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Scoping the Industry 4.0 Reconfigurability

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Scoping the Industry 4.0 Reconfigurability

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Abstract

Industry 4.0 defines the organization of production and manufacturing processes based on technological advanced solutions and devices autonomously communicating with each other. Within the context of this industrial revolution, the smart reconfigurable manufacturing systems are introduced. These systems shall be able to provide a dynamic level of reconfigurability based on the production demand and system availability. The introduction of the manufacturing reconfigurability constitutes a particularly important and expensive decision for the organizations and therefore scoping methods are becoming constantly essential.

The present work covers a first approach to defining reconfigurability methods and drivers for the manufacturing systems within the context of Industry 4.0. The thesis introduces five main reconfigurability use case scenarios for manufacturing systems and the description of a two – dimensional model of scoping parameters.

The first dimension is based on the potential business targets and reconfigurability drivers, while the second dimension focuses on the system functions and technologies, which are required for the successful realization of the reconfigurability use case scenarios. Finally, the thesis concludes with a brief comparison between the traditional software product line scoping approach and purposed scoping method for the reconfigurability of manufacturing systems.

Table of contents

Abbreviations

ICT	Information and Communications Technology
IoT	Internet of Things
OT	Operation Technology
PLC	Programmable Logic Controller
RAMI4.0	Reference Architecture Model Industrie 4.0
IIRA	Internet Industrial Reference Architecture
LLC	Low-Level Control
RMS	Reconfigurable Manufacturing Systems
SOA	Service-Oriented Architecture
CP(P)S	Cyber-Physical (Production) System
AI	Artificial Intelligence
HMI	Human Machine Interface
MHS	Material Handling System
BoM	Bill of Materials
IIoT	Industrial Internet of Things

List of figures

1 Introduction

1.1 Problem statement

The term Industry 4.0, the fourth industrial revolution, was first introduced in 2015. The main objective of this initiative is to bring the automation of the manufacturing system and processes to a new level, introducing customized and flexible mass production methodologies. The defined design principles for Industry 4.0 are: the interoperability & interconnection between the machines and system components, the virtualization & technical assistance, the decentralization & decentralized decision making, the real-time capability & information transparency, the service orientation and finally the modularity. The modularity is characterized as the ability of a manufacturing system to adapt dynamically and fast to new market demands, manufacturing requirements, technological trends as well as based on the overall system availability. The introduction of reconfigurable manufacturing techniques and technologies is a very vital and important business decision, which affects the business organization holistically. Therefore, scoping tools and methods are required to justify the cost and the extent of the manufacturing reconfigurability introduction and finally calculate the potential return of the investment for the organization.

1.2 Thesis objectives

The central thesis target is the state of the art identification of the reconfigurability methods within the context of Industry 4.0 and the introduction of a scoping approach for the reconfigurability in the manufacturing systems. The scoping approach is based on several reconfiguration use cases, which define the various reconfigurability characteristics and drivers. More precisely, the following objectives are outlined:

O1: Identification of the state of the art methods in planning Industry 4.0 reconfigurability.

O2: Collection of industrial examples, which illustrate the reconfiguration needs and respective reconfiguration solutions.

O3: Design of a conceptual framework, which allows the characterization of reconfiguration needs, approaches and technologies.

O4: Research if and how the traditional software product line engineering scoping approach can be adapted to support the scoping of Industry 4.0 reconfigurability.

Thus, the related research questions are:

R1: What are the main benefits from the business point of view for applying reconfigurable solutions?

R2: What are the major reconfigurability use case scenarios and how they can be applied?

R3: How the scoping method for reconfigurability in the context of Industry 4.0 can be introduced?

R4: What are the main types of functions and technologies, necessary for a reconfigurable system within the context of Industry 4.0?

1.3 Contribution

With this work, a first approach to define reconfigurability methods and drives for the manufacturing systems is presented. The primary motivation was to exam if a similar concept to the product line engineering may also be applicable for scoping manufacturing system.

The main contribution of the thesis is the identification of reconfigurable use case scenarios for manufacturing systems and the definition of a two-dimensional model of scoping parameters. The first dimension focuses on the business targets and reconfigurability drivers, while the second dimension concentrates on the system functions and technologies. The latter is necessary for the successful implementation of the reconfigurability use case scenario.

As a further contribution, the state of the art in the field of the reconfigurable manufacturing systems is depicted, and relevant details and characteristics from the field of production and manufacturing engineering are presented.

Finally, the work closes with a brief comparison between the traditional scoping approach and a scoping method for the manufacturing systems reconfigurability.

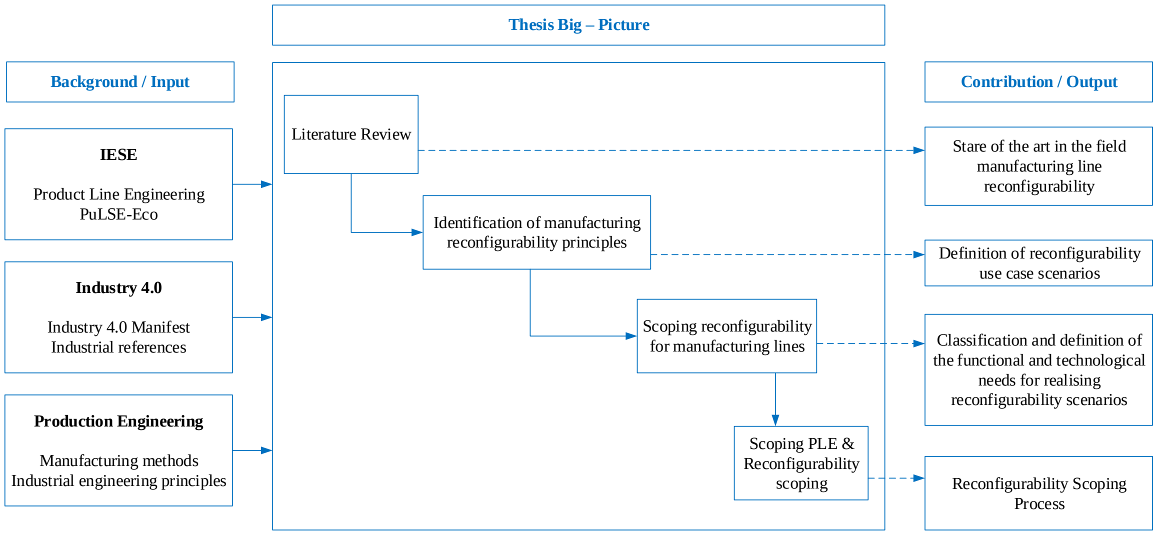

Figure 1: Thesis big – picture

As a proposal for future extensions of the present work is the identification of a plethora of use case scenarios and their related execution of case studies, which can be applied to design reconfigurable manufacturing systems. Furthermore, the detailed identification of the influence each scenario may have for the low-level controls, high-level controls software and system architecture can be an extension of the current work. Lastly, extended research shall take place, dedicated to the different industrial environments, for example, for the process industry, the assembly-based production units, the manufacturing production lines, logistics and similar.

1.4 Thesis structure

Based on the described objectives, the thesis is structure as follows.

Chapter 1: The general thesis objectives and outline as part of Chapter 1.

Chapter 2: In Chapter 2, presents an overview of the current state of the art if the field of manufacturing system reconfigurability. The state of the art focus is on the control systems used to achieve reconfigurability within the context of Industry 4.0. The reconfigurability methods are divided between the high-level control and the low-level control manufacturing components, as the ISA95 standard defines these.

Chapter 3: Chapter 3 defines the use case scenarios in the field of the manufacturing systems, where the reconfiguration of the system design can be beneficial. Several use cases are introduced, while their benefits and characteristics are defined.

Chapter 4: Chapter 4 summarizes some of the available in the literature industrial use cases and method validation test procedures with focus the reconfigurability of the manufacturing systems.

Chapter 5: In Chapter 5, the different characteristics and potential categories of the reconfigurability drivers are given. The characteristics create a group of six main categories.

Chapter 6: Chapter 6 presents, the reconfigurability scoping approach, based on the defined reconfigurability use case scenarios.

Chapter 7: Chapter 7 shows, a comparison between the traditional software product line scoping and the scoping of the manufacturing system reconfigurability in the context of Industry 4.0.

2 State of the art

In this chapter, a state of the art overview of practices and technologies in Industry 4.0 applications is given, fulling the first thesis objective **O1** for the identification of the state of the art methods in planning the reconfigurability in the context of the fourth industrial revolution. The focus is on the reconfigurability aspect of the industrial applications, which follow the Industry 4.0 principles. The first part of the chapter portraits the importance of the standardization and a summary of the Industry 4.0 principles; since the standardization is considered a critical factor in planning reconfigurable solutions. The chapter continues with an overview of the currently available reference architectures in the field of the Industry 4.0. Finally, the chapter focuses on the decision-making mechanisms that are essential for distributed industrial solutions.

2.1 Industry 4.0

The term Industry 4.0 refers to the 4^{th} industrial revolution and the introduction of cyber-physical systems.

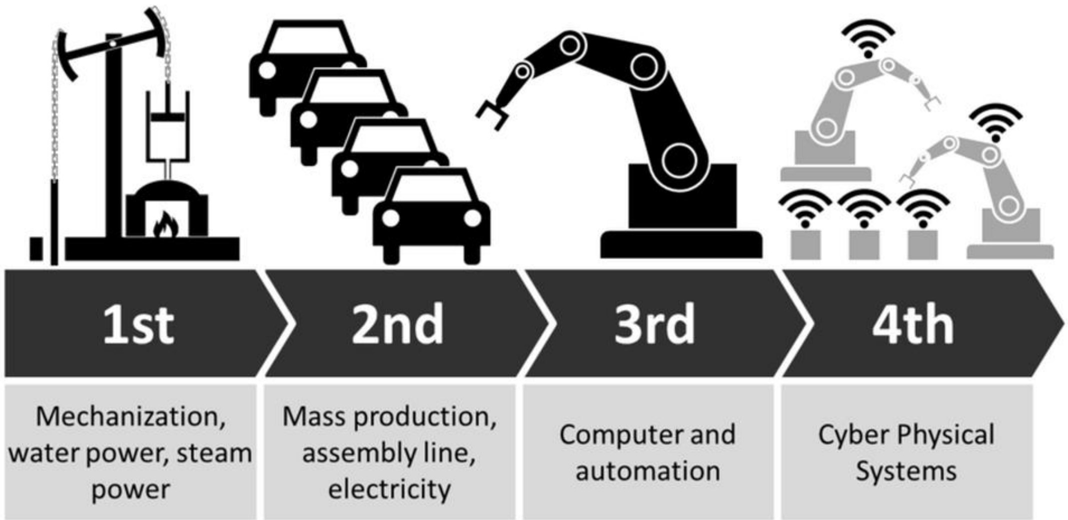

Figure 2: The 4th industrial revolutions (by Christoph Roser at AllAboutLean.com)

Industry 4.0, as a concept defines the organization of production and manufacturing processes based on technological advanced solutions and devices autonomously communicating with each other along the value chain. The main features and design principles of Industry 4.0 are (ITRE, 2016) (M. Hermann, 2016):

- Interoperability & interconnection: the cyber-physical systems allow humans and smart factories to collaborate.
- Virtualization & technical assistance: the introduction of a virtual twin.
- Decentralization & decentralized decision making.
- Real-time capability & information transparency: the provision of information and the introduction of data analytics.
- Service orientation.
- Modularity: flexible adaptation of the production processes to meet the changing requirements.

The main particularity of the Industry 4.0 is the fact that first time an industrial revolution is predicted a- priori, not detected ex-post (R. Drath, 2014).

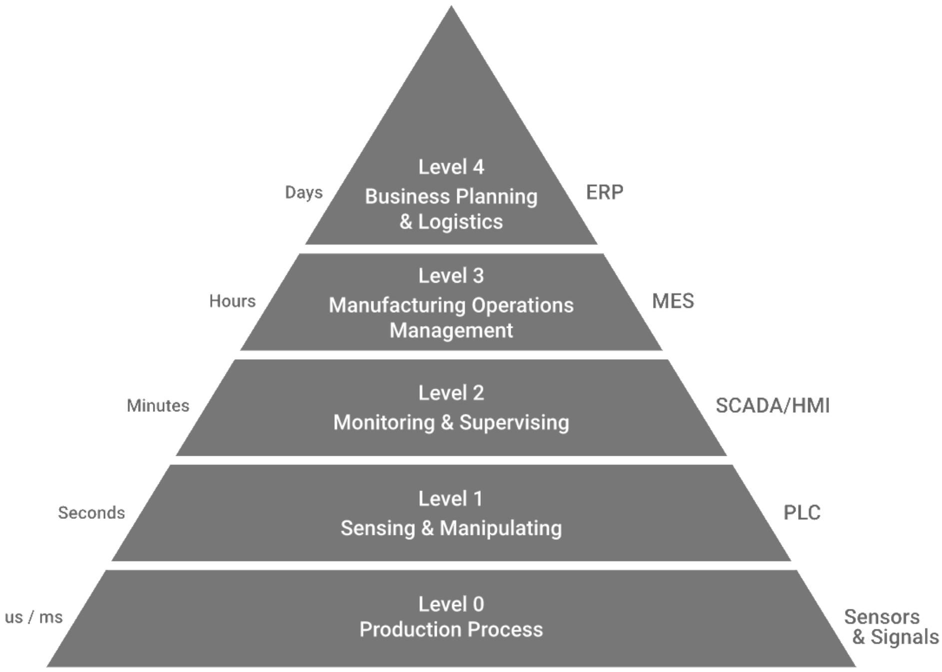

Figure 3: The automation pyramid, according to the ISA 95 model.

The transition into the Industry 4.0, however, requires a transition from the traditional reference hierarchical reference models (Figure 2) to the introduction to new models and reference architecture, where the holistic integration of the involved objects is possible and realizable.

2.2 Standardization

The success of the Industry 4.0 concept relies mainly on the incorporation of the information and communications technology (ICT) in industrial operations and production (Operation Technology), with the main target, the flexible and efficient manufacturing with collaborative behaviour. The flexibility of the manufacturing systems and the introduction of new business models is essential for the companies and the organizations to keep up with the demanding market requirements and the trends. Thus, for the main existing reference architectures (RAMI 4.0 and IIRA) in the field, the standardization is considered as a critical factor. The holistic integration of all the involved in the manufacturing components is necessary. Holistic integration requires both vertical and horizontal integration. Prerequisite for the holistic integration is the transformation from the hierarchical control approach to a dynamically distributed service-based architecture and decentralized decision making, where the objects, involved in the manufacturing processes, are loosely coupled. The vertical integration refers to the communication between the different levels of the OT world, while horizontal integration refers to the integration among people processes and technology. Such an Integration can be only achieved based on clearly defined standards (N. Velásquez Villagrán, 2019).

The standardization landscape, however, is characterized currently by significant heterogeneity, with more than a hundred of various organizations involved (ISO, IEC, ETSI, LNI4.0, OCF, SCI4.0, DIN, W3C, ETSI, etc.). Furthermore, due to the continually changing objectives, the definition of relevant standards is currently unrealistic (O. Meyer, 2018).

2.3 Reconfigurability

The definition of the reconfigurable manufacturing systems (RMS) and the differentiation of them from the flexible manufacturing systems and the dedicated manufacturing systems, took place long before the introduction of the Industry 4.0 principles (Figure 3). The critical characteristic of an RMS is the fact that the system functionality and capacity are not fixed (MG. Mehrabi, 2000).

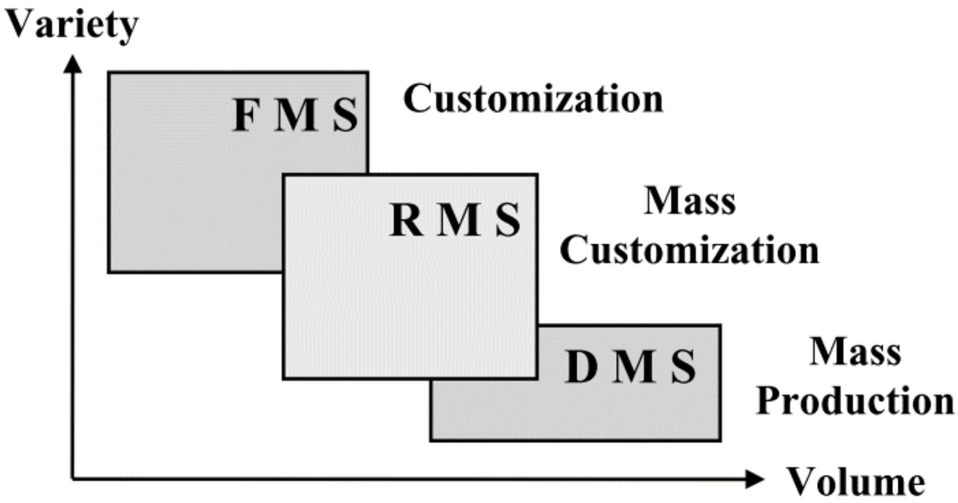

Figure 4:Manufacturing paradigms-A hypothesis (Hu, 2005)

Consequently, reconfigurable manufacturing systems are defined as the systems which are designed for rapid manufacturing changes and adjustable production capacity and functionality, within a family of parts, in response to rapid market requirements change. The main objective is to deliver the exact functionality and capacity that is needed when it is needed (ElMaraghy, 2005).

A second definition for the reconfigurable manufacturing systems focuses on the capability to add, remove or rearrange the system components and adapt the system functionality in a timely and cost-effective way, which can result in a desired alternative configurations (McFarlane, 2007).

The primary differentiation between FMS and RMS is the fact that these systems have different goals. The FMS target to an increased variety of produced parts, where the main goal of the RMS is the increased responsiveness to the upcoming market needs. Higher production rates than the FMS characterize the RMS but within the borders of a family of parts, while the FMS aims to a wide range of products, usually with small capacity.

The main six characteristics of a reconfigurable manufacturing system are (Koren, General RMS Characteristics. Comparison with Dedicated and Flexible Systems., 2006):

1. The modularity
2. The integrability
3. The scalability
4. The convertibility
5. The customizability
6. The diagnosability.

In the next paragraphs, the state of the art for the different reconfiguration solution is given based on the implementation level (low-level control and high-level control). However, as stated, there is not any available work in the literature, which presents a systematic design and configuration methodology for an RMS (Maksane, 2019).

2.3.1 Reconfigurability in low-level control

In the field of automation technology, several approaches have been developed over the last decade to enable methodical reconfigurability. As automation technology (LLC) is defined; the group of logical objects, which belong near to the field devices (sensors, actuators) or as a direct connection to the traditional operation technology approach. These devices belong to level 01 of the ISA95 hierarchical pyramid. The introduction of the object-oriented approach of the IEC 61131-3 and the development of the IEC 61499 are the two primary approaches to introduce reconfigurability on this level (A. M. Farid, 2015).

The IEC 61131-3 has been released in 2013 as an updated version of the IEC 61131, which was initially published back in 1993. The IEC 61131 is a widely accepted standard in the automation domain and the main and the widely supported method for the development of PLC Software. Several literature references have been found where the use of IEC 61131-3 is the driver for easily configurable solutions.

An open architecture for flexible manufacturing with main target the quick reconfiguration, using PLCs and OPC UA communication, has been proposed (G. Neugschwandtner, 2013).

A cyber-physical system approach which, includes PLC controllers within a service-based architecture is published (Thramboulidis, "A cyber–physical system-based approach for industrial automation systems", 2015).

The implementation of a solution which combines web–services and PLC Software based on IEC 61131-3 following the main instructions of the RAMI4.0 architecture is available (R. Langmann, 2016).

A multi–agent based solution for an extended distributed system, which can support reconfigurability is recommended (Karnouskos S., 2012), while an implementation based on the IEC 61131-3, included PLCOpen XML and OPC UA interfacing has been used for the dynamic reconfiguration of an automated production system (S. Bougouffa, 2017).

The IEC 61499 architecture was introduced in 2005, and it mainly provides (Figure 4):

- support of the traditional IEC 61131-3 PLC programming languages in combination with distributed software techniques
- modelling development approach for distributed control applications
- event-driven execution flow
- function block concepts
- encapsulation

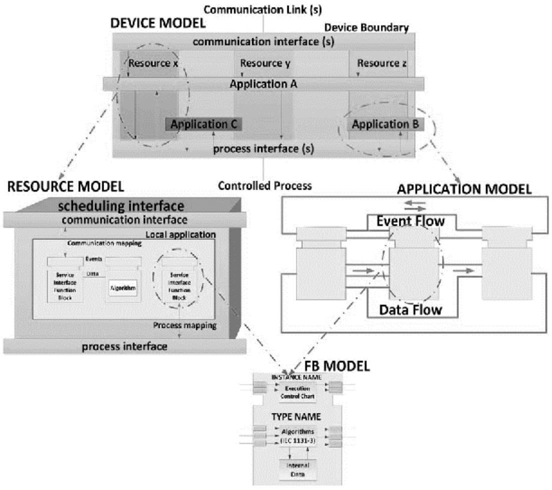

Figure 5: IEC-61499 function model

The primary motivation of the introduction of the new standard was the support of the reconfiguration, distribution, portability and interoperability by design to cover the complicated demands and requirement of the modern automation systems. It is claimed that the currently available architectures, for instance, the IEC 61131-3 could not support the new requirements and development of the IEC 61499 was essential to address these issues (T. Strasser, 2011). IEC 61499 standard defines a generic model based on function blocks (FBs) for distributed control systems and industrial automation. Those are the FB model, application, resource and device. The IEC 61499 is highly cited and promoted by the academic community.

The IEC 61499 as a reference architecture is considered as the first option for the development of flexible and configurable automation solutions. The main driver is the increased complexity of the information and control systems and the need for distributed design and architectures. However, the lack of maturity and engineering tools is currently a strong barrier for the broader adoption of the IEC 61499. (Vyatkin, 2011).

The challenging online reconfiguration for flexible and customizable manufacturing systems is addressed using IEC 61499 function blocks. The solution is based on the IEC 61499 reference architecture for the reconfiguration and the cooperation of the ontology-based agents (Figure 5), while the reconfiguration takes places without affecting the operation of the remaining system components (G. Wan, 2017).

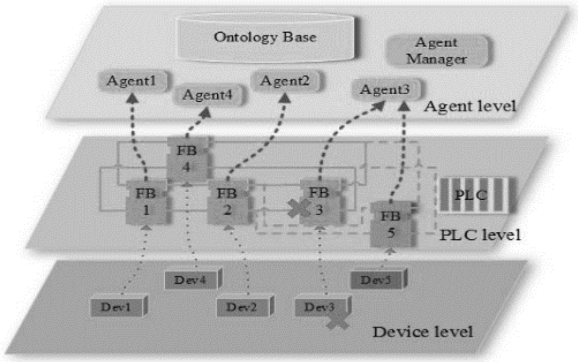

Figure 6: Overview of solution architecture (G. Wan, 2017)

The use of the IEC 61499 standard and the implementation of the object communication via OPC UA resulted on an Industry 4.0 compliant solution based on reusable software components and support of a fundamental dynamic reconfiguration (T. Terzimehic, 2017).

Similar implementations, based on the IEC61499 reference architecture and the distributed control systems, have been proposed for applications in the field of oil & gas and onshore oil field industries (Marcelo V. García, 2017) (LUCIAN-SORIN DOBRESCU, 2015).

Finally, in the field of the healthcare industry, a solution for functional reconfiguration and flexible schedule has been proposed as a requirement for the dynamic pharmaceutical market. The solution is based on cloud computing and ontology knowledgebase CPS in combination with the IEC 61499 architecture (J. Wan, 2019).

Research in the comparison of the IEC 61131 and IEC 61499 architectures concluded that for the IEC 61499 can support better service oriented approaches (W.W. Dai, 2014). However, the use of IEC 61499 is also highly criticized, due to the limited support of commercial tools and industrial references, while in parallel solutions have proposed where the IEC 61131 could support and used as a mean for portable, distributed and reconfigurable implementations (Thramboulidis, "IEC 61499 vs. 61131: A Comparison Based on Misperceptions", 2013).

2.3.2 Reconfigurability in high-level control

As high-level control components, we define the objects, which belong to the upper three levels of the ISA95 hierarchical structure. These systems control the execution of the manufacturing process, and they are based on decision-making mechanisms. This kind of mechanisms are grouped into three main categories in the literature (Zhang, 2018):

1. knowledge-based systems
2. service-oriented systems
3. multi-agent systems.

The knowledge-based approach has collected several references within the academic community. The basic idea of those systems is that the decision making of the control algorithm is based on external information and requirements collected in the form of an ontology.

By using a knowledge base ontology system for the description of the mechanical skills and AI techniques, researches have presented a system, where the robots work autonomously side-by-side with humans, in a dynamic manufacturing environment (Maj Stenmark, 2015). A new method has been introduced to improve the manufacturing planning and scheduling, while the results in the distributed collaborative manufacturing and logistics have been stated (B. Gernhardt, 2016).

In another example, the combination of the reconfiguration principle in the use of the IEC 61499 for the low-level control components in combination with an ontology centred knowledgebase system in the perception layer has resulted to a reconfigurable data-driven manufacturing process for the healthcare applications (J. Wan, 2019).

A model-driven engineering approach to support the automatic configuration of the CPS control layer based on the knowledge base description of the capabilities of the active components and the environment has also been introduced. Two use cases support the approach of the automatic configuration of the control layer and the automatic creation of assembly plans (Munir Merdan, 2019).

A summary (Ryashentseva, 2016) of the advantages, disadvantage and drawbacks of the knowledge-based systems have been demonstrated in the literature (Legat C., 2011) (C. Legat, 2013) (Tzafestas, 1989):

- The knowledge-based systems are built on control rules.
- The knowledge-based can lead to the detection of disturbances since they rely on a vast amount of information.
- With the knowledge-based systems, the representation of knowledge is given uniformly.
- The use of a knowledge-based system can reduce the engineering effort for upcoming manufacturing system design and reorganization.
- Implementation and the development of a knowledge-based system are complicated and require expert's knowledge.
- The system generalization is quite limited, and the control capabilities should be enumerated explicitly.

A service oriented architecture (SOA) is an architecture characterized by autonomy, interoperability, platform independency and encapsulation in distributed systems (L. Ribeiro, 2008).

Service-oriented architectures have been proposed to improve reconfigurability, adaptability and interoperability of industrial automated applications (A. Pohl, 2008) (K. Thramboulidis, 2006).

A multi-agent system (MAS) as per definition is a group of several agents, each having incomplete information to solve a specific problem. However, the individual agents can communicate and cooperate, in a decentralized and asynchronous way, in order to solve the defined problem. The main characteristics of a MAS are the autonomy, the sociability, the rationality, the reactivity, proactivity and last but not least, the adaptability (L. Ribeiro, 2008).

Both concepts support the principle of distributed autonomous entities and provide a useful modelling metaphor for complexity encapsulation. Nevertheless, SOA focuses on contract-based descriptions of the hosted services without a reference programming model. MAS, however, support methods to describe the behaviour of an agent (L. Ribeiro, 2008).

A first approach for the design of a MAS reference architecture with a focus on the reconfigurable manufacturing systems has been presented in 2015, where the five discrete stages of designing such an agent system are defined (Figure) (A. M. Farid, 2015).

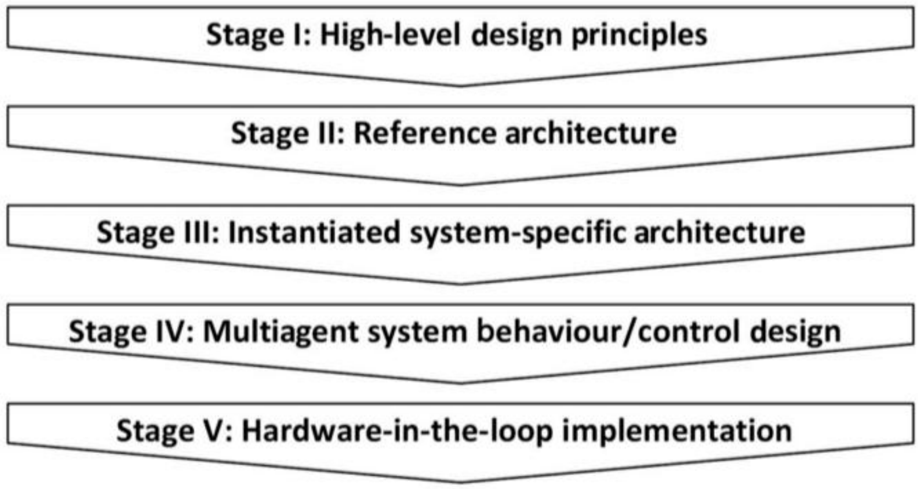

Figure 7: Five-stage MAS design methodology (A. M. Farid, 2015)

In other implementations, the MAS approach is used to increase the flexibility and the reconfigurability for Material Flow Systems (J. Fischer, 2018) (Regulin D, 2016). Furthermore, it is claimed that a MAS based implementation could lead to CPPS, which can provide the desired flexibility and reconfigurability for the production processes and at the same time could be designed independently to the applied production system (Luis Alberto Cruz Salazar, 2018). Extensive analysis and review of the MAS design patterns lead to the conclusion that a CPPS manufacturing architecture, compliant to the RAMI4.0 principles, can be based on the four mandatory sub-agents (Recourse agent, Process Agent, Agent Management System, Communication Agent) (L.A. Cruz Salazar, 2019).

MAS is considered an appropriate approach to achieve flexibility, robustness and responsiveness using decentralized controls over distributed, autonomous and cooperative intelligent control nodes. However, the main weaknesses are the real-time constraints and emergent behaviour in industrial environments (Wooldridge, 2002).

2.4 Reference architecture

A reference architecture aims at describing an essential and independent, production-process function. It can be used as the foundation for the development of concrete system architecture.

The two major and most popular reference architectures, which currently cover the requirements for the implementation of a CP(P)S such as integration, communication, interoperability and support harmonized interfaces and protocols for communication are the RAMI4.0 and the IIRA (O. Meyer, 2018).

The RAMI4.0 is defined within a model with three-dimensional layers (Figure 6). The first axis refers to the “hierarchy levels”, the second axis describes the individual “Layers” and the last one the “Life Cycle & Value Stream”. The model is quite popular within the European academic community with several publications referring to it.

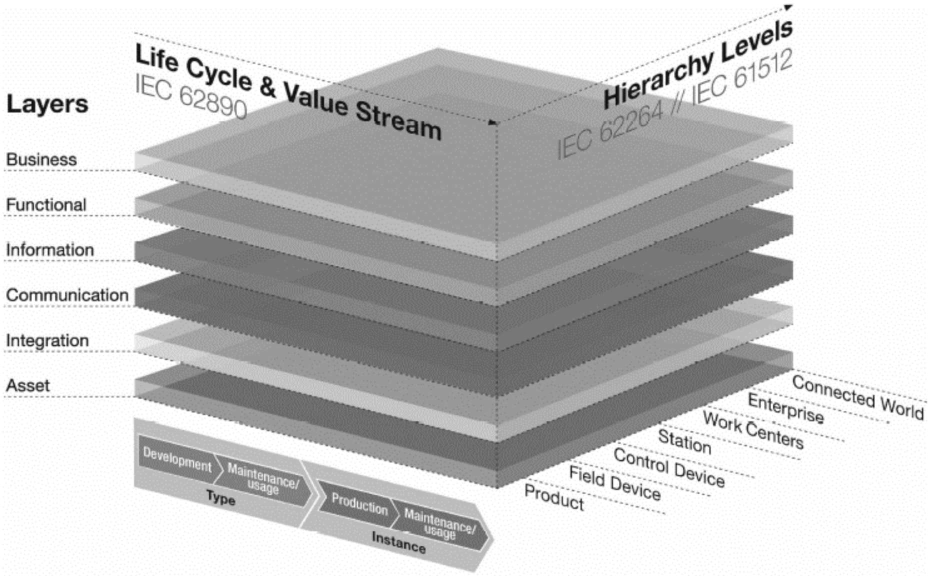

Figure 8: Reference architecture model Industrie 4.0 (DIN, 2016)

Based on the principle structure of the RAMI4.0 reference architecture (Bekanntmachung des BMBF, n.d.), the BaSys 4.0 has been introduced as a platform-independent modular system in the form of a virtual open-source middleware. BaSys 4.0 targets in the realization of a basic system for the manufacturing plants providing the following main benefits (IESE Fraunhofer):

- Provision and implementation of the primary Industry 4.0 concepts
- Easy dynamic production changes
- Easy realization of digital twins, using defined interfaces
- Predictive maintenance
- Online access from the process data
- Easy integration of both existing and new devices

The realization of BaSys 4.0 is based on three principal technologies, which are characterized as the central pillars of the Industry 4.0 compliant production architecture. These pillars are:

- The virtual automation bus
- The asset administration shell
- The control components.

The IIRA reference architecture, on the other hand, focuses more on the field of the IIOT. The IIRA specifies four main viewpoints (business, usage, functional and implementation form) and different functional domains, crosscutting functions, and system characteristics (Figure 7).

Both reference architectures follow similar goals, and all approaches are in general valid for the description of Industry 4.0 production systems. Differences arise for their scope and field of application. RAMI 4.0, however, focuses exclusively in the area of Industry 4.0. Furthermore, it provides a solution, which is more detailed in comparison to others. Even though it can be used as a conceptual basis for the concrete implementation, further research is required. (S. Unverdorben, 2018).

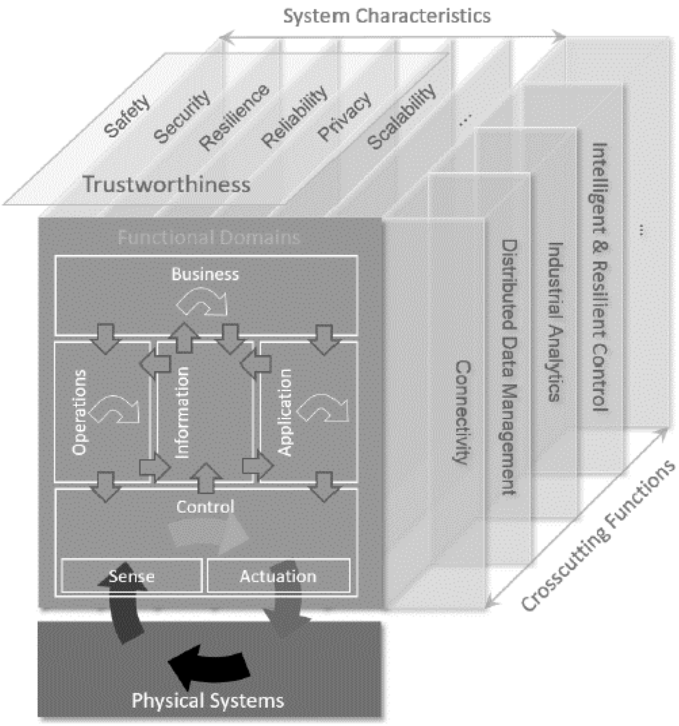

Figure 9: Functional domains, crosscutting functions and system characteristics (Consortium, 2017)

3 Reconfigurability – Use case scenarios

The focus of the chapter is the presentation of practical and possible use case scenarios, where reconfigurability can be applied during the production process. The use cases are categorized by the environment (Where?), the reconfigurability stimulus (When? and Who?), the system response (What?) and finally the potential benefits for the organization, who is willing to invest and introduce production processes based on the reconfigurable manufacturing principles (Why?). Defining these use case scenarios, the second research question **R2** is answered.

3.1 Use case 01 – Lot size 01

3.1.1 Main characteristics

The manufacturing of products with small or even single batch size is continuously getting attention in our economic environment, which demands very often individual but also financially sensible solutions. The essential characteristics of the use case are given on the table below:

Use Case Name	**UC01 - Lot size 01**
Environment	The manual assembly of pneumatic and electric automation products.
Stimulus	Placement of a customer-specific order for an on-demand combination of pneumatic valves and electronic actuators.
Response	The system should guide the operators and the quality control engineers for the correct assembly of the individual components.
Benefits	Extended Product Portfolio Increased Customer Satisfaction

3.1.2 Scenario

A leading manufacturing company of pneumatic and electric automation products allows the customers to configure and order custom-designed configurations based on individual components, which belong in the same product family. In this case, an OEM manufacturing company of industrial packaging machines requires a unique configuration of pneumatic valves, servo actuators and a specific interface module for the communication with the PLC controller. Furthermore, since the end customer is in the USA, the final assembly of the electro-pneumatic module must be certified based on the existing American standards (UL Certified).

The leading engineer of the machine-building company configures online the necessary component and place the purchase order, respectively. Once the order is received and characterized as a Lot size 01 configuration from the manufacturing system, the next steps are followed.

The assembly of the unique product can only be done manually in one of the manual assembly workbenches in a particular location in the factory. All the necessary parts must be collected and transferred to the dedicated work cell. The parts can be transferred with AGV or conveyors. Once the parts arrived at the destination, the operator should get on the screen intuitive instructions for the assembly of the parts and the operational control of the automation component. Finally, the assembled component will be collected and transferred to the logistics area for shipment.

In this case, the crucial processes are:

- The collection of the necessary parts as well as the material handling processes before and after the final product assembly.
- The uninterrupted tracking of the parts and components throughout the manufacturing process execution.
- The intuitive assembly instruction to the engineers for both the assembly and controlling of the final automation unit.

3.2 Use case 02 – Last-minute changes

3.2.1 Main characteristics

In some manufacturing fields, the ability for the customer to make changes on the fly to the final product can be quite attractive and therefore increase both the market shares for the organization and the general customer satisfaction for the services the manufacturing company offers. The primary characteristics of the use case are given on the table below:

Use Case Name	**UC02 - Last-minute change**
Environment	Car manufacturing production line.
Stimulus	Change request from the customer.
Response	The system should continuously inform the customer for the manufacturing status of the car and the changes that he still might be able to make (e.g. colour). In case a change request is received, the necessary changes to the production schedule must be performed.
Benefits	Increased customer satisfaction Ability to react to market changes

3.2.2 Scenario

Usually, once a car has been ordered in the showroom, its configuration can only be modified before the car production start. In this case, we emphases on configuration changes, for instance, the colour of the car, even after the manufacturing start. To achieve the desired configuration level, the customer should be provided with an interface, where the status of the manufacturing and the currently available options are shown dynamically. For instance, the colour of the body can be modified before the "body in white" chassis arrives in the painting station of the facility. The available resources of raw materials (e.g. colour paints) should also be monitored in ordered to make only feasible modifications available to the customer.

In this case, the crucial processes are:

- The modularization of the product in a configurable way in order to support the on fly reconfiguration, even after the manufacturing start.
- The uninterrupted monitoring of the manufacturing processes.
- An intuitive interface where the customer could access the production data in reference to his order.

3.3 Use case 03 – Real estate flexibility

3.3.1 Main characteristics

The cost of the buildings and real estate assets are one of the highest overheads a manufacturing facility has to overcome. The spatial footprint of a production facility may be sometimes quite extended and not easily adaptable to the dynamically interchangeable production needs and requirements.

Use Case Name	**UC03 - Real estate flexibility**
Environment	Motor manufacturing company
Stimulus	Extension of the warehouse and increase of the production output. Increase the amount of manual assembly work cells.
Response	The rerouting of the AGV transport units.
Benefits	Improved production throughput with a small investment in the real estate assets. Flexibility for the internal logistic processes without significant changes in the equipment. Minimal start-up and commissioning time after the realization of the modification.

3.3.2 Scenario

An expansion of the warehouse facilities led to a necessary rearrangement for the manual assembly work cells. Without any building extension or real estate investment, the warehouse storage location is increased, and the assembly work cells have been relocated to another available space. The material handling system, which is based on AGV units, for the transport of materials between warehouses and assembly lines and consequently from the assembly lines to the logistics shipping units, had only to be retaught for the new routes and destinations.

In case of a transport system based on conveyors lines, the extended medication could have led to an increased level of capital investment, long leading times and production outage.

In this case, the crucial processes are:

- The digitalization of the logistic processes.

- The continuous tracking of the materials and final products before and after the assembly.
- The initial investment on an AGV material handling system.

3.4 Use Case 04 – System maintainability

3.4.1 Main Characteristics

Equipment breakdown during operation or even planned maintenance activities could be quite crucial for production lines, especially for intralogistics facilities with continuous operation. The maintainability of the crucial equipment without any interruption of the operation is the subject of this use case. The primary characteristics of the use case are given on the table below:

Use Case Name	**UC04 - System maintainability**
Environment	Baggage handling system
Stimulus	Required maintenance for baggage transport unit.
Response	The transport unit reaches its maintenance cycle.
Benefits	Uninterrupted operation of the system. Proper and on-time system maintenance based on the manufacturer requirements.

3.4.2 Scenario

A baggage handling system based on an independent carrier system could be a key design element for a reconfigurable and maintainable baggage handling operation, where downtimes and operational outages for maintenance are extremely crucial.

The system consists of several carriage units for the transportation and the sortation of the baggage units, which are running on special maintenance-free fixed rails. Thus, the system can be quite extendable in terms of handling capacity, and the units are easily maintainable without any operation outage. Once the maintenance cycle of the unit is reached, the unit is automatically re-directed to the dedicated maintenance stations, where the operator should perform without any significant time constrain the necessary actions. In comparison with traditional conveyor lines where the larger transport areas should stop for planned maintenance, the independent carriage system could uninterruptedly continue its operation. Another advantage of the system is the possibility to remove a carriage unit out of the railing system in case of a breakdown.

In this case, the crucial processes are:

- The initial investment on an independent carrier system
- The tracking of the carrier units' operational statistics
- A maintenance management system, which can detect premature wear of crucial mechanical and electrical components.

3.5 Use Case 05 – Reduction of production defects

3.5.1 Main characteristics

Product defects during the production operation or even after the introduction of a new product is a common issue each manufacturing system has to overcome. The early detection of defects and the system reconfiguration shall ensure the optimal operation and system performance. Hence, quality control and the reduction of product defects are the main subjects of this use case. The primary characteristics of the use case are given on the table below:

Use Case Name	**UC05 – Reduction of production defects**
Environment	Manufacturing of microcontrollers
Stimulus	Recognition of repeated product defects
Response	The system reports the issue, and the production flow is redirected.
Benefits	Early detection of product defects Non-intrusive quality control Adjusted system operation in case of defect detection

3.5.2 Scenario

The manufacturing of microcontrollers is a very precise and challenging operation. The final product, the microcontrollers, shall be inspected once the primary manufacturing is completed and before the final packaging. The inspection is part of an intelligent computer vision system, which can detect micro-anomalies on the surface of the microcontroller using image recognition and thermal inspection software. In case repeated variations from the desire dimensions and characteristics are detected, the system shall inform the operators and provide or even perform the necessary corrective measurements in the production machinery, e.g. lithographic laser, autonomously.

In this case, the crucial processes are:

- The initial investment on the computer vision quality control system.
- The tracking of the defected products.
- The automatic adjustment of the machinery based on the results of the quality control system.

4 Reconfigurability – Practical examples

In this chapter, several example and cases will be presented, where solutions to achieve system reconfigurability on different levels have been introduced and implemented. The solutions focus on the different fields of production, for instance, assembly, manufacturing and process industry. It shall be stated, that due to low maturity level of the RMS within the context of Industry 4.0, the cases have been collected from the academic community and they refer mostly to test loops and models for the validation of the proposed solutions. The chapter fulfils the second thesis objective **O2**, presenting reconfigurable manufacturing examples.

4.1 Reconfigurability for pallet transport systems

The following use case has been published from the Practical Robotics Institute in Vienna (Munir Merdan, 2019). The solution takes the advantages of the knowledge-based technologies and introduces the automatic configuration of a low-level control layer of a CPS. The solution is applied in a pallet transport system for assembly lines. The system consists of 45 conveyor belts with 32 intersections and six index stations. Each module is represented by a cyber-physical component with reconfiguration and monitoring capabilities.

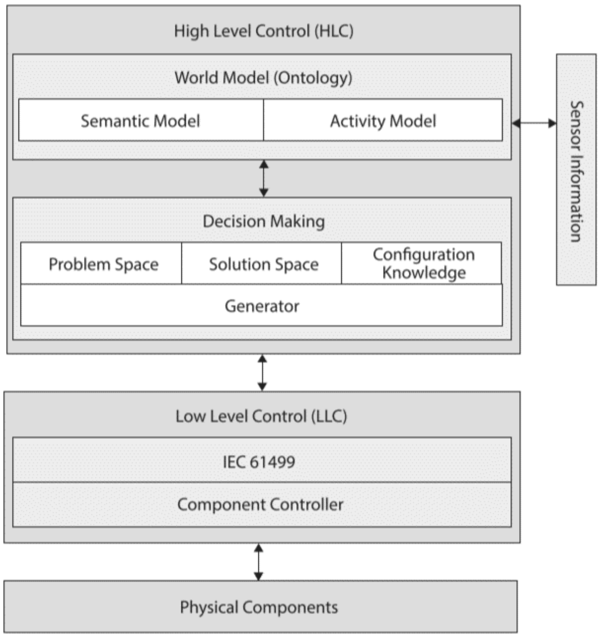

Figure 10: CPS component architecture (Munir Merdan, 2019)

As shown (Figure 10), the system is divided into two main groups. The LLC follows the IEC 61499 architecture, where an ontology and a knowledge-based decision-making mechanism is built in the HLC.

The semantic model contains the information for the component's characteristics and their relationship with each other, while the activity model summarizes the tasks, actions and targets of the components. Finally, the decision making is used for the automatic configuration taking into account the information from the semantic model.

The LLC is designed with two main priorities in mind. The increased reusability of the components and the capability of a dynamic reconfiguration of the components to support the quick adaption to the dynamically changed production requirements. Thus, the IEC 61499 standard is used as more suitable for use in flexible and distributed systems, in comparison with the IEC 61131. The final system is realized based on a library of 11 function blocks. The configuration process is depicted below (Figure 11):

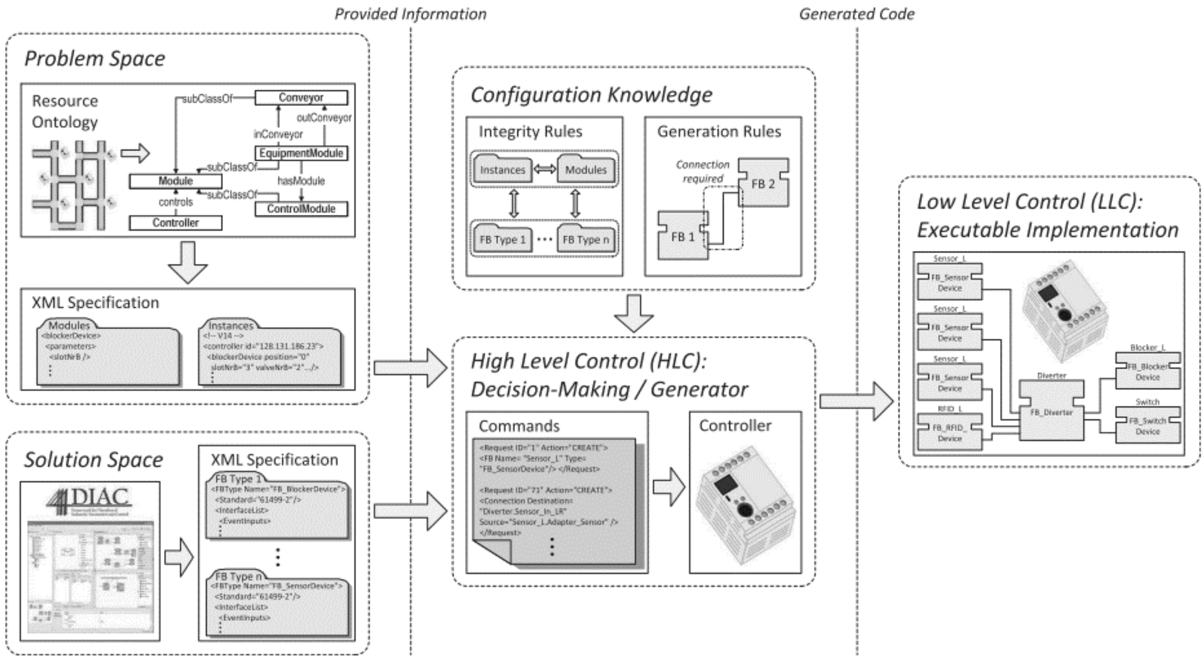

Figure 11: Configuration workflow (Munir Merdan, 2019)

The model-driven approach resulted in quick reconfigurable control software. The reconfiguration relies on the update of the resource ontology, and it can be performed within minutes. However, the physical layout adaption of the pallet transport system required reasonable effort.

4.2 Reconfigurability for oil & gas industry

In the field of oil & gas industry, the reconfigurability can be achieved using distributed software architecture. The proposed solution focuses on converting each field equipment into an intelligent mechatronic component. Thus, an abstract control layer with PLC Software developed based on the IEC 61499 architecture is established. The controllers should communicate with each other (peer-to-peer communication) to utilize the distributed control and intelligence, while centralized control is absent (LUCIAN-SORIN DOBRESCU, 2015).

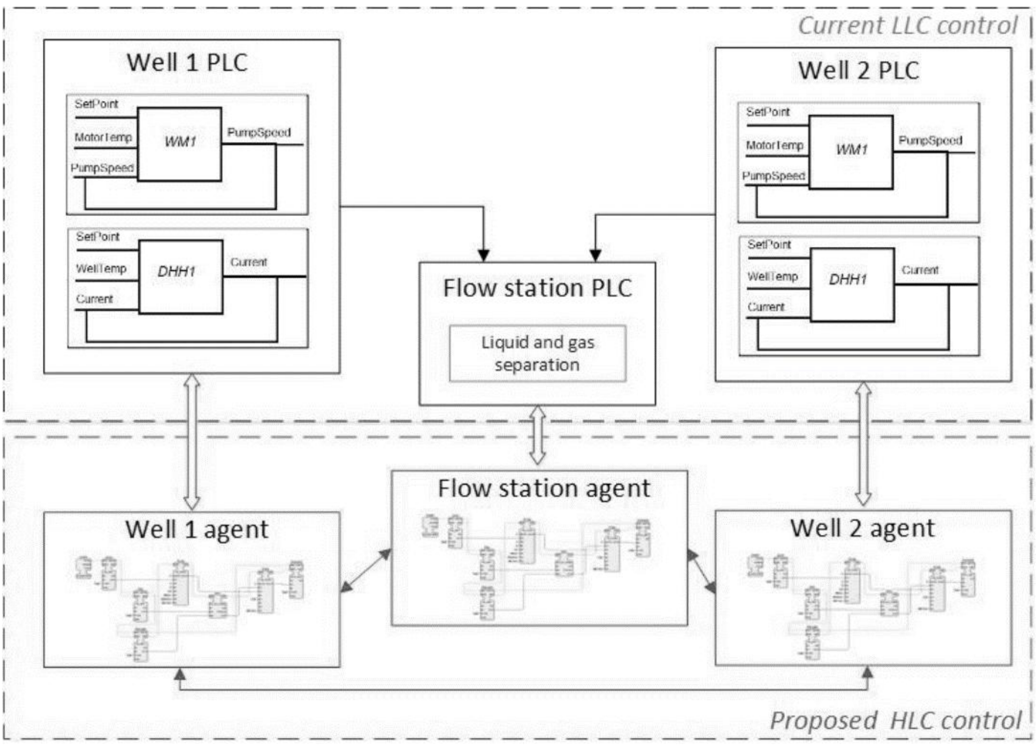

Figure 12: Control strategy – Redesign (LUCIAN-SORIN DOBRESCU, 2015)

The system architecture is based on a MAS framework. It introduces the speciality that the agent-like functionality is mapped directly into the IEC 61499 architecture; generating a synergy not only with MAS but also with SOA The agents establish the inter-component communication, which is necessary for the synchronization of the tasks and the reconfiguration of the control strategy in order to reach the ultimate production performance.

The advantage of the purposed solution is the cost-effectiveness in comparison with classic hierarchical approaches and the by definition interoperability with MAS framework, which makes the integration in general easier. Finally, self-reconfiguration strategies and cloud solutions can be easily defined and combined due to the non-centralized character of the system.

4.3 Reconfigurability for micro-flow production cells

A solution created with an agent-based reconfiguration architecture for a micro-flow production system; in the manufacturing field of the aerospace, metallic engine components is available in the literature (J. Dias, 2017). The solution is developed as part of the PERFoRM[1] project. It targets on an establishment of a flexible environment for manufacturing in the context of Industry 4.0.

[1] Production harmonized Reconfiguration of Flexible Robots and Machinery

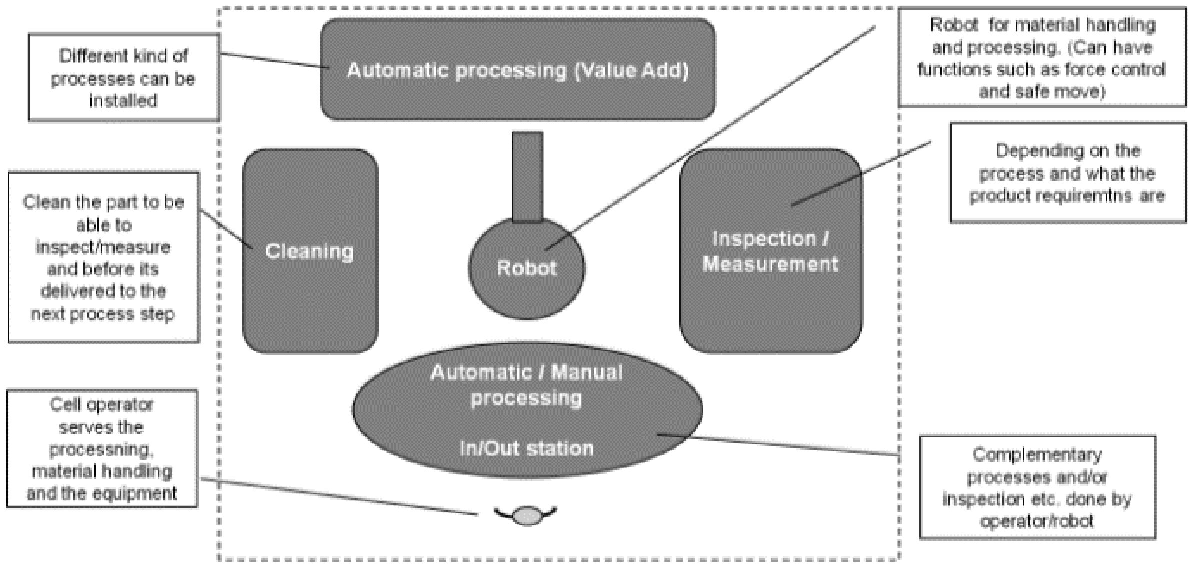

Figure 13: "Micro flow cell"- Principle description (J. Dias, 2017)

The micro-flow cell operation is summarized in Figure 13, and it consists of:

- A computer, which controls the functions within the cell.
- A PLC as a controller for the LLC components included an HMI.
- A robotic system for the handling and processing of parts.
- A safety system for the manufacturing cell.

The concept is that the reconfiguration depends on the production schedule. Once the schedule is defined; the process modules are plugged/ unplugged to complete the work orders as defined in the schedule. The robot program in parallel is being downloaded each time to the robot which operates.

The agent-based reconfiguration tool, as part of the PERFoRM ecosystem, emphases on the re-organization of micro-flow production cell logic, utilizing the dynamic and automatic plug-in and plug-out of the predefined modular processes. The reconfiguration tool is developed following the MAS-based system principles, consisting of two agents. The “Robot Agent” responsible for the management of robot resources and the “Process Agent” for the process modules. The agents need to interact with each other to keep the configuration of the cell updated while the reconfiguration is taking place. The agent's interconnection with their physical counterparts is realized based on the OPC-UA communication standard. As a result, the system flexibility and modularity are increased due to the defined agent functions, specifying in parallel the similarity between the logical and the physical level.

4.4 Reconfigurability based on plug and produce concept

A decision-making approach built on a multi-agent system architecture with the primary goal to achieve system reconfigurability based on task relocation is presented as an innovative plug and produce system (Antzoulatos, 2014). The solution is designed to cover the following requirements and attributes:

Table 1: Design requirements (Antzoulatos, 2014)

Stimulus	Physical or logical plug/unplug of a module
Response	The reconfiguration of the assembly system, meaning the tasks reassignment and the related HMI representations
Stimulus trigger	Cold: Trigger by the operator Hot: Trigger by technical or operational failures
Quality characteristic	The HMI layout is updated within 2sec The reconfiguration of the physical components takes no longer than 15sec

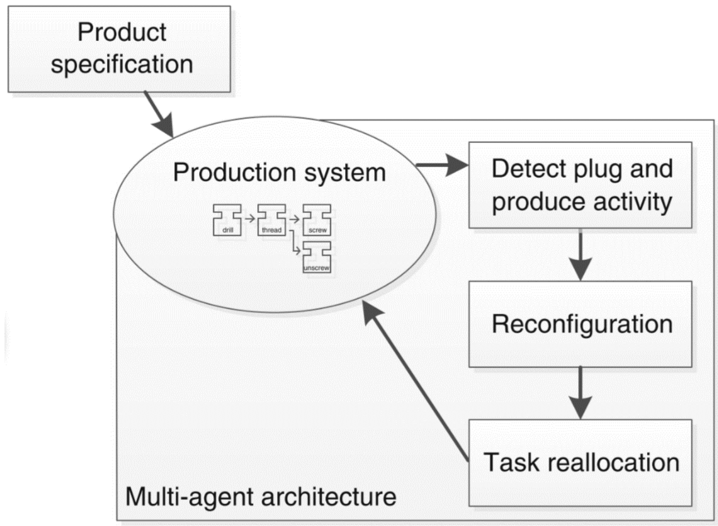

Figure 14:Reconfiguration methodology (Antzoulatos, 2014)

The reconfiguration of the assembly line takes place based on the following steps:

- Step 1: Definition of the set of the product specification.
- Step 2: Product selection on the HMI and trigger of the production start.
- Step 3: Calculation of the ultimate use of the available resources, based on the product specification as defined in Step 1.
- Step 4: Allocation of tasks to the related components and inform the associated agents.
- Step 5: Download of the PLC configurations from a database to the controllers associated with the scheduled tasks.
- Step 6: In case the agent identifies a plug and produce activity, the HMI displays the related message.
- Step 7: Recursion of the steps 3 to 6.

The system architecture includes four agent-based core modules (Production components module, HMI module, monitoring and data analysis module and the plug and produce management module) as shown in Figure 15.

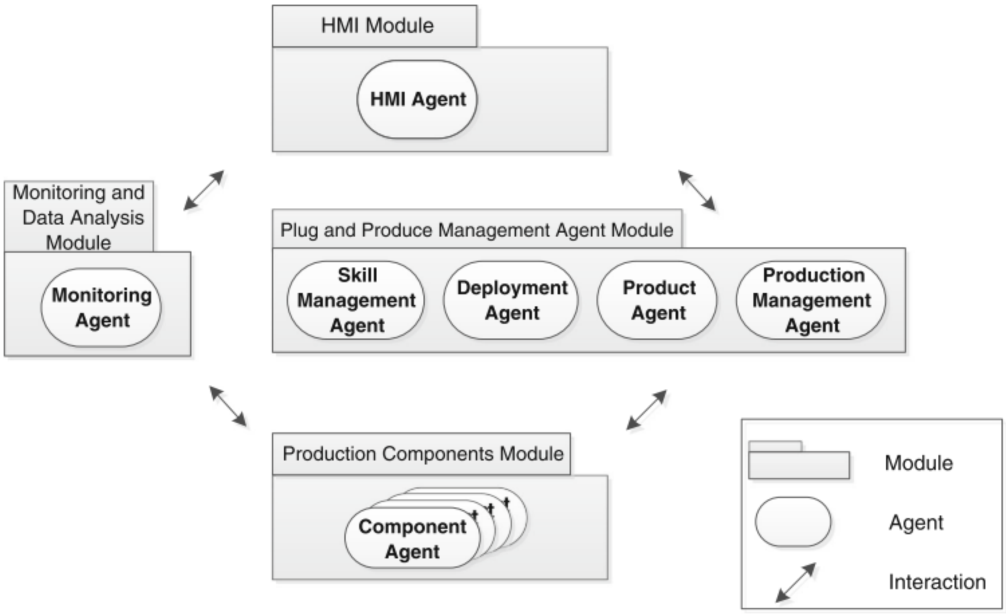

Figure 15:Multi-agent architecture (Antzoulatos, 2014)

For the concept validation, an industrial production system from Feintool Automation has been used. As a result, the reconfigurable multi-agent architecture for the assembly line performs well, and the system was able to detect the available modules and adapt its behaviour accordingly, which the time constants, which have been defined as quality attributes.

4.5 Perform project

The PERFoRM project has been executed as part of the European Program Horizon 2020 and is targeted in the development of an Industry 4.0 compliant system architecture for the effortless reconfiguration of robots and machinery components.

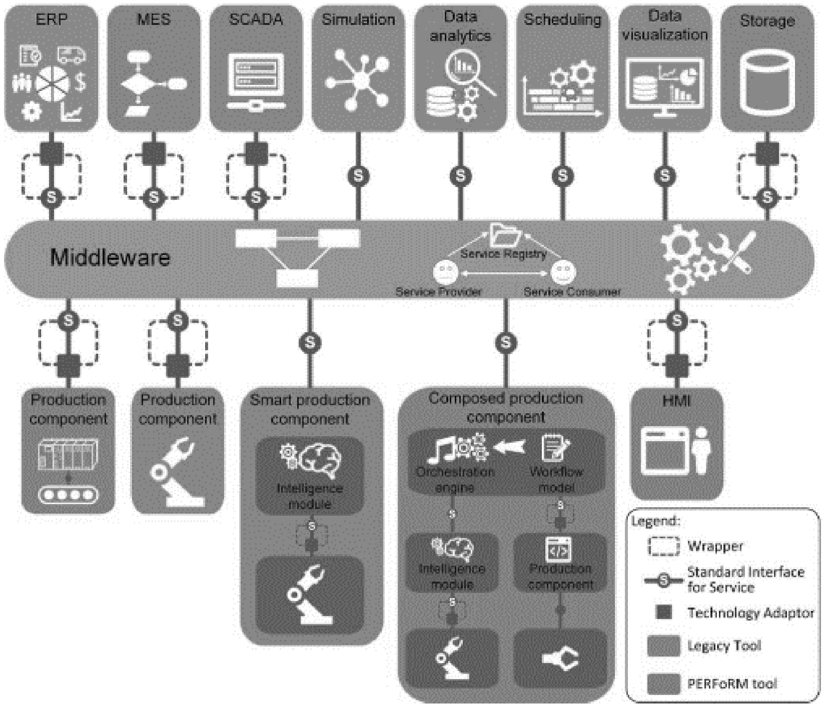

Figure 16: PERFoRM system architecture (J. Dias, 2017)

The architecture is designed to be flexible and open in order to be adapted quickly and cover several manufacturing domains. It is based on the service-oriented architecture principles, where the components are interconnected with each other by using an industrial middleware (Figure 15).

In the literature, several use cases have been described, where the PERFoRM system architecture has been validated (T. Borangiu, 2016).

4.6 Reconfigurability for the healthcare industry

The next example is based on the reconfigurability case proposed for the healthcare industry. The solution targets on accommodating the increased demand for flexible and agile manufacturing processes in the healthcare industry (J. Wan, 2019).

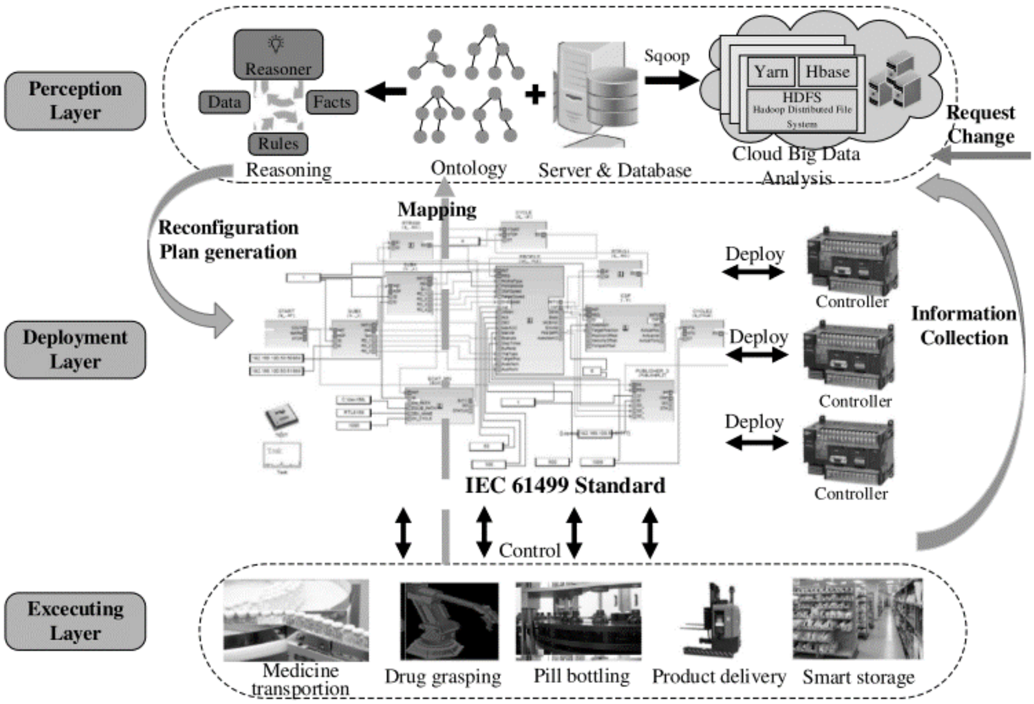

Figure 17: Data-driven reconfiguration for the healthcare industry (J. Wan, 2019)

The system architecture is divided into three discrete layers. The ontology-based knowledgebase HLC components belong to the perception layer. For the current solution, the MANSON ontology is used. It is dedicated to the manufacturing domain, and it was introduced ten years ago. The ontology and the created reconfiguration plans are established on the cloud, where the LLC related function blocks are generated. The reconfiguration plans are based on the production demand and the status of the LLC components. The function blocks are designed based on the IEC 61499 standard, which can support the reconfigurable character of the application.

The case confirms the proposed solution as a valid method for reconfigurable pharmaceutical production.

5 Manufacturing reconfigurability characteristics

In this chapter, an approach to defining the business perspective and benefits of the reconfigurable manufacturing system is depicted. Furthermore, several characteristics of the reconfigurability in the manufacturing systems are given. These characteristics can be grouped into two main categories. The first category focuses on business targets and strategies, while the second covers the technologies and system functions. The characteristics will be used in the next steps to portray a classification matrix, which can be used as an initial scoping method for introducing reconfigurability within a production environment. Based on these essential characteristics the reconfigurability scoping framework is shaped and the third thesis objectives **O3** is fulfilled.

5.1 Definition of business targets

The business targets are taxonomized into three main categories, providing a vision and direction to the organization and the individuals, while at the same time they define the clear targets to be achieved, by using reconfigurable manufacturing approaches. These targets, finally, justify the investment towards reconfigurable solutions.

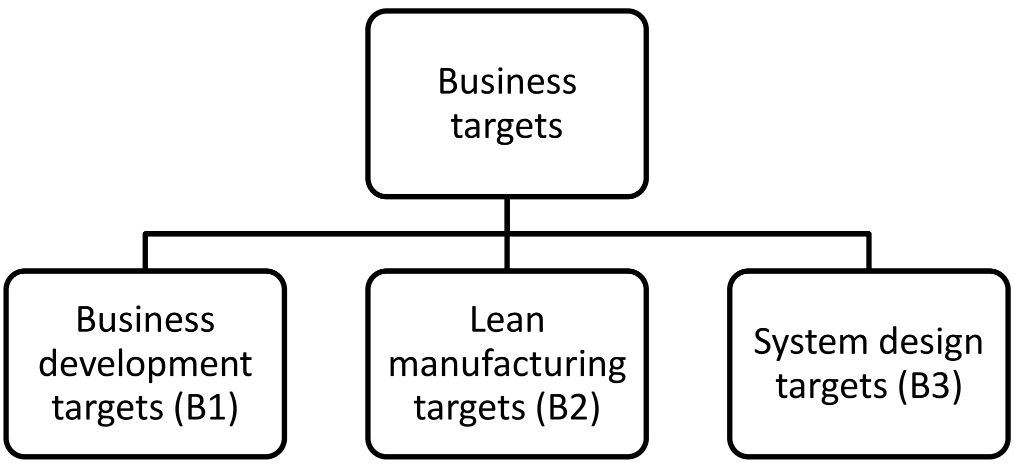

Figure 18: Definition of business targets

The first group includes the targets, which are related to the business development strategies and growth of the organization turnover. These targets can be achieved with systematic penetration to new markets and further development and extension of the current market share.

The second category is focused on the production and manufacturing targets. These include, but are not limited, to lean manufacturing approaches, increased system availability and high quick return of investment of the manufacturing equipment.

The third category is related to the targets, which refer to the manufacturing system design and the initial investment for the construction or refurbishment of the existing manufacturing facilities.

This categorization answers the first research question **R1**, stating the main benefits from the business point of view for applying reconfigurable industrial solutions.

5.1.1 Business development targets

The primary individual goals that could be included in the business development target category are:

- The increased market penetration
- The extension of the product portfolio
- The reduced time to market

By applying reconfigurable manufacturing solutions, market penetration can be increased. This development can be achieved due to the availability of new products that can be quickly produced as a response to new and upcoming markets demands. Alternatively, customer individual and highly customizable products can be offered. This approach could lead to an extended product portfolio and the better placement of the organization against the competition, especially in terms of market shares. Last but not least, the adaptability of the manufacturing system could lead to a reduced time to market not only for individually designed products but also for mass-produced products. Thus, the position of the company in comparison with the completion, as well as customer satisfaction, can be improved.

5.1.2 Lean manufacturing targets

The main specific targets that could be included in the lean manufacturing target category are:

- The increased system availability
- The increased system efficiency
- The increased system usability
- The increased product quality

By applying reconfigurable manufacturing concepts, the overall system availability and performance could be increased. The on-demand reconfiguration of the manufacturing schedule or manufacturing layout could be the driver for increasing the frequency of the preventing maintenance activities without affecting the final production volume and therefore increase the availability of the system indirectly, due to the minimized production outage creating by system failures and malfunctions. Consequently, both the system usability and efficiency would be increased. System usability could also be increased by producing highly customizable products based on specific customer requests. In this case, the organization could beneficially use the manufacturing system during time frames with low demand for the massively produced products. Finally, the product quality could be increased, applying extended quality control techniques by using the manufacturing data and the product tracking mechanisms that are required by a reconfigurable manufacturing system.

5.1.3 System design targets

The system design targets include individual targets related to the system planning, either during the engineering of a new manufacturing facility (greenfield planning) or the engineering of the existing manufacturing facilities refurbishment. These targets can be the following:

- The reduced manufacturing footprint
- The reduced logistics costs

The reduced real estate footprint can be achieved using a reconfigurable manufacturing layout. The reduction could be beneficial due to the lower initial cost of investment. Additionally, it could have a positive impact on the future cost of ownership, which also include environmental related taxes, maintenance facility expenses, among others. The reduction of logistics cost could be achieved by achieving the best synchronization between customer demand and production volume. The reduced production stock and the elimination of the warehousing costs due to not only the better manufacturing planning but also highly customizable products could be feasible by applying reconfigurable manufacturing solutions.

5.2 Definition of manufacturing systems

The manufacturing systems based on the production engineering literature are classified as stated in Figure 19.

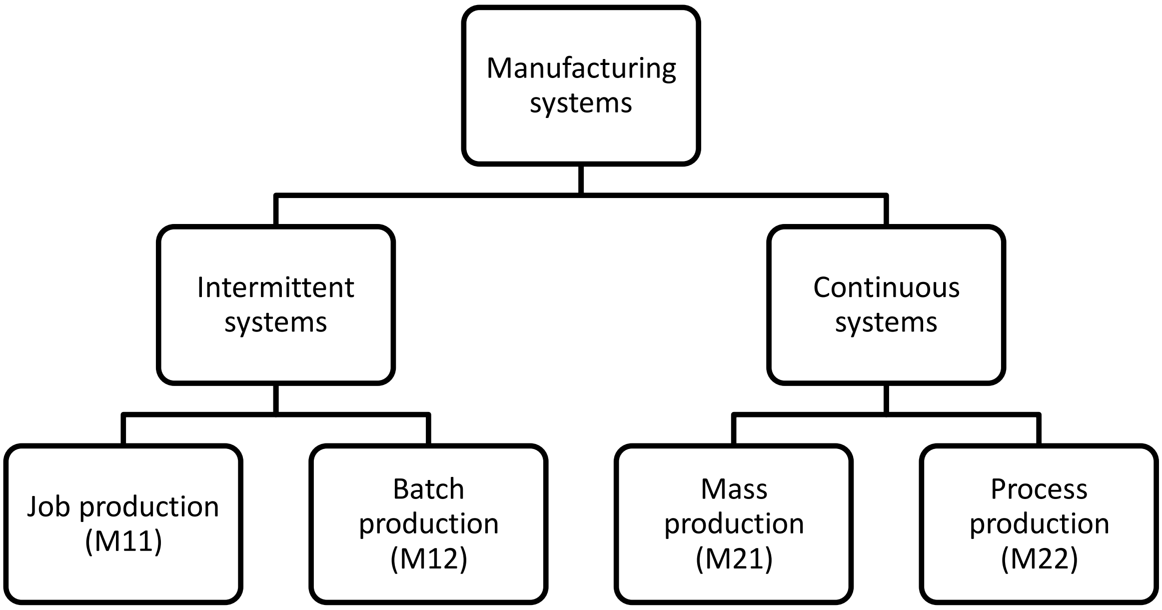

Figure 19: Definition of manufacturing systems

5.2.1 Intermittent manufacturing systems

This system aims to manufacture goods which fulfil customers' orders instead of creating stock. The production facilities are agile; enabling the handling of a wide variety of products and sizes. This system can contribute significantly to product manufacturing with the basic nature of input changes with the change in the design of the product, and the productions process requires continuous adjustments. However, increased size of storage location is required between the operational units to achieve independent and individual operation. The main characteristics of an intermittent system are the followings:

- Most of the products are produced in a small quantity
- Machines and equipment are laid out by the process.
- The workloads are unbalanced.
- Operators with high skills are essential to use the machines and the equipment efficiently.
- The process inventory is extensive.
- It is flexible, allowing to be adapted to production varieties.

The Intermittent system can be further classified as follows:

M11 – Job production: it is the production of a single complete unit by either an operator or a group of operators, i.e. bridge or shipbuilding. In this case, a whole project is considered as operation, and the work finishes on each project before continuing to the next. Each product is a class and requires a separate job for the production process. The system also requires adaptable and highly skilled labour and high capital investment. The control of the operations is also high. The produced products are based on customers' orders. This means that there is not any assurance of continued demand for specific items, and the manufacturing is subject to the receipts of the customers' orders.

M12 – Batch production: in this case, the production of the products is divided into parts or operations. Each operation must be completed before the next one starts making the machine available to another batch of similar production. In this system, many specialized labours can work for each operation but with a relatively lower investment. However, it is essential to point out that both the organization and the planning are more complicated. Another essential characteristic is the irregular work which is added to the raw material. The chemical industry is a typical example of batch production as different medicines are produced in batches. The production schedule may vary based on specific orders or demand predictions. In case of batch production, the items are processed in lots or batches while in job type production, the new batches require all items of a batch to be completed before they start. A job type production could be considered as an extension of the job type systems.

5.2.2 Continuous manufacturing systems

As aforementioned, in the case of intermittent manufacturing system, the items are produced for specific orders. On the contrary, in the continuous systems, the items are produced for stock. For this reason, it is required a sales prediction to plan the manufacture. A master schedule is also required to adjust the sales forecast based on past orders and the level of inventory. In this system, the inputs are standardized while a set of processed or sequence of processes can be standardized through a master production schedule. Necessary manufacturing information and bills of material are recorded. Information for machine load chart, material and personnel need and equipment are be also arranged. Each production runs manufacturers in large lot sizes, and the production process is carried out in predefined operation sequences. Storage is not required allowing to reduce the material handling and transportation facility. It is crucial to follow First in first out (FIFO) priority rules in a continuous manufacturing system. This kind of systems could be categorized as follows:

M21 – Mass production: the main characteristic of this system is the standardization. The items are produced in large quantities without being exclusively depended on customers' orders. The standardization regards both the materials and the machines. Uniform and continuous flow of material are maintained by predefined operation sequences which are required for the product production. It is essential to mention that the system can produce only one type of product at a time. However, nowadays, mass production is mainly used to manufacture sub-assemblies of components of an item. These components are assembled by the enterprise to get the final product.

M22 – Process production: the system is similar to mass production system emphasizing in the production process as the production volume is usually much higher. This method is preferable when the demand is continuous and high such as petroleum products, heavy chemical industries, plastic industries. In these cases, a single raw material can be transformed into various kind of products at various phases of the production process, i.e. crude oil process, gasoline.

5.3 Definition of reconfigurability drivers

The reconfigurability drivers and consequently, the reconfiguration methods can be classified into five main categories (USA Patent No. US 6349237 B1, 2002).

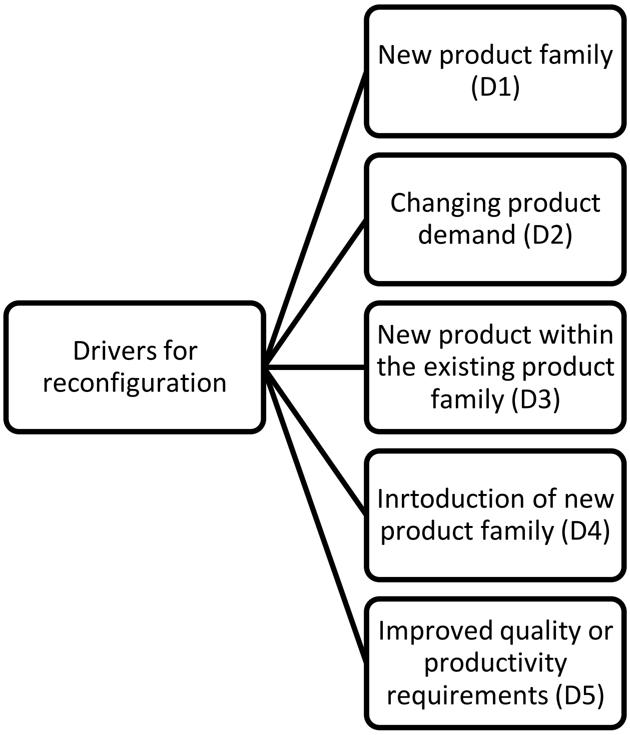

Figure 20: Definition of reconfigurability drivers

D1 – New product family: The introduction of a new product family is considered as the first significant reconfiguration driver. The primary applied method, in this case, is an anew design of a reconfigurable manufacturing system; to cover both the required capacity and the system functionality, which is required for the manufacturing of the new product family.

D2 – Changing product demand: The dynamic character of the product demand and production capacity in comparison with the scheduled production capacity within a specific time frame is defined as the second reconfiguration driver. The reconfiguration method applied for this case; is the adaptation of the production capacity, without any significant modification for the reconfigurable manufacturing system.

D3 – New product within the existing product family: The third driver is defined as the introduction of a new product, which strictly belongs to one of the pre-existing product families. In this case, the functionalities within the manufacturing system should be upgraded by adding removing or modifying manufacturing modules, which are required to realize the production of the new product.

D4 – Introduction of a new product family: The introduction of a new product family is defined as the fourth reconfiguration driver. In this case, modifications in the RMS system are required, but the introduction of a completely new system is avoided. The modifications could be however quite extended, including hardware and software modifications as well as rearrangement of the production cells and machine components.

D5 – Improved quality or productivity characteristics: The last reconfiguration driver is the quality and productivity improvements for an existing reconfigurable manufacturing system. These actions could include changes in the control system, increase the final product quality, elimination of production defects and better overall system performance.

5.4 Definition of reconfigurability levels

The main elements and reconfigurability level of an RMS can be grouped into three main categories: the production control and production system, the plant layout of the manufacturing system and finally the type and the philosophy of the material handling system and equipment (Rahman, 2019).

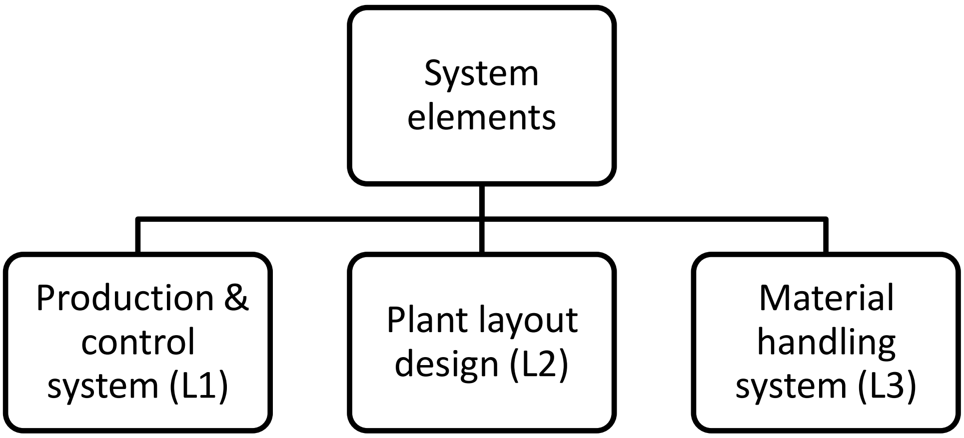

Figure 21: Definition of system elements

5.4.1 Production and control System

The system design is a core element for the RMS design process. The system design involves the designing of RMS at the system level and machine level. Koren et al. presented a systematic design approach of the RMS, which included designing the RMS at the system level. According to the authors, an RMS must be designed each time a new product family is introduced. A crucial requirement for RMS designing is to know the number of machines which are needed to fulfil the product and market requirements (Koren & Shpitalni, Design of Reconfigurable Manufacturing Systems, 2011). The number of machines depends on the daily demand and machine reliability, and it is considered as an input for designing the RMS plant layout system.

The system and the machine should be designed as an independent integral part of a modular entity with characteristics such as scalability and adaptability in order to handle the capacity and functionality changes. Designing a machine for modularity allows modules to be added, removed, rearranged and reutilized. Thus, it influences the scalability, convertibility and customizability of the system, and consequently, it enhances the reconfigurability. Thus, the system design is tailored to the number of machine blocks which are independent of modules, known as base machines, and the number of modules associating each other independently. This characteristic allows the manufacturer to design the RMS system and to adapt it to the capacity changes. These machines can be categorized based on two features, their flexibility and their production rates.

Spicer proposed in his research a deterministic mathematical approach to select the optimal number of module positions on a scalable machine. A scalable machine consists of a single module level, a single module type and an n-module position architecture. The machine structure must be generalized as modular to have a scalable machine architecture. The basic architecture of the modular machine contains three basic parameters:

- **Module-level:** As module-level is defined the number of levels in which the modules can be attached. In Figure 22, two machine tool architecture are presented, a general machine tool (a) and a scalable machine tool (b). In the case of Figure 22a, there are three different levels. The first level contains the modules which are attached to the machine base. The second level contains the modules that are attached to the first level and so forth. The performance of the machine is depended on the number of module levels because it improves the ability of the machine to react to various product types. However, when the level of modules increases, the scalability of the machine decreases. The integrability of the modules affects the scalability of the system simultaneously. For this reason, it is aimed to design machines with a single level.

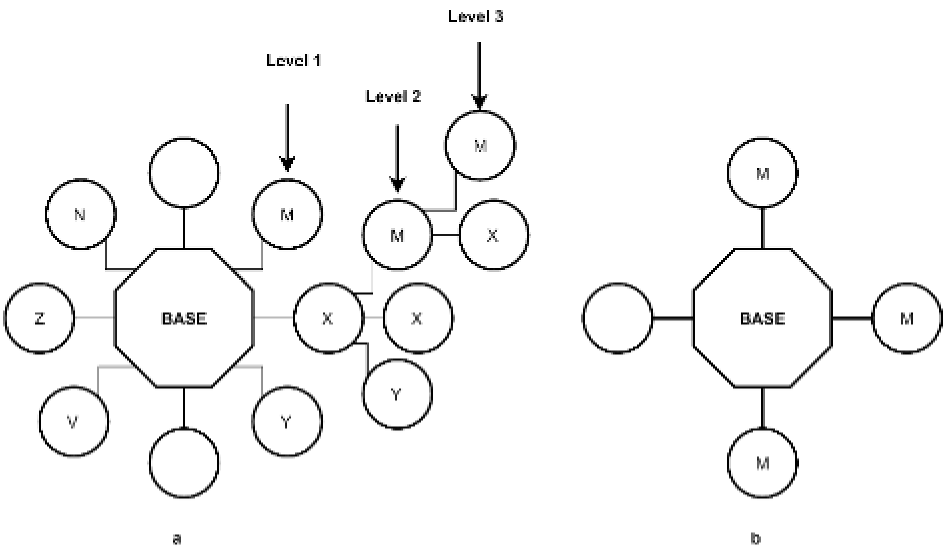

Figure 22: Machine tool architecture (a) General machine tool, (b) Scalable machine tool (Spicer, 2005)

- **Module type:** Module type is the value of the unique module designs for a machine. A manufacturer can put various module types based on the required functionality. By adding more module types, a machine is more probable to reach to different product designs. However, these additions can have an impact on the integrability of the modules and the production rate. For this reason, the manufacturer should select the same type of functioning modules that will diminish the integrability issues and the complexity of reconfiguring the machine obtaining at the same time the required production rate.
- **Module position:** Module position is the most significant parameter which affects the scalability. The proper design will increase the machine production rate and the capability of a machine to scale up the capacity (Maksane, 2019).

5.4.2 Plant layout system

A plant layout, designed for RMS, differs significantly from the traditional, robust and static layouts. In the RMS layout, a cellular configuration is accommodated for a product part family. On the contrary, a traditional layout is designed for various product types. Furthermore, a reconfigurable layout problem also differs from a traditional layout problem as it considers the deterministic material handling and relocation costs as a stochastic operation cost in a dynamic and uncertain environment. The traditional layout considers the current and future planning periods. More precisely, it views the current period, and then it designs the layout aiming to minimize the relocation cost and material flow and inventory costs for the following period. The reconfigurable layout is based on a deterministic product mix for the upcoming planning period when the data is available in contrast with the traditional layout, which is based on future palling period. Reconfigurable layout problem addresses the transition from the current period to the following.

The calculation of the number of RMS configurations is based on the number of the available machines in the system and a simple mathematical method (Koren & Shpitalni, Design of Reconfigurable Manufacturing Systems, 2011). The number of RMS configurations is calculated if the machines are arranged in several production stages. In general, the total number of available configurations augments when the number of machines increases. In case of large production systems, the product is partially produced on one stage, and then it is transferred to another production stage until all the operations have been completed. The machine arrangement in the production stage is a crucial step of designing RMS configuration as every machine can be designed to have a particular module configuration which is required to perform the same set of processes. It is significant to have the correct number of stages based on product functionality and the most appropriate machine arrangement. Designing an RMS configuration in production stages decreases the number of configurations in comparison with the classical configurations.

Consequently, there are no obstacles for the designer. The machine arrangement in the production stages allows calculating the available configurations. The mathematical results are feasible to be arranged in a triangular format which is known as Pascal triangle. The Pascal Triangle is beneficial because it allows the designers to visualize the available configurations for designing reconfigurable manufacturing systems. If the machines are arranged in an exact number of stages, the number of configurations can be minimized.

After the calculation of the number of configurations, a configuration design is required, which meets the manufacturing requirements. Furthermore, the configuration must be seen from both a design aspect and a reconfigurability aspect aiming to encounter future requirements. The configurations can be classified as follows:

- Symmetric Configurations: it is a configuration which resembles symmetricity when drawn a line along the axis of the configuration. Figure 23 depicts the symmetric configuration of five machines which are arranged in various numbers of production stages.

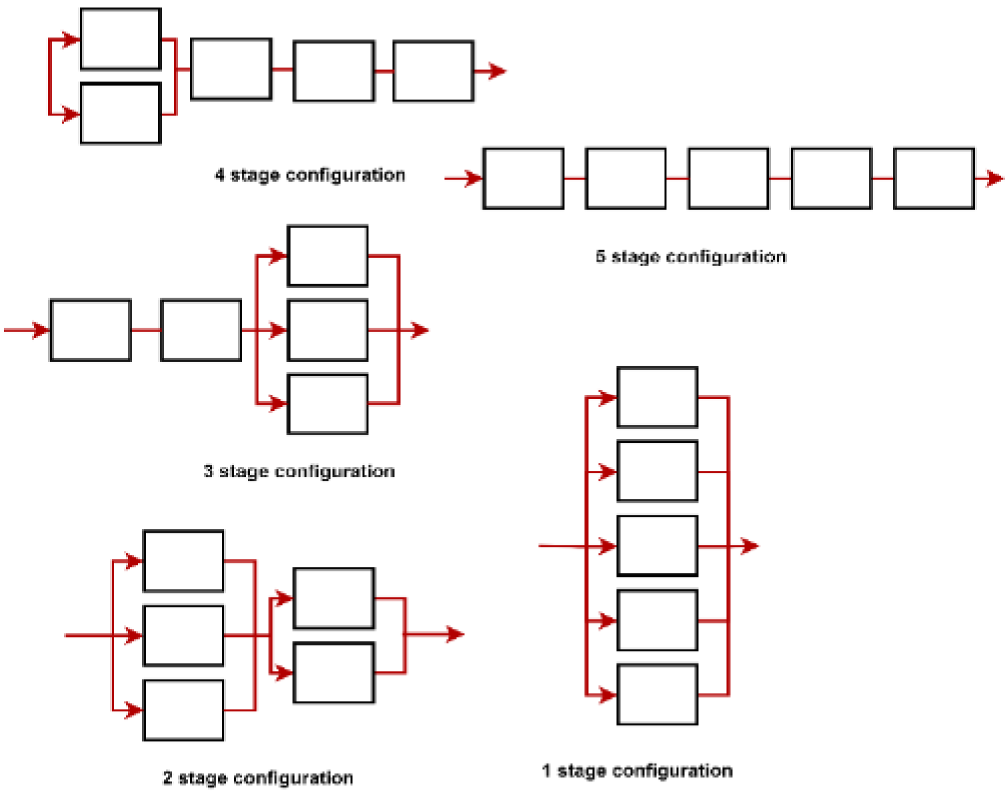

Figure 23: Symmetric configurations (Maksane, 2019)

- Asymmetric Configurations: when drawn a line along the axis of the configuration and the configurations are not the same, there is asymmetric configuration. This kind of configurations is complex configurations because they are situated differently in a real manufacturing environment. Figure 24 presents the asymmetric configurations.

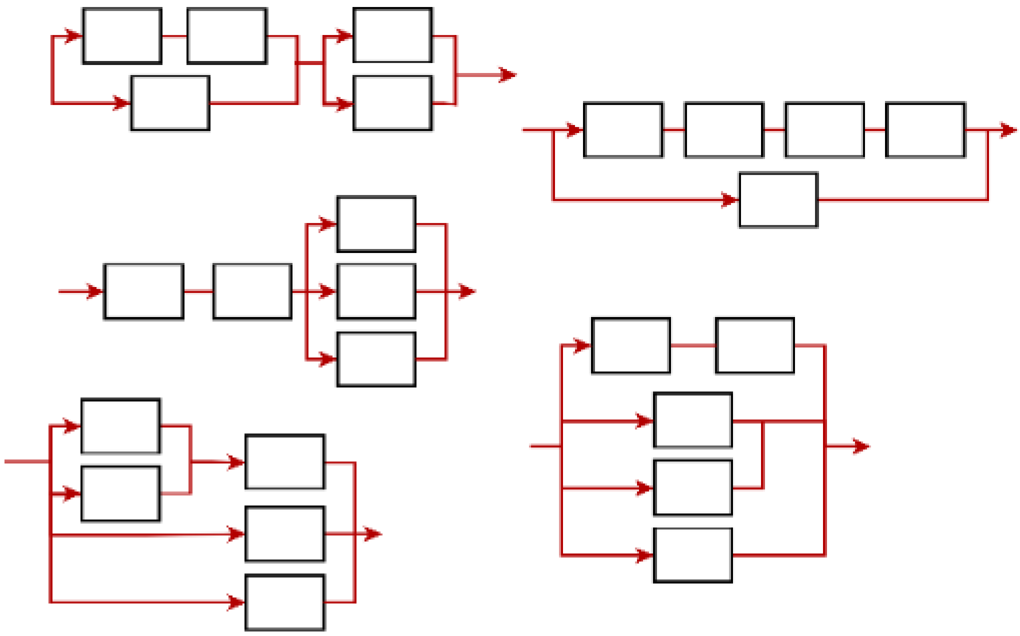

Figure 24: Asymmetric configurations (Maksane, 2019)

The Asymmetric Configurations can be further categorized as follows:

- Viable-process configurations: In these configurations, there are many possible non-identical flow paths to produce a part. The more the number of flow-paths, the more complicated it is for the designer to evaluate the process plans for the same part. In the case of RMS, there are more product types and leads to more complicated flow paths. The reason is that it is impractical to design a multiple process plan for a product or a product family. Furthermore, various process plans and corresponding low paths can degrade the quality of the item making the quality error detection more challenging simultaneously.
- Single process configurations: in this case, the process planning is the same in each flow-path, but the machines differ at least in one stage. Nevertheless, it is not practical to mix different type of machines which perform precisely the same sequence of the tasks in the same production stage as it will lead to complexity increase of the system (Maksane, 2019). Koren and Shpitalni suggest the use of the symmetric configuration, which can be easily adjusted in the system facilitating the ultimate goal of Reconfigurable Systems (Koren & Shpitalni, Design of Reconfigurable Manufacturing Systems, 2011).

5.4.3 Material handling system

The performance of a manufacturing system is influenced not only by the system configuration but also by the material transfer amongst the operations. Every machine in the configuration must be related to the material handling system (MHS). The connection to MHS allows to minimize the work in process (WIP), inventory control costs and improve the performance of the system (Maksane, 2019). The traditional layouts have buffers in the system which have an impact on the WIP and the performance (capacity and throughput) of the system (Freinheit, 2003). Buffers removal can contribute to accomplishing the WIP and performance time, but it will also affect the productivity of the system as in case of a single failure can cause a total system failure. This leads us to the following conclusions: (a) a simple buffer removal is not an adequate strategy and (b) the right type of material handling connectivity of the MHS amongst the machine arrangements is essential.

The machine arrangements in the configuration can be totally dependent on other machines or not. In case of a product which is manufactured on a line blocked because of a failure down-stream then it can be transferred to another parallel line. This method is defined as a crossover. These connections can be categorized as follows (Maksane, 2019):

- Cell configurations (with no crossovers): in this case, the machines are independent of the configurations, and there is no crossover. The configurations can be just some serial manufacturing lines which are arranged in parallel. In case of a machine failure, the other machines stop leading to total line failure.
- RMS configurations (with crossovers): in this case, the machines are arranged in parallels-serial lines with a cross-over type of connection. A cross-over exists when a product manufactured on a line blocked because of a down-stream failure is transferred to another line (Freiheit, 2004). Therefore, the machines in the system are interconnected. If a machine fails, the other machines remain functional, avoiding a total line failure. It is also important to point out that each additional line in parallel with crossover adds productivity which is dependent on the machine availability. This leads to the conclusion that productivity from crossover is increased when the machine availability is lower than when it is higher (Maksane, 2019). The reliability of the MHS must remain high to understand the benefits of parallel systems configurations. The RMS configurations with cross-over connections

have higher productivity rates when there are complex and large systems. However, the RMS layout must be carefully planned as it must be able to adapt the product mix with changing functionality and demand requirements. This means that is must provide equal and efficient travel times for the product families without distorting the routing sequences of the product. Also, the RMS layout design must hold a close and parallel connection with the MHS. In the case of multi-product multi-demand scenarios, the MHS cannot always be available. Thus, there is the prerequisite to designing each MHS layout configuration with a specific rate of flexibility and availability. To sum up, the layout and the MHS must be designed simultaneously (Maksane, 2019).

5.5 Definition of system functions

The system functions define part of the necessary system functionalities a reconfigurability manufacturing system shall offer. The system functions are essential for the success of the use cases, as these are described in the previous chapters. The system functions on the next state will be combined with the required technological feature. Figure 25 shows a proposed summary of the system functions.

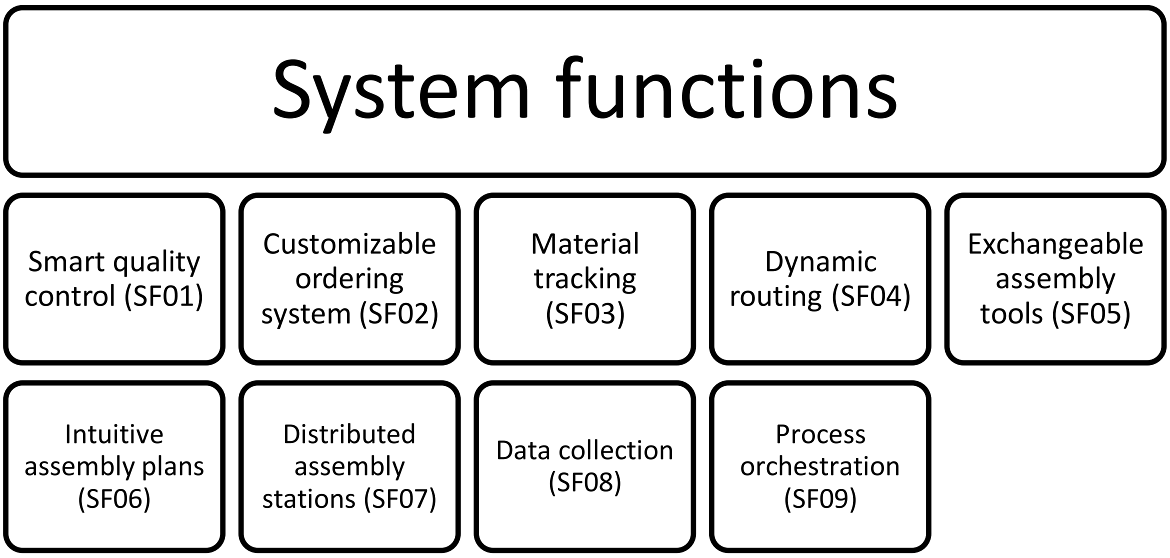

Figure 25: Definition of system functions

The related to the system functions facts are given below:

- **Smart quality control (SF01):** A smart quality control functionality will support the execution of the quality control process for an assembly or manufacturing system. The quality control shall be non-intrusive and take advantage of state of the art methods and technologies, like computer vision and artificial intelligence.
- **Customizable ordering system (SF02):** With a customizable ordering system function, a potential customer will be able to order products based on variable configurations. The assembly and the manufacturing of the product shall be based on modular bill of materials, built upon the same product family.
- **Material tracking (SF03):** Material tracking is an essential function not only for the collection and distribution of the assembly components but also for the of the execution of the logistical processes for the final product.
- **Dynamic routing (SF04):** The dynamic routing, as a core function of the material handling system, supports the implementation of reconfigurable and distributed manufacturing layouts. Furthermore, it endorses the system availability and maintainability, providing alternative material routing in case of unexpected system malfunctions or scheduled maintenance actions.
- **Exchangeable assembly tools (SF05):** The function refers to an integrated feature industrial machinery should have. By quickly exchanging assembly tools, for example, to a robotic arm, a variety of tools can be used. The different tools combined with the pre-loaded software configuration for the robotic arm, may fully utilize the operation and the adjustability of a robotic arm as part of a reconfigurable manufacturing system.
- **Intuitive assembly plans (SF06):** The intuitive assembly plans will support the machinery operators and the assembly personnel, in the case of manually assembly processes, to prevent issues and flatten the learning curve, due to the rapid alternation of the product configurations.
- **Distributed assembly stations (SF07):** A non-centralised manufacturing layout can boost the distribution of system functions and operations towards to a reconfigurable manufacturing system.
- **Data collection (SF08):** A manufacturing system shall operate as a data provider for the higher-level components in the system’s automation hierarchy. Analysing the production

data as well as operational data even for every single element, preventing maintenance actions can be performed, and the overall performance of the manufacturing system can be analyzed.

- **Process orchestration (SF09):** The orchestration of the process is an essential function for every distributed or not manufacturing system. The process orchestration is responsible for the execution of the production schedule, the management of the production resource and the control of the material handling on the production floor.

5.6 Definition of technological features

The technological features list defines a minimal fraction of the required technical characteristics and technologies. These are essential for the proper execution of the system functions, as defined previously and consequently, the successful implementation of the reconfigurability use cases. Figure 26 shows a proposed summary of these technologies.

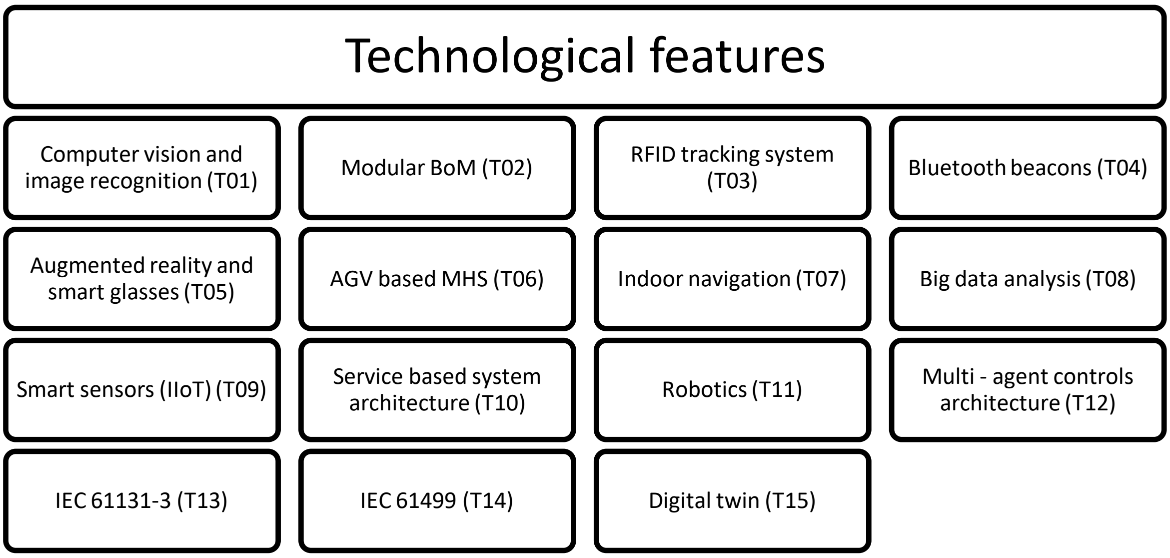

Figure 26: Definition of system technologies

Thus, related details to the technological features are stated below:

- **Computer vision and image recognition (T01):** The use of non-intrusive computer vision techniques and image recognition based quality control system can increase the performance of the manufacturing system and the reduction of the production defects.
- **Modular BoM (T02):** The modularity of the Bill of Materials and the production plans is an essential feature, which supports not only the on-demand and custom based assembly of goods, belonging in the same product family but also the implementation of an intuitive customer ordering system.
- **RFID tracking system (T03):** RFID technology may be used for the tracking of the finished product within the production and logistics facility. The tracking of the product through the production cycle is essential for the majority of the reconfigurability use cases.
- **Bluetooth beacons (T04):** Similarly to the RFID technology, Bluetooth beacon systems can be used for the tracking and the location detection of the assembly parts or finished products, as well as the monitoring of the production resources.
- **Augmented reality and smart glasses (T05):** Augmented reality applications and the use of smart glasses can guide the personnel on the assembly shop floor, providing intuitive instructions and guidance. The feature may be quite critical considering the individuality of products a reconfigurable manufacturing system aims to.
- **AGV based MHS (T06):** Automated guided unmanned vehicles (AGVs) is a technological feature that is transforming rapidly the way the intralogistics systems operate. The flexibility an AGV-based material handling system can offer is unquestionable. In parallel is the main prerequisite for the design and realization of distributed manufacturing systems.
- **Indoor navigation (T07):** An indoor navigation systems in combination with AGV-based material handling systems can support the dynamic routing of the produced goods and the assembly parts utilizing the system performance based on the system availability and production capacity.
- **Big data analysis (T08):** The analysis of the production data may be quite beneficial to increase the manufacturing system flexibility and reconfigurability. This data is provided from smart sensors, “intelligent” automation elements and general production data. Analysing the data, system malfunctions and downtimes can be prevented, while in parallel, the manufacturing system usability and performance can be increased.
- **Smart sensors – Industrial IoT (T09):** The smart sensors category, covers the low-level control components, which can emit more information rather than a binary signal status.

The additional information is provided as input to the main process orchestration components or Big data analysers, where the analysis of it takes place.

- **Service-based architecture (T10) and Multi-agent controls architecture (T12):** As stated in the state of the art review, the existence of a high-level control or Process Orchestration level is an essential component of a reconfigurable and distributed manufacturing system. A service-based or multi-agent controls architecture can differ significantly, based on the implementation environment, but both can support the introduction of the reconfigurability use cases.
- **Robotics (T11):** The use of flexible robotic arms with exchangeable tools increases the system reconfigurability characteristics in comparison with fixed purposed machinery.
- **IEC 61131-3 (T13) and IEC 61499 (T14):** As introduced as part of the state of the art overview, the main drivers for the RMS implementation in the low-level control is the modularization and the on the fly parametrization of the PLC software. Currently, two primary standards are available, the parametrised version of the traditional IEC61131 and the premature IEC61499, which both support the main principles of the RMS.
- **Digital twin (T15):** The implementation of a digital twin is a fundamental part of an Industry 4.0 based system. By introducing a digital twin, the risk of system modifications can be prevented, and the analysis of the system performance and optimization becomes feasible and easily realizable.

By defining the primary type of system functions and technologies, as these are introduced in chapters 5.5 and 5.6, the fourth research question **R4** is answered.

6 Classification of reconfigurability use cases

This chapter focuses on building a connection between the reconfigurability use case scenarios and the scoping characteristics as these have previously defined. The connection is based on a two-dimensional model. The first dimension covers the related to the business targets characteristics, while the second involves system functions and technological characteristics.

6.1 Lot size 01

The realization of a capable manufacturing system, where Lot size 01 production can be applied, requires not only system modifications or a new system design but also the related organizational changes and the necessary support on the business level.

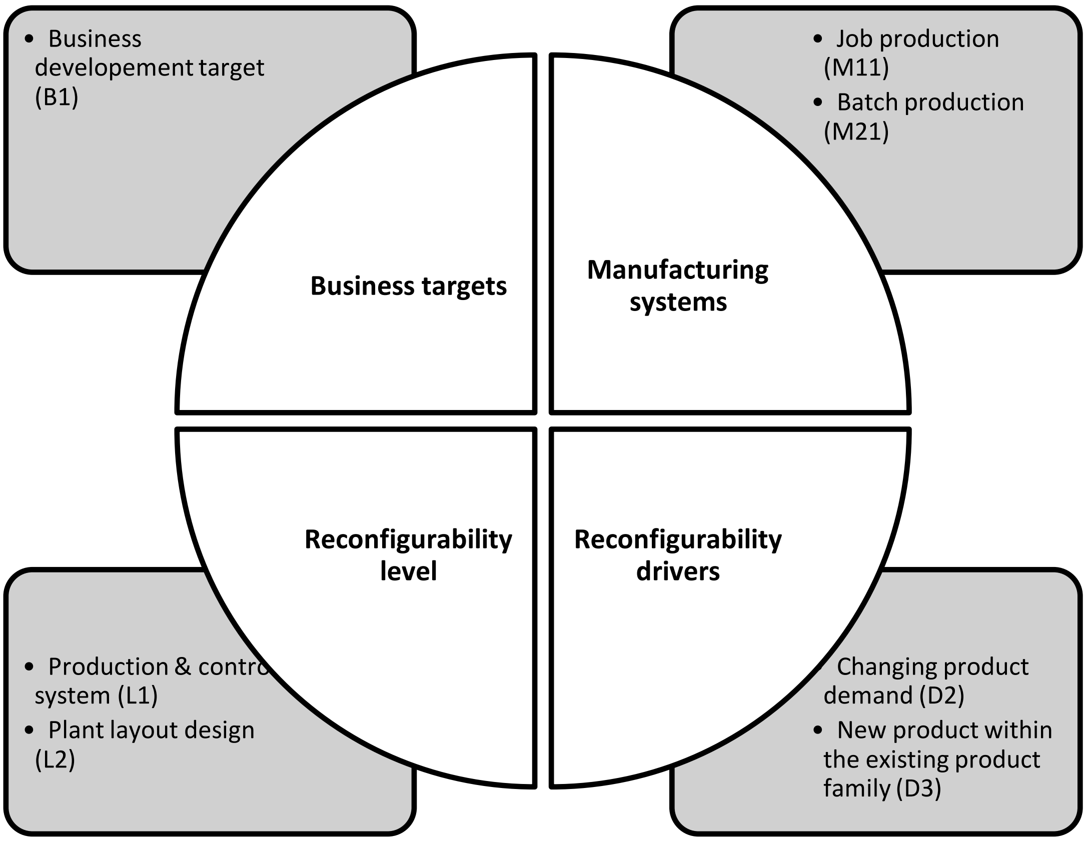

Figure 27: Lot size 01, Business perspective

As shown in Figure 27, as part of the first dimension of the scoping approach, a connection between the different characteristics of this reconfigurability use case is given. The principal business target, which is covered with the Lot size 01 use case is further market penetration and business development. This kind of reconfigurability use case can be applied to job production and batch production manufacturing system. Moreover, the use case is driven by changes in the product demand or the introduction of a new product within an existing product family. Lastly, the implementation of the Lot size 01 use case affects and requires changes to the Production and the control system as well as the layout of the production shop floor.

As part of the second dimension of the scoping approach, the focus is on system functions and the required technologies for the implementation of the functions. An overview is given in Figure 28.

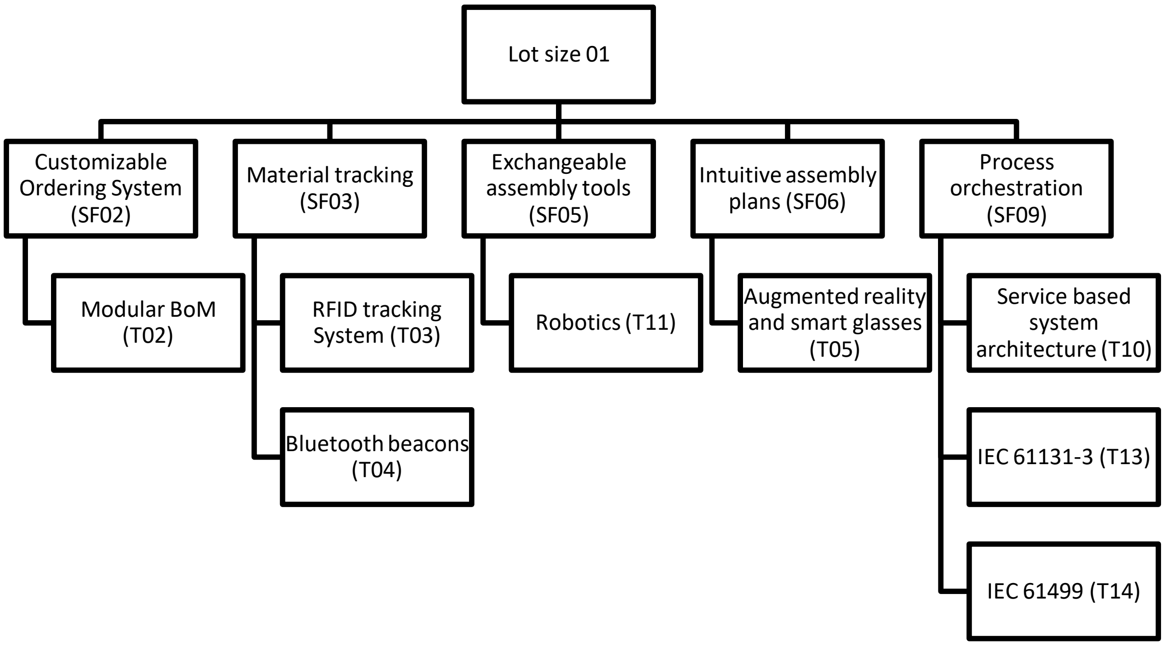

Figure 28: Lot size 01, Functions and technologies

A customizable ordering system, the material tracking, intuitive assembly plans as well as the existence of a process orchestration level are essential functions for the realization of the Lot size 01 reconfigurability use case scenario. These functions are supported by technologies, as an RFID tracking system, modular BoM and service-based system architecture.

6.2 Last-minute changes

The introduction of the Last-minute changes reconfigurability use case into a manufacturing system requires a certain level of modifications and updates on the existing systems or the initial architectural decisions for new systems.

Figure 29 depicts the interconnection between the reconfiguration characteristics and features that are related to this use case. Here the core business target is defined as the further development and increase of market shares, out of the better customer experience and satisfaction. The use case can be feasible for manufacturing systems that follow job production or mass production principles. At the same time, the primary drives can be identified as the introduction of a new product family or the anew design of a manufacturing system for a particular family of products, for instance, a new car model. The production and control system shall be modified and provide the necessary features and function for the successful implementation of the Last-minute changes use case.

In terms of functions and technologies, an overview of the minimum requirement is depicted in Figure 30. For the realization of the Last-minute changes, reconfigurability use case scenario, functions as the customisable ordering system and the comprehensive data collection for the current production status and the available resources are essential. These functions are supported by technologies, as big data analysis and smart sensors. Lastly, the real-time tracking of the product under manufacturing is an essential function for this use case scenario.

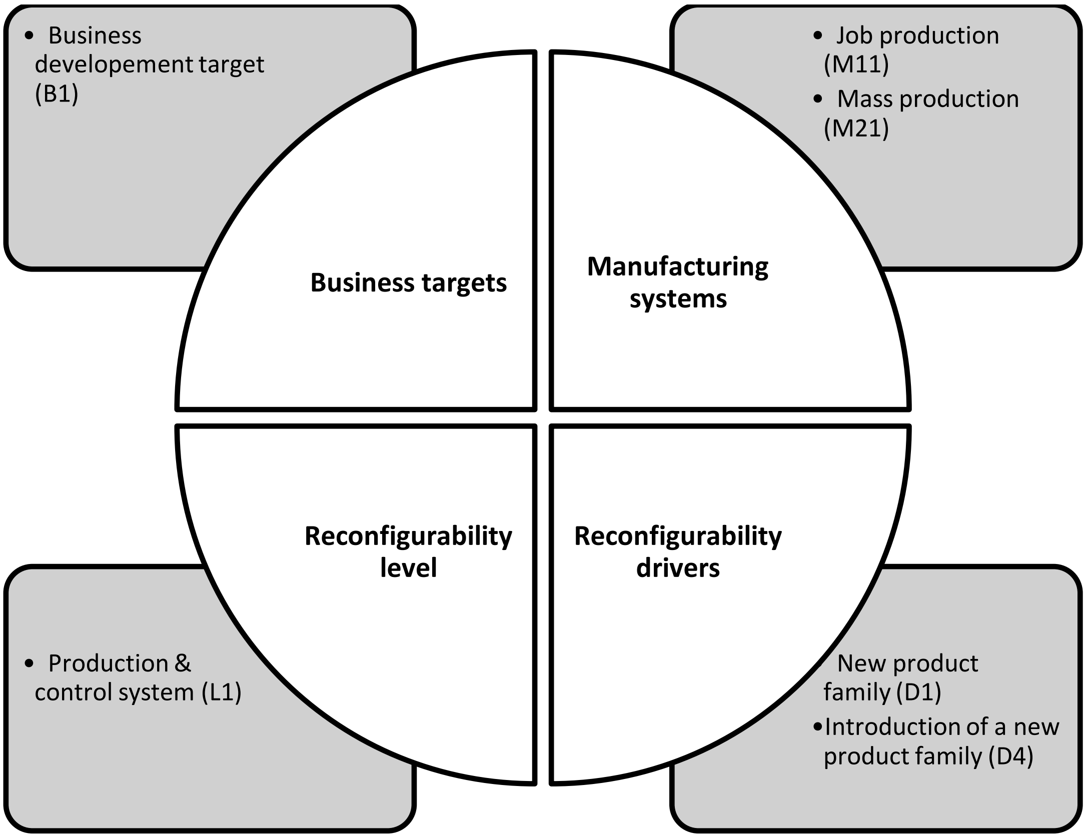

Figure 29: Last-minute changes, Business perspective

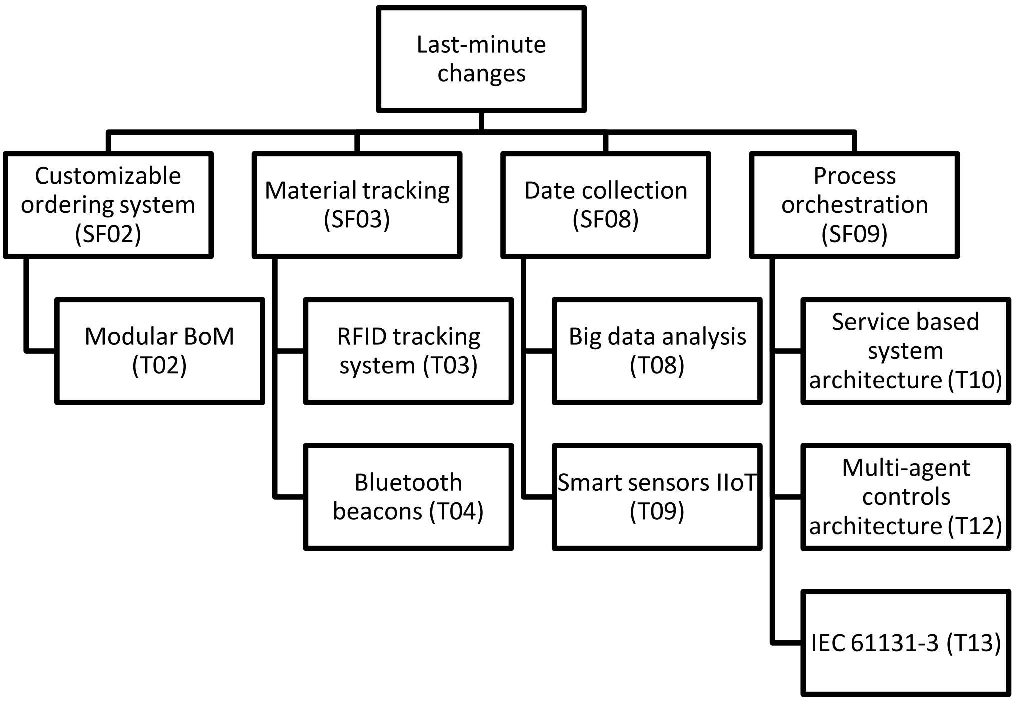

Figure 30: Last-minute changes, Functions and technologies

6.3 Real estate flexibility

The flexibility on the factory real estate level and the optimal use of the manufacturing area footprint is defined as one of the reconfigurability use cases. The main business targets an organization tries to fulfil by introducing this use case is the lean manufacturing and the system design targets, as those have been defined. The use case can be applied to job production batch production and mass production manufacturing systems. The major reconfigurability drivers are the production of a new product family and the improved quality and productivity. Finally, since the use case requires quite extended modifications, it affects the production facility holistically, requiring changes on all three reconfigurability levels, the production and control system, the plant layout and the material handling system.

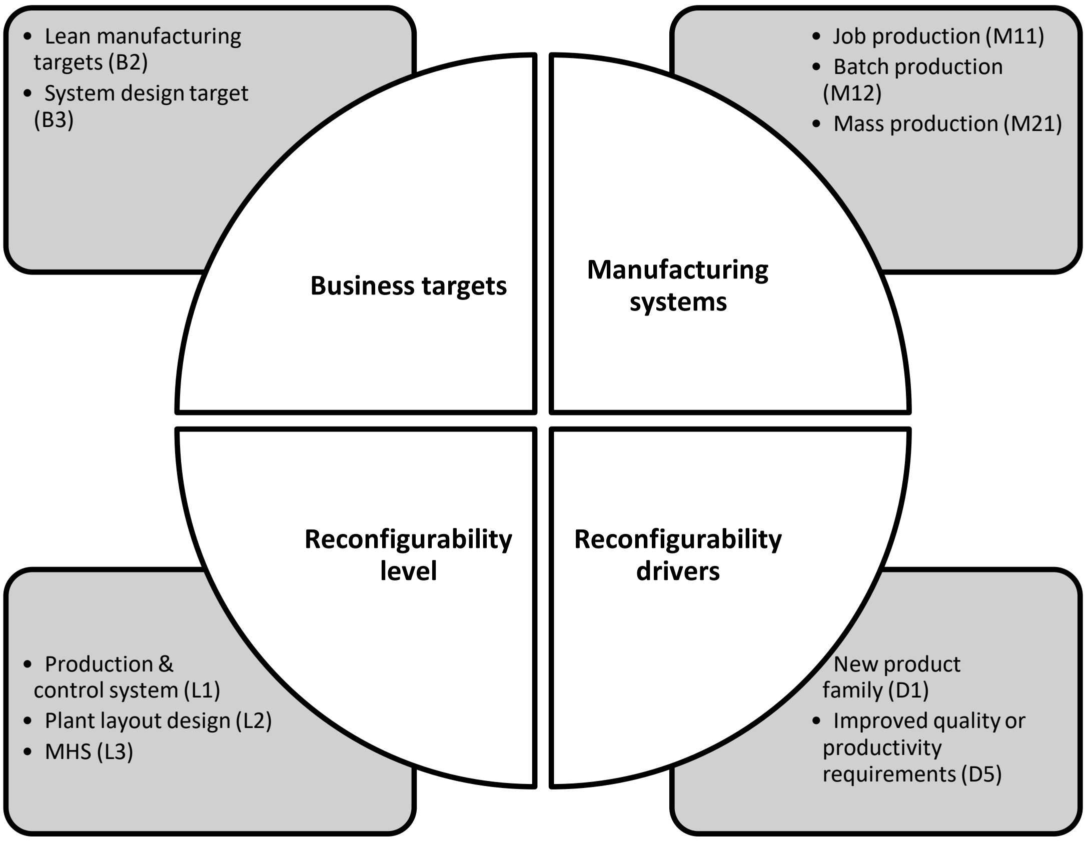

Figure 31:Real estate flexibility, Business perspective

An overview of the second scoping dimension of this reconfigurability use case, in terms of functions and technologies, is shown in Figure 32.

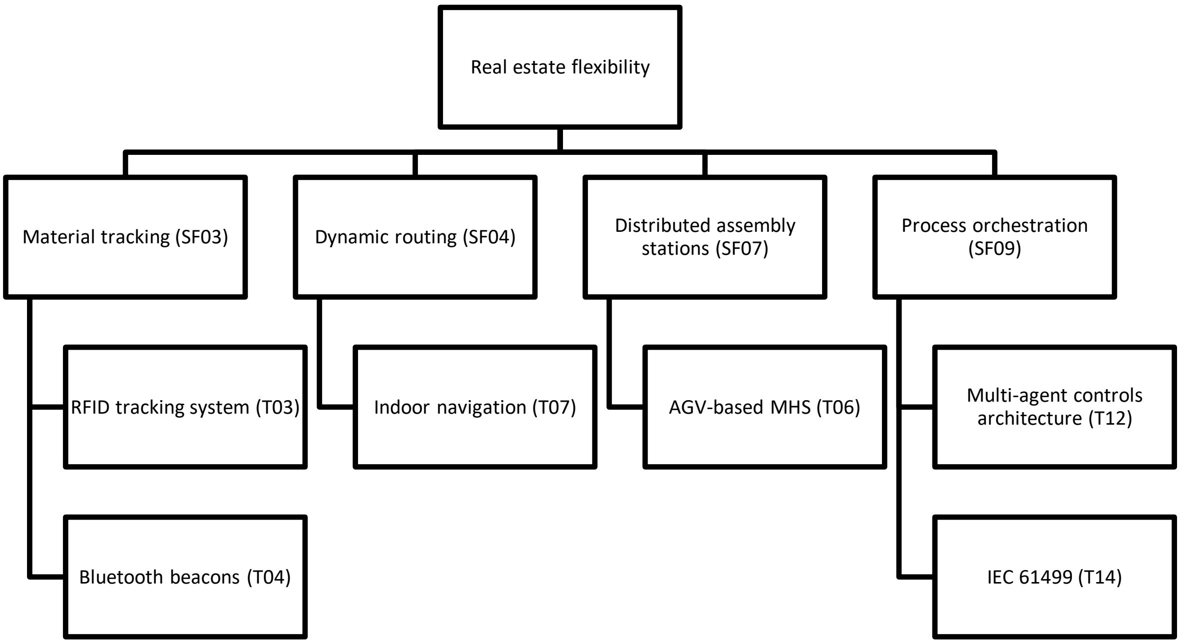

Figure 32: Real estate flexibility, Functions and technologies

For the fulfilment of the real estate flexibility, reconfigurability use case scenario, functions as the dynamic routing and the distributed assembly stations are essential in order to transform a centralized and inflexible and into a dynamic and decentralized one. These functions are supported by technologies, like indoor navigation and AGV-based material handling systems. Lastly, the real-time tracking and position detection of the product is an integral function in this scenario.

6.4 System maintainability

To achieve the ultimate system maintainability, a manufacturing system which can be easily reconfigurable shall be introduced. The introduction of such a use case serves both the lean manufacturing and system design business targets. It can be applied to all four different manufacturing systems, and it can be mainly driven by the need for improved quality and productivity requirements. Lastly, the implementation of such a use case influences not only the plant layout but also it affects the production and control system significantly.

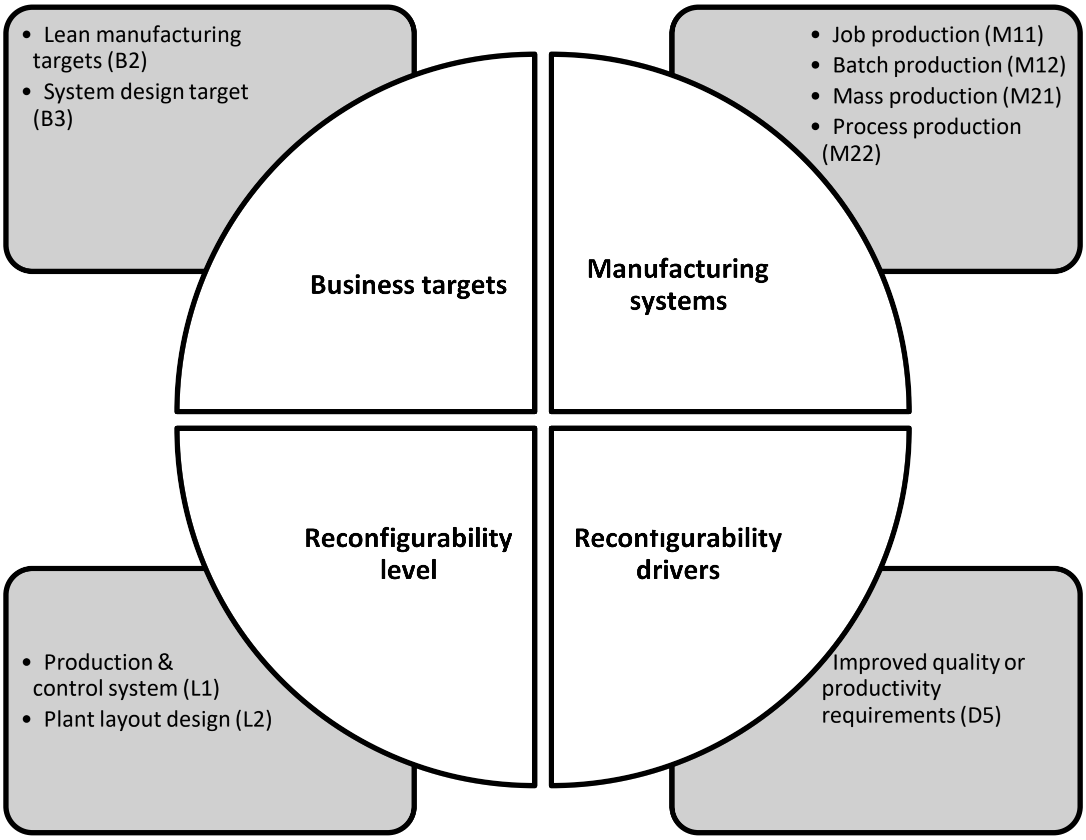

Figure 33: System maintainability, Business perspective

An overview of the second scoping dimension of this reconfigurability use case, in terms of functions and technologies, is shown in Figure 34.

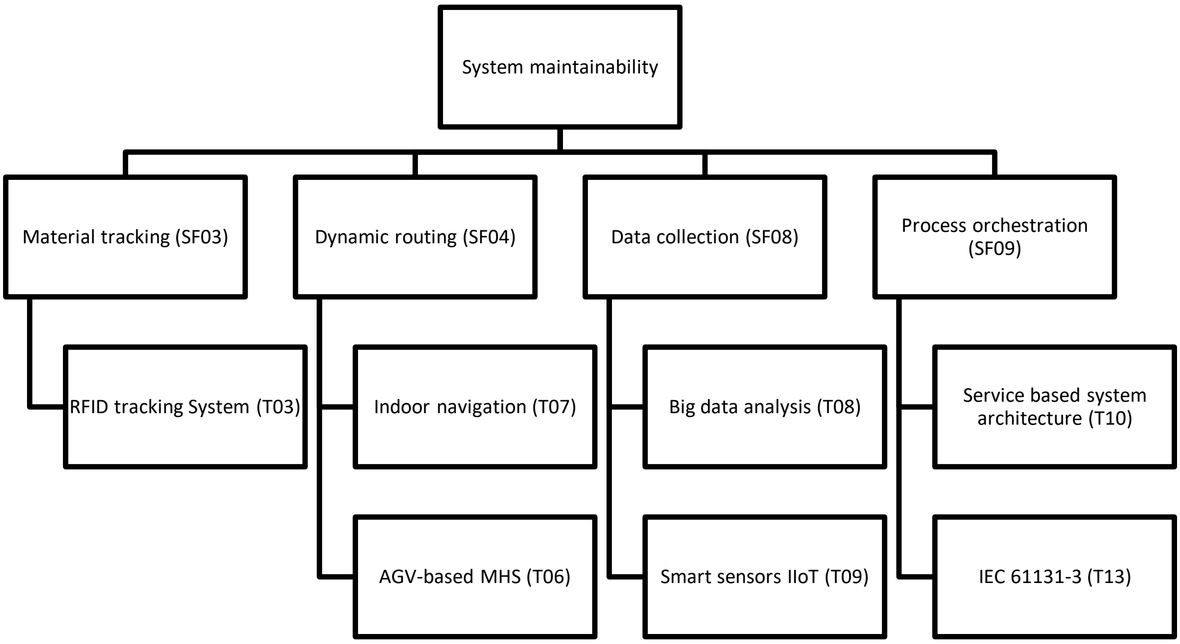

Figure 34: System maintainability, Functions and technologies

The realization of the system maintainability, reconfigurability use case scenario, is built upon functions, as the dynamic routing and data collection. With these functions, the premature malfunction detection and the optimal system reaction in case of breakdowns is optimized.

6.5 Reduction of production defects

Building a system based on the RMS principles may have a positive effect on the reduction of the production defects and the improvement of the plant efficiency. The motivation to implement the use case is the achievement of the business development and lean manufacturing targets. The use case can be applied to all four manufacturing systems, and it mainly introduces changes in the production and control system.

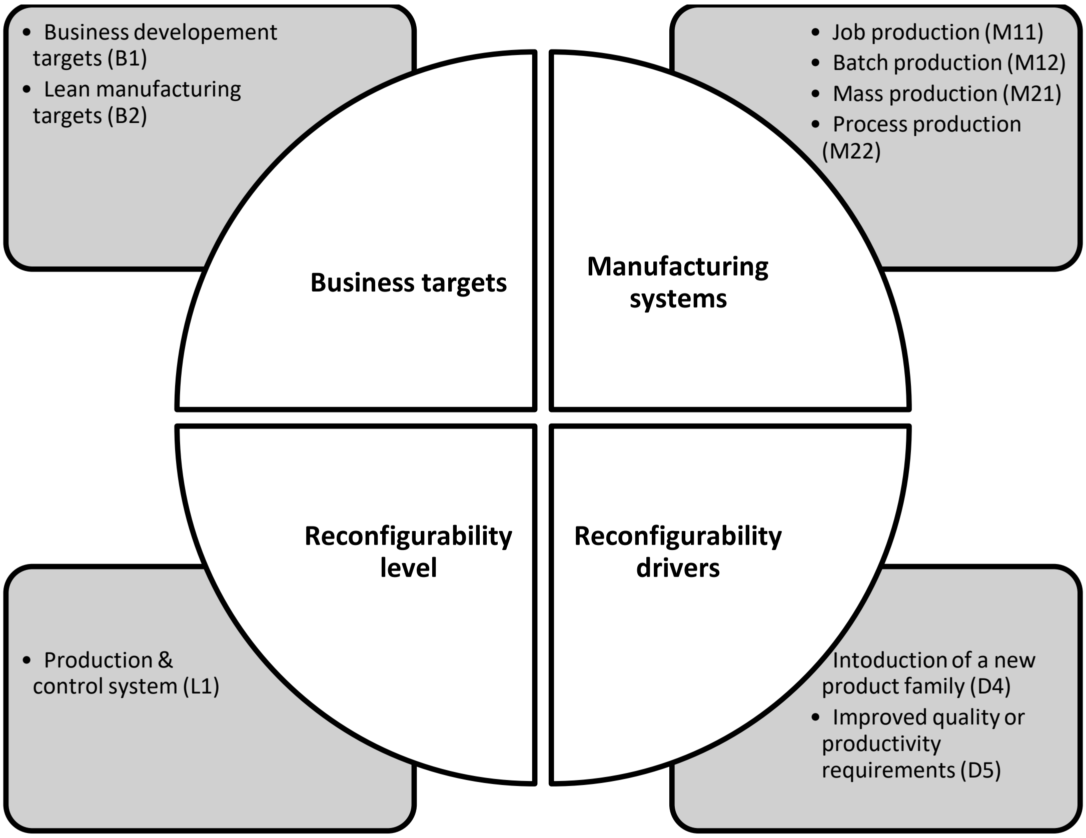

Figure 35: Reduction of production defects, Business perspective

A summary of the required functions and technologies as part of this reconfigurability use case realization is shown in Figure 36.

The primary function introduced with this reconfigurability use case is the smart quality control feature. Using computer vision systems and image recognition technologies the detection of product defects can take place with a non-intrusive and holistic manner. The reconfigurability aspect of this use case is the automatic adjustment of the production parameters in case of repeated detection of defective products. Lastly, in the case of manual assembly working cells, the introduction of technologies, such as augmented reality and smart glasses, could have a significant influence on the defect reduction.

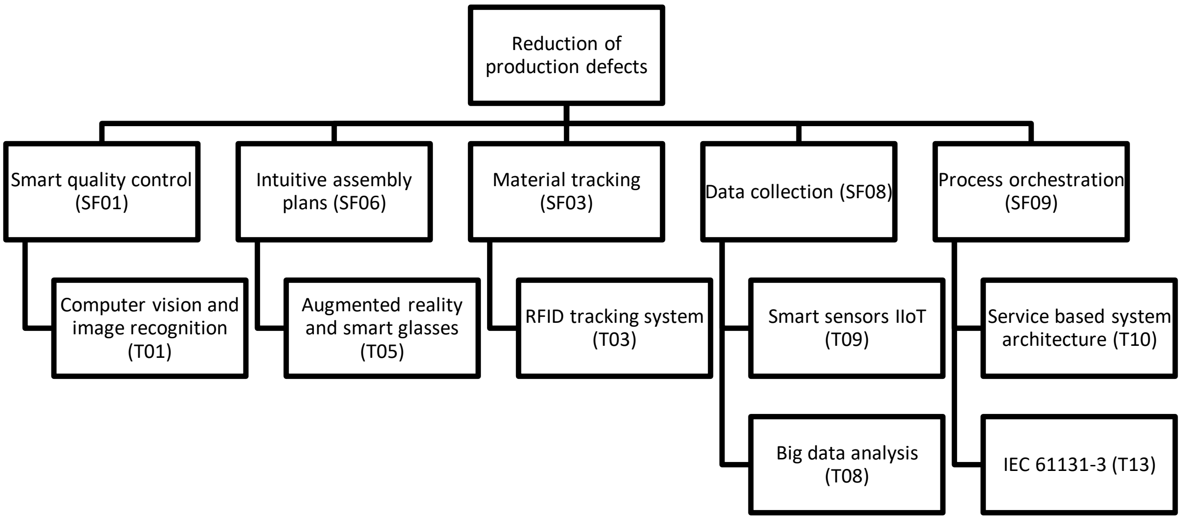

Figure 36: Reduction of production defects, Functions and technologies

7 Scoping process

The objective of this chapter is to provide an overview and a brief comparison between the generalized software product line scoping approach and the proposed scoping method for the reconfigurability in the context of Industry 4.0. The chapter contributes to fulfilling the fourth thesis objective **O4** adapting the traditional software product line engineering scoping approach to support the scoping of Industry 4.0 reconfigurability and answers the third research question **R3** by introducing a reconfigurability scoping method.

7.1 Software product line engineering

The software product line engineering mainly targets on:

- The decision-making mechanisms about the systematic reuse of software products.
- The cost-benefits analysis of the introduction of software product lines.
- The cooperation with all the related stakeholders for the decision making against the introduction of the software product lines.

A unified approach for the software product line scoping process is given in the figure below (LEE, 2010).

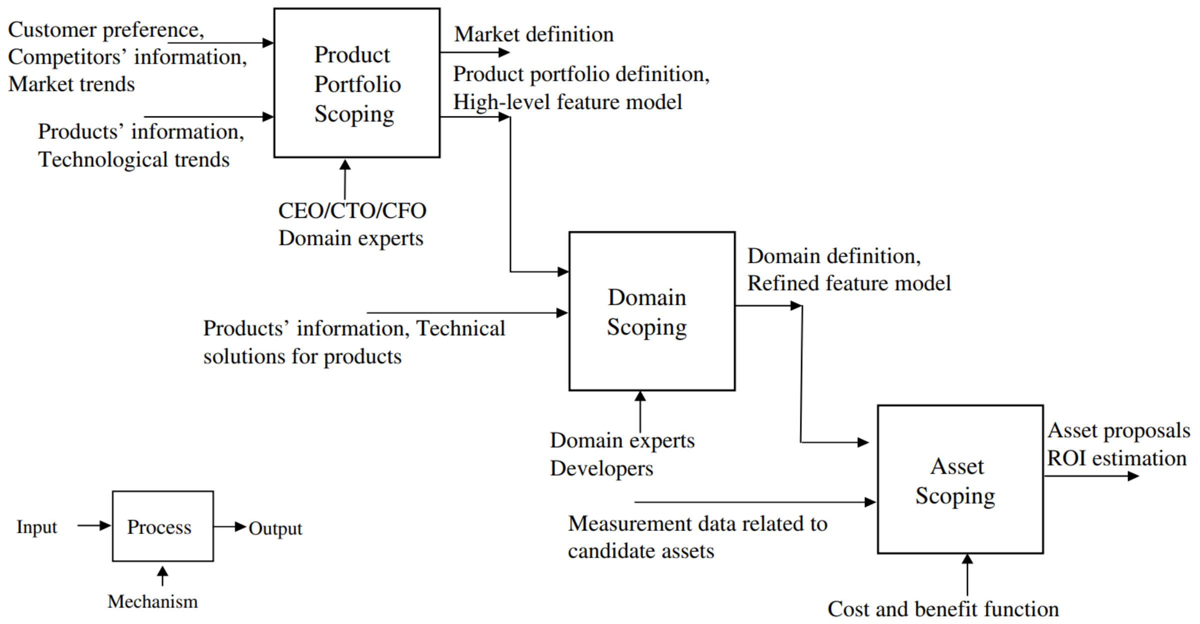

Figure 37: A unified approach for product line scoping (LEE, 2010)

The unified approach divides the scoping process of the software product line engineering into three main subprocesses:

1. **Product portfolio scoping:** It decides the product portfolio definition, which is:
   - the products that must be developed, produced, promoted and sold
   - the standard and variable features which the products must provide to achieve long and short-term business targets of the product line organization
   - a plan to introduce products into the markets
2. **Domain scoping:** It detects and limits the functional areas which are significant for the intended product line, and for the provision of adequate reuse potential to justify the creation of the product line. This kind of scoping method is based on the definitions of the product categories, which are produced by the product portfolio scoping.
3. **Asset scoping:** It defines reusable assets and estimates the cost/benefit based on each asset, aiming to decide if it is plausible for an organization to launch a product line.

7.2 Industrial reconfigurability scoping

The proposed process for scoping the reconfigurability in the field of Industry 4.0, even though it deviates significantly in terms of context, in comparison with the software product line scoping process, it can be based on the similar principle and logic.

The primary process can be divided, similarly, into three main subprocesses, as shown below:

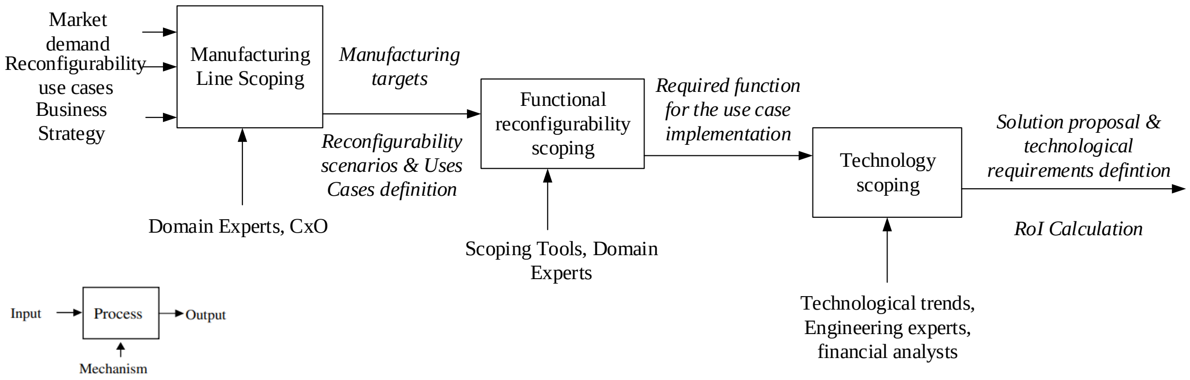

Figure 38: Reconfigurability scoping process

1. **Manufacturing line scoping:** The first sub-process indicates the objectives and the strategy the organization and the manufacturing units would like to achieve. During this step, the production targets and necessary reconfigurability use cases, which must be followed, are defined. Individuals, which represents the business level together with domain experts, shall be involved during the execution of this step.
   Part of this step is the first dimensional scoping, which concentrated on the definition of the business targets, the manufacturing system type, the reconfigurability drives and lastly the reconfigurability level.
2. **Functional reconfigurability scoping:** The following step, departing from the manufacturing line scoping process, focuses on the necessary functions the new or the upgraded production line should include. The introduction of the new functionalities is essential for the successful implementation of the reconfigurability use case scenario.
3. **Technology scoping:** In the last step, the output of the functional reconfigurability scoping sub-process and the definition of the required system functionalities will be used to define

the essential technological system attributes the reconfigurable system shall be equipped. Hence, the optimal introduction of the reconfigurability use case scenario at the shop floor level can be achieved.

8 Conclusions

With Industry 4.0 the management of the production and the manufacturing process is optimized, using technological advanced solutions beneficially, and realizing an autonomous interconnection between the involved machines and systems. An Industry 4.0 compliant production system shall be able to reconfigure itself dynamically based on the production demands, market trends and system availability.

The investment towards the manufacturing reconfigurability is a particularly important and expensive decision for any organization. Thus, scoping methods are becoming constantly essential. A scoping method may support the organization to identify the extent of the reconfigurability the new or updated production system will support; based on the business targets and the required capital spending for the realization of new system functions and technologies.

With this work a scoping method for the reconfigurability withing the context of Industry 4.0 is introduced. The method is based on five basic use case scenarios, as these are identified from industrial references. Additionally, a two-dimensional model of scoping parameters has been developed. The first dimension focuses on the business targets and reconfigurability drivers, while the second dimension concentrates on the system functions and technologies. The combination of the use case scenarios and the scoping parameters creates the framework of the reconfigurability scoping approach. This framework helps the organizations to recognize the required functions and technologies for the realization of each reconfigurability use case scenario, while in parallel defines the business targets such a scenario will fulfill. Finally, a process for the scoping method is established, initiated from the traditional software product line engineering process.

The identification of additional use case scenarios and the execution of case studies in the real world are purposed as the main extensions to this present work. Moreover, dedicated to the different industrial environments scoping methods may be developed, to cover better the special needs of each manufacturing domain.

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