schuh et al., 2019)	x
(Jiang et al., 2019)	Product		(Abramovici et al., 2016; Rijsdijk & Hultink, 2009)	x
(W. J. Lee, 2019)	Product		(Lin et al., 2017; Maass & Varshney, 2008; McFarlane et al., 2003; Rijsdijk & Hultink, 2009)	x
(Y. P. Li et al., 2019)	Product		(Y. Li et al., 2015)	
(Lu et al., 2019)	Product User		(Valencia et al., 2015)	
(Oluyisola et al., 2020)	Product		(Günther Schuh et al., 2020)	
(Pan et al., 2019)	Product		(Wu & Pillan, 2017)	
(Popolo et al., 2021)	Product		(Raff et al., 2020)	
(Raff et al., 2020)	Product	x		
(Thurer et al., 2021)	Manufacturing		(McFarlane et al., 2003; Meyer et al., 2011)	

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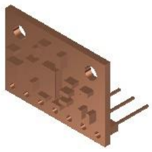
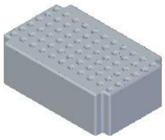
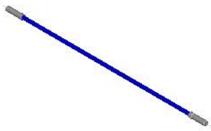
(Z. X. Wang et al., 2020)	Product		(Kuhlenkötter et al., 2017)	
(H. Zhang et al., 2020)	Manufacturing		(Leitão et al., 2015; McFarlane et al., 2002; Meyer et al., 2009; Wuest et al., 2018)	x
(Zheng et al., 2020)	Product		(Porter & Heppelmann, 2014; Rijsdijk & Hultink, 2009)	x
(Yang et al., 2021)	Manufacturing	x		
(W. M. Wang et al., 2020)	Product User		(O. Thomas et al., 2017)	
(X. Gu, 2020)	Product	x		
Sum		**6**	**37**	**10**

Appendix C: Bill of material for functionality upgrade of the workpiece carrier

The contents of the Bill of Material have been compiled on the 30th of May 2022.

	Description	**Image**	**Quantity**	**Cost**
1	NodeMCU V3.4 ESP8266 ESP-12 E Lua CH340		1	4,70€
2	VL53L1X Time-of-Flight Distance Sensor		4	13,95€
3	ZY-55 Solderless Mini-Breadboard		1	0,41€
4	Electrical power bank		1	2,56€
5	Jumper connector cable		-	14,59
6	Mount for VL53L1X		4	0,32€
7	Housing for components		1	2,15€
Sum				79,34€