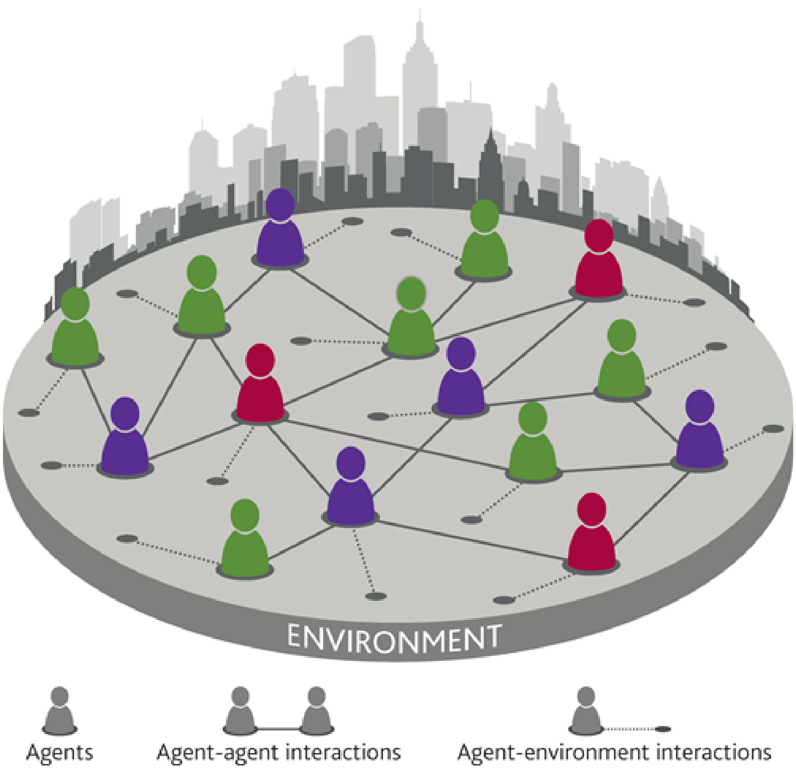
Bachelor Thesis

Analysis and evaluation of multi-agent systems for digital production planning and control



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Number of Thesis:	CS-2021-1
Date:	December 15, 2021

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Kaiserslautern, den 15 Dezember 2021

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Abstract

Industrial manufacturing companies have different IT control functions that can be represented with a so-called hierarchical automation pyramid. While these conventional software systems especially support the mass production with consistent demand, the future project "Industry 4.0" focuses on customer-oriented and adaptable production processes. In order to move from conventional production systems to a factory of the future, the control levels must be redistributed. With the help of cyber-physical production systems, an interoperable architecture must be, implemented which removes the hierarchical connection of the former control levels. The accompanied digitization of industrial companies makes the transition to modular production possible. At the same time, the requirements for production planning and control are increasing, which can be solved with approaches such as multi-agent systems (MASs). These software solutions are autonomous and intelligent objects with a distinct collaborative ability. There are different modeling methods, communication and interaction structures, as well as different development frameworks for these new systems. Since multi-agent systems have not yet been established as an industrial standard due to their high complexity, they are usually only tested in simulations. In this bachelor thesis, a detailed literature review on the topic of MASs in the field of production planning and control is presented. In addition, selected multi-agent approaches are evaluated and compared using specific classification criteria. Moreover, the applicability of using these systems in digital and modular production is assessed.

Kurzfassung

Industrielle Fertigungsbetriebe besitzen unterschiedliche IT-Steuerungsfunktionen, die über eine sogenannte hierarchische Automatisierungspyramide dargestellt werden können. Während diese konventionellen Software-Anwendungen besonders die Massenproduktion mit konsistenter Nachfrage unterstützen, werden im Zukunftsprojekt „Industrie 4.0“ kundenspezifische und anpassbare Produktionsprozesse in den Mittelpunkt gestellt. Um von den herkömmlichen Produktionsanlagen zu einer Fabrik der Zukunft zu gelangen, bedarf es einer Neukonzeption der Steuerungsebenen. Hierbei muss eine interoperable Architektur mit Hilfe von Cyber-Physischen Produktionssystemen durchgesetzt werden, die die hierarchische Verknüpfung ehemaliger Steuerungsebenen aufhebt. Die damit einhergehende Digitalisierung von Unternehmen ermöglicht den Übergang hin zur modularen Produktion. Gleichzeitig steigen die Anforderungen an Produktionsplanung und -steuerung, die mit Ansätzen wie Multi-Agenten Systemen (MAS) gelöst werden können. Diese neuartigen Softwarelösungen sind autonome und intelligente Objekte mit einer ausgeprägten kollaborativen Fähigkeit. Für diese neuen Methoden existieren unterschiedliche Modellierungsmethoden, Kommunikations- und Interaktionsstrukturen, sowie unterschiedliche Entwicklungsframeworks. Da sich Multi-Agenten Systeme wegen ihre hohe Komplexität noch nicht als Industriestandard durchgesetzt haben, werden sie meist nur in Simulationen getestet. In dieser Bachelorarbeit wird eine ausführliche Literaturrecherche zum Thema MAS im Bereich der Produktionsplanung und -steuerung vorgestellt. Außerdem werden mit spezifisch ausgearbeiteten Kriterien ausgewählte Multi-Agenten Ansätze bewertet und miteinander verglichen. Darüber hinaus wird die Möglichkeit des Einsatzes dieser innovativen Technologien in der digitalen und modularen Produktion beurteilt.

List of Abbreviations

ACL Agent Communication Language

AOP Agent-Oriented Programming Language

AUML Agent Unified Language

CNET Contract Net Protocol

CIM Computer Integrated Manufacturing

CPPS Cyber-Physical Production System

CAN Controller Area Network

DAI Distributed Artificial Intelligence

DPWS Device Profile for Web Services

DML Dedicated Manufacturing Line

ERP Enterprise Resource Planning

FIPA Foundation for Intelligent Physical Agents

IFAC International Federation of Automatic Control

KIF Knowledge Interchange Format

KQML Knowledge Query Manipulation Language

MES Manufacturing Execution System

MAS Multi-Agent System

MPS Master Production Scheduling

MRP Material Requirements Planning

PLC Programmable Logic Controller

PPC Production Planning and Control

REST Representational State Transfer

TC IES Technical Committee on Industrial Agents

SCADA Supervisory Control and Data Acquisition

SOA Service-Oriented Architecture

OPC-UA OPC Unified Architecture

OWL Web Ontology Language

VDI/VDE Verein Deutscher Ingenieure/Verein Deutscher Elektrotechniker

XML Extensible Markup Language

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1 Introduction

1.1 Motivation

The process of globalisation is a central aspect of today's society. The interdependency of social and technological areas makes it possible to have worldwide access to various products. This increases the market competition. Therefore, industrial companies need to focus on customer-oriented and flexible production in order to be able to defend their place in the industry. In addition to globalisation, advanced technological developments and digitalisation are crucial in today's world. This process is also referred as "Industry 4.0". The use of multi-agent systems (MASs) can support production planning and control in industrial enterprises in order to make a factory of the future possible. A MAS consists of several autonomous agents. These agents have to communicate and coordinate in order to reach a global goal. Agent-based systems can be located in the field of artificial intelligence and have major advantages. They can adapt quickly to new customer demands and are robust in sudden changes. However, the transition towards agent-based manufacturing systems is very complex, because this transition requires a massive financial investment in new software and hardware. Therefore, MAS are mostly tested and evaluated in simulators. Only a few real-life scenarios have been applied so far, such as the MAS approach by [Karn08]. This system was demonstrated on the customised assembly system called Prodatec/FlexLink DAS 30 demonstrator (Figure 1.1). This flexible production system is controlled by a MAS to transport pallets between two workstations.

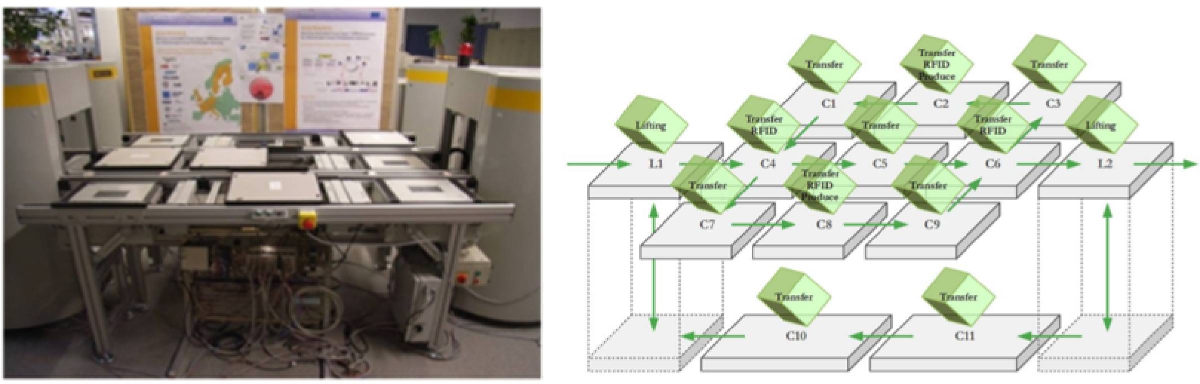

Figure 1.1: Prodatec/FlexLink DAS 30 MAS demonstrator at the Schneider Electric Automation GmbH [Colo15]

1.2 General Objectives

In this thesis, different MAS approaches for production planning and control will be analysed and evaluated. A selection of fitting approaches must be made to limit the amount of proposals. Several classification criteria have to be proposed in order to evaluate and compare different agent-based systems in detail. Moreover, the applicability of the selected MAS approaches in the context of digital and modular production will be discussed.

This bachelor thesis is divided into four chapters. In chapter 2, the state of the art of MASs is discussed. This includes the transformation from the traditional industry 3.0 autonomous pyramid towards an interoperable architecture to make industry 4.0 possible. MASs can be applied in both worlds to provide an autonomous and intelligent production planning and control feature. Therefore, different MAS architectural models, communication and interaction protocols and as well as different development frameworks are introduced. In chapter 3, a detailed literature review and evaluation of selected agent-based systems in the context of production planning and control is presented. Furthermore, the applicability of these MAS in digital and modular production is discussed. In chapter 4, a summary of the thesis' results is given, as well as the challenges that will need to be dealt with in the future.

2 Foundations of multi-agent systems

The concept of industry 4.0 has only been the center of attention for a few years. This term indicates that the industry has already gone through four industrial revolutions. At the end of the 18th century, the first mechanical enterprises came into being. Technical innovations, such as steam power and weaving looms, dominated the industry until the first revolutions' lifespan reached its limit. With the emergence of assembly lines, the era of the second industrial revolution had begun. Mass production and electric energy changed the industrial area significantly. The third revolution began in the 1970s and is the dominating industry to this day. Information technologies, such as computers, and advanced electronics enable the industry 3.0 to achieve a certain level of automation. The transition towards the fourth industrial revolution is still in progress. The industry 4.0 focuses on digitalisation with the Internet of Things (IoT), which can be realised via cyber-physical systems. In Figure 2.1, a graphic representation of the four industrial revolutions can be found. [KARA20]

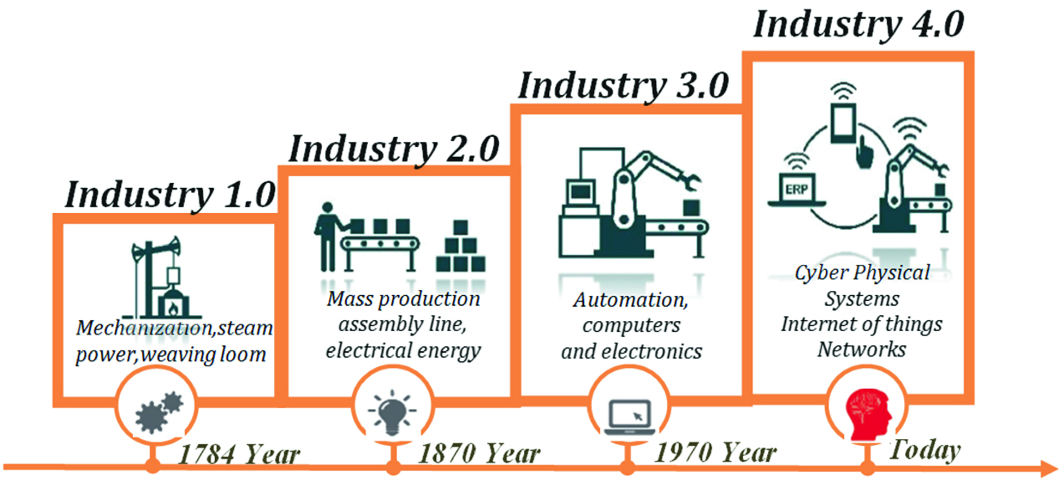

Figure 2.1: The four industrial revolutions [KARA20]

In this section, the transition from industry 3.0 towards a digital production in industry 4.0 is examined. The automation organisation has to shift towards an interoperable architecture in order to end the third industrial revolution. To enable the technical implementation of a factory of the future, agent-based systems are applied to provide autonomous and intelligent features. The functionality of multi-agent systems (MASs) for production planning and control is set in focus. Moreover, the MAS concepts, such as agent organisations, communication and interaction protocols, as well as frameworks and simulation environments, are discussed.

2.1 State of the Art: applying multi-agent systems in industrial manufacturing

Today's factories are mostly designed to manufacture homogeneous and high-quality products. These types of factories are also called Dedicated Manufacturing Lines (DMLs). They represent a conventional transfer line where each part is dedicated to the production of a specific component at a high production rate. DMLs provide a medium automation level and aim to fulfil the execution of high-demand products at low costs . It seems to be obvious that theses factories cannot keep up with the current dynamic changes of varying customer requirements and high competition markets. DMLs are not able to provide reliable delivery dates and fixed price frames when sudden changes from customers or factory failures occur. This issue can be explained by the fact that cost and time consuming process plan reconfigurations have to take place in order to handle adjustments. Therefore, the concept of DMLs seems to be outdated and a new production idea has to become the focus of attention. [Hoff19]

A shift towards customer-orientated and changeable production organisation has to take place. In order to get close to that stage, an interconnection of the factories' management and operational process levels has to take place. From a management point of view, long-term production planning is no longer feasible due to highly competitive markets. Consequently, agile short-term decision-making has to be the basis of a future-oriented factory. From the process perspective, mid-term and short-term scheduling will become even more important, as the dynamic requirements demand high process reconfigurability at shop floor level in a real-time manner. The interconnection of these different production layers must be implemented via an interoperable architecture. This architecture should include being "more flexible, robust and configurable by supporting agile and adaptive responses to changing conditions through a dynamic reconfiguration of their ongoing processes". It must be highlighted that these characteristics increase the complexity of a production system massively. [Hoff19, Leit15a]

Digitalisation is one of the crucial ingredients for reconfigurable and adaptable production procceses. The solution for transforming conventional factories into "factories of the future" can be reached with Cyber-Physical Production Systems (CPPSs). CPPSs are able to transform the real-world process data into a digital representation. Additionally, they increase the interaction of all involved human and physical components that are related to the production process. The use of modern technologies is also the major objective for the "fourth industrial revolution", the so called industry 4.0. After the industrial area had already gone through several transitions, the concept of industry 4.0 wants to enable autonomous and smart entities (agent-based systems) to connect with the Internet of Things (IoT). [Hoff19, Leit15a]

The following subsections will give a further look inside of the current state of the art in modern production systems.

2.1.1 ISA-95: the automation pyramid

The automation pyramid is a hierarchical representation of all functional layers of an industrial factory. It represents the current state of the art architecture for industry 3.0. The need for this pyramid characterisation occurred when the connection of all layers had to be made available for a seamless and autonomous information exchange. The automation pyramid provides machine-readable data for all levels and shows the systems' interdependence . This representation was the first attempt to compromise the goal for Computer Integrated Manufacturing (CIM), which deals with the integration of computer support systems in manufacturing enterprises. The automation pyramid is part of the ANSI/ISA-95 standard according to the International Electrotechnical Commission (IEC 62264). The pyramid consists of five factory levels that are organised in a traditional top-down control hierarchy. The shape of the pyramid represents the increasing density of information from top to bottom. Whereas the control flow is top-down oriented, the information flow is meant to go from bottom to top. A graphic representation of the ISA-95 pyramid can be found in Figure 2.2. [HOFF19]

The top level of the pyramid contains the Enterprise Resource Planning (ERP). This level manages the rough production planning of resources, transportation and finances. It is mostly used for the factory-wide strategy planning. The ERP manages the business planning and logistic in a time frame of months and weeks.

Between the high-level ERP management and the low-level shop floor, an intermediate level is located, namely the Manufacturing Execution System (MES). The MES joins the rough planning and the manufacturing execution by "transforming the information from high-level systems into concrete tasks to be executed on the field" [HOFF19]. Consequently, the MES can be located in both management and process level. Its goal is to perform detailed production planning, control process operations, determine maintenance and handle quality management. Moreover, it should forward information from the field to the management level in an ideally real-time manner. The MES manages the manufacturing operation in a time frame of days and hours. This level is put in focus in the following sections to describe an autonomous integration of production planning and control with agent-based systems.

The Supervisory Control and Data Acquisition (SCADA) level provides diagnostic features on the shop floor. For high-level supervision, a graphical interface is often used for visualising status information of the physical devices. The SCADA manages supervising and monitoring on the shop floor devices in a time frame of minutes.

The Programmable Logic Controller (PLC) level has a direct physical connection with several inputs and outputs to the field level via field bus communication. This level has access to raw data and interacts directly with the actuators and machines of the factory. The PLC manages the sensing and manipulation of the shop floor devices in a timeframe of seconds.

The field level contains the majority of data sources and performs all instructed processes on the physical devices via sensors and signals. This level executes the production processes in a real-time manner of milliseconds/microseconds.

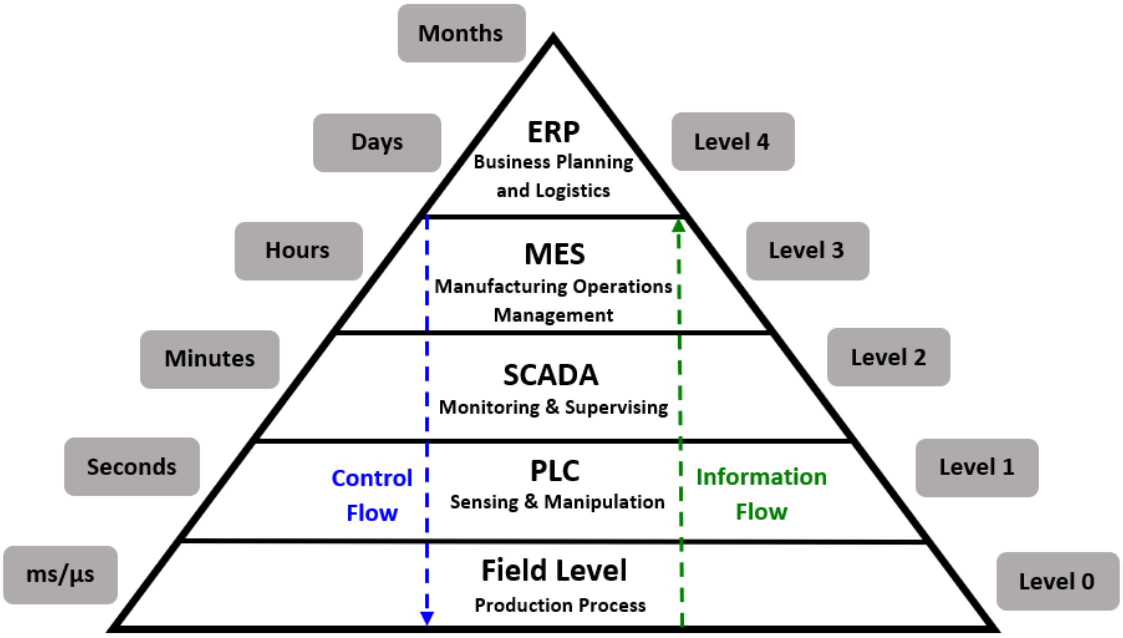

Figure 2.2: ISA-95 automation pyramid for manufacturing control in industry 3.0

2.1.2 Towards multi-agent systems in industry 4.0

As already explained in section 2.1, industrial enterprises need to change their principal goals to deal with the consequences of globalisation. Highly competitive markets, customer-oriented products and shorter product life cycles have to be considered to stay relevant in the global business. The focus of a modern industrial enterprise has to shift from optimising scheduling algorithms towards several other goals: flexibility, reconfigurability/adaptability, robustness, autonomic features, efficient communication and real-time capability. *Flexibility* of a system is an unavoidable goal that must be fulfilled to adapt to dynamic business needs. Efficiency (dynamic optimisation capability) and effectiveness (appropriate reactions to internal production problems) must be given for frequently changing demands. *Reconfigurability and adaptability* are closely related to flexibility. *Reconfigurability* described the process of quick software or hardware changes in order to deal with sudden capacity or functionality adjustments. *Adaptability* on the other hand must be given to survive in competitive markets where sudden costumer or market changes demand a quick reaction . *Robustness* in error-cases must ideally be given at all times. It implies that the software system finds optimal solutions autonomously and deals with problems in a self-sustainable way. The *autonomic features* are closely related to the characteristics of flexibility, reconfigura-

bility/adaptability and robustness. The autonomic features mean that a modern system should provide "self-healing, self-configuration, self-organisation and self-optimisation" [LEIT15a]. *Efficient communication* is absolutely necessary in a "factory of the future." Because of the need for an interconnection of all production layers, an interoperable architecture with a reasonable number of messages is required. *Real-time capability* can only be realised if an efficient communication and cooperation of all involved parties is applicable. In order to react up-to-date, real-time information "has to flow through all different layers from the shop floor up to the management and business process level" [HOFF19]. [LEIT15a, CRUZ19, HOFF19]
These goals can only be accomplished if the integration of high-functional software applications is accepted by the industrial enterprise. A computerisation, in the means of equipping hardware devices with software-controlled intelligence, improves the factory's production processes by constantly receiving feedback of the physical devices' performance.

All the aforementioned goals and requirements can be fulfilled with the introduction of digitalisation. The term of digitalisation can be explained in a concise way by describing it as a transformation of physical information into digital representation. In the area of manufacturing, Cyber-Physical Production Systems (CPPSs) are able to connect to the factory and transform physical data into a digital format. Therefore, a coexistence of the real world and virtual cyberspace can handle the transition towards a "factory of the future". CPPSs have an impact on several components in an industrial factory and support the factory-wide communication of all involved parties. The "5M system" contains all manufacturing domains that are affected by the establishment of a CPPS. The five "Ms" stand for materials, machines, methods, measurements and modelling. Several internet-based communication technologies to enable web-service devices can be found nowadays. The most common are the Device Profile for Web Services (DPWS), Representational State Transfer (REST) and OPC Unified Architecture (OPC-UA). Moreover, the web-services should comply with certain semantics, e.g. Extensible Markup Language (XML) and Web Ontology Language (OWL). Service-Oriented Architectures (SOAs) are one of the main organisation principles that are implemented in CPPSs. SOAs are built to cover a whole distributed system, meaning that all ISA-95 levels can be controlled. This architecture provides and requests services. "A service is a software piece that encapsulated the control logic or functionality of an entity that responds to a specific request" [HOFF19]. For a technical implementation of SOAs, cloud-based infrastructures are often used which have the advantage of "feeling like they were installed locally" [HOFF19]. [HOFF19]

The requirements for modern factories and the accompanied integration of CPPSs can be defined under the term of industry 4.0. The concept of industry 4.0 was first introduced in 2011 by a German research team. The industry 4.0 reference architecture (RAMI 4.0) was developed in order to serve as standard and highlight the requirements of digitalisation in the industrial production. However, the transformation from an industry 3.0 factory towards an industry 4.0 factory is challenging. A real-time interconnection of all levels from the ISA-95 automation pyramid must be established to reach an interoperable CPPS architecture. The characteristic of changing from an hierarchical architecture towards interoperability is one of the main problems that has to be approached. In an interoperable architecture, the ability to exploit useful information is used to make it accessible to all components of the factory via high-communication protocols. In Figure 2.3, the transition process towards industry 4.0 with an interoperable CPPS architecture can be found.

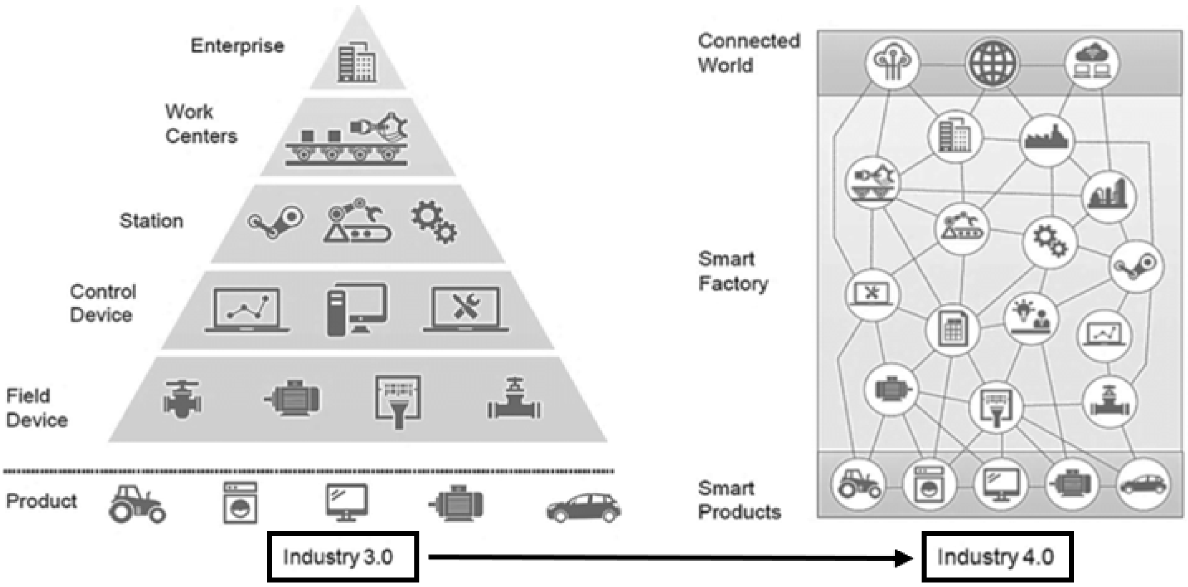

Figure 2.3: Transition from industry 3.0 (ISA-95) towards industry 4.0 (CPPS) [FRER18]

There are many more reasons why the transformation towards digital production is struggling. One of them contains the well-established production standards that were in place in the last decades. Moreover, the necessary change away from long-term production cycles requires a massive investment and costly expense of new software and hardware [HOFF19]. The development of an industry 4.0 factory is connected with a high risk, considering economic danger and safety aspects. Therefore, the current aim of researchers is to conduct a transition into industry 4.0 "without risking the stability and functionality of currently running systems" [HOFF19].

The use of agent-based systems is a widely adopted technology for including an autonomous and intelligent characteristic into a future factory. These systems are able to handle the complexity of shifting towards short-term production. Moreover, Multi-Agent Systems (MASs) can provide an interoperable architecture for CPPSs. Since the concept of industry 4.0 was first introduced in 2011, only a handful of solution-based MAS approaches in industry 4.0 have been developed so far. Nevertheless, MASs that were not developed in the context of industry 4.0 can be modified and applied for digital production. There are several ways to construct, develop and implement these systems. Because of the aforementioned challenges, MASs are mostly developed to be evaluated in simulators and are currently not integrated as a standard in the industrial area.

2.1.3 Multi-agent-based production planning and control

As already mentioned in section 2.1.1, the MES is part of Production Planning and Control (PPC). The PPC handles various fields in an industrial enterprise: from a broad perspective, "product development, supply, distribution, personnel, equipment maintenance, power, customers, dealers, joint ventures outside a company" [ZHAN17] and many more tasks are included. From a narrow perspective, the PPC makes time, operative and quantity related production decisions for the execution process. The responsibilities of the PPC are widely distributed and consequently a careful and efficient consideration of every aspect has to be made to generate an economic benefit for the enterprise. The PPC can be divided into production planning and production control, which consider in combination the optimisation of the whole production system.

The production planning can be divided into three processes: Master Production Scheduling (MPS), Material Requirements Planning (MRP) and Process Scheduling. The MPS takes all manufactured products of the factory into account and detects their impact on the short-, medium- and long-time planning of the enterprise. The MRP handles the resource planning of materials and staff members by considering the available amount of materials and shift plans. The Process Scheduling establishes the sequence planning of products and reorganises tasks if the capacity of a certain machine or the deadline of a customer's order is at risk. It establishes an optimal arrangement of resources to plant devices. Altogether, the main scope of the production planning is to generate an optimal organisation of a certain number of products while maximising the resource capacity and minimising the execution time. The production planning activity has a time horizon of a couple of days or weeks. [ZHAN17]

The production control executes the tasks that the production planning has organised. To achieve the predefined production plans, the production control performs supervising, inspection, deviation detection and adjustments for an optimal execution. Moreover, it records data for a constant improvement of the ongoing operations. The process of production control is performed in real-time. The aforementioned ISA-95 level 3 (MES) can be located in the production control area. Whereas the production control describes a general procedure, the MES represents an instantaneous state of a real industrial enterprise. [ZHAN17]

A MAS offers the functionality of dealing with the task of production planning and control at once. MASs are capable to "cope with complex problems concerning the engineering and application of production control systems" [LEIT15a]. A MAS divides the planning and control related tasks into different sections to reduce their complexity. For that matter, different architectures have been developed in the past years for an autonomous performance of production planning and control. Most systems were developed in the context of automation in industry 3.0 and do not consider the area of digital production. Regardless, MASs can be integrated into industry 4.0. Therefore, the performance of such systems has to be evaluated in the context of digital production.

2.2 State of the Art: multi-agent systems

The first agent technologies emerged in the early 1970s. Nevertheless, it took almost 20 years for agent-based systems to receive major attention in the area of artificial intelligence. Agent-based research marks an exceptional case in computer science, because it was not only engineers who were interested in this advanced technology, but also psychologists, sociologist and natural scientists. Agents have a high social ability and therefore, the humanities influenced their development as well. In 1990s, "these huge influences from many sides led to some chaotic and hardly controllable research" [Leit15a]. Today, the field has calmed, and agent-based technology has found its purpose in the industrial area. [Leit15a]

Agent technology belongs to the field of Distributed Artificial Intelligence (DAI). DAI is dedicated to decision-making and the solving of complex real-world problems, especially if these tasks require a large amount of data. The area of DAI is a subfield of both artificial intelligence and distributed computing. There are two important branches in DAI: distributed problem solving and Multi-Agent Systems (MASs). Distributed problem solving was the first approach to explain DAI problems. It solves the distributed problems by decomposing the task among nodes while sharing its knowledge system-wide. This field was extended by MASs in which the containing agents complete a task collaboratively by communicating with each other and coordinating their knowledge in an autonomous manner. In Figure 2.4, the decomposition of DAI into its subfields can be found. [Genz13]

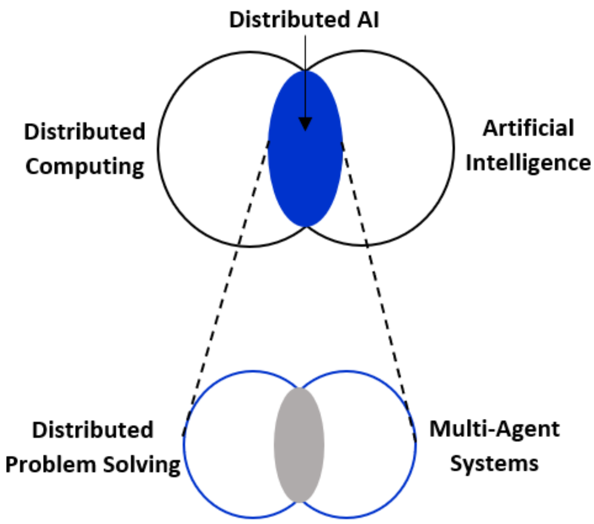

Figure 2.4: Embedding multi-agent systems in the field of distributed artificial intelligence [Genz13]

Various standards, workgroups and committees deal with MAS technology. The Foundation for Intelligent Physical Agents (FIPA) IEEE Society is the most important committee for MASs. The FIPA deals with agent-based technology and interoperability standards and publishes norms on how to provide interoperation of heterogeneous agents. The Verein Deutscher Ingenieure und

Elektrotechniker (VDI/VDE) with its Society of Measurements and Automatic Control mostly focusses on field level control with MASs in the industrial area. They provide four norms and standards for dependable, reliable and real-time MASs. The Technical Committee on Industrial Agents (IEEE TC IES) as well as the International Federation of Automatic Control (IFAC TC 3.1) focus on different disciplines for CPPSs and the industry 4.0. It is worth to mentioning that there are many more participants that pursue research for MASs.

The following sections will give a state of the art overview on MAS architecture, communication and interaction, as well as on development support.

2.2.1 Fundamental concepts of agent systems

The term "agent" has multiple definitions. The most widely accepted definition is the one proposed by Wooldrige [Wool09]: "An agent is a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives." Therefore, an agent is based on both software and hardware. Moreover, Wooldrige [Wool09] propose four basic agent properties: autonomy, reactivity, social ability and initiative. *Autonomy* describes the agents' behaviour of controlling internal states by itself. This characteristic sets apart an agent the most compared to other distributed systems. *Reactivity* is given when an agent responds appropriately to external changes in its located environment. Due to its additional autonomous behaviour, an agent cannot be forced by its environment to react in any way. *Social ability* enables a single agent to exchange information and collaborate with other agents in its environment. Agents behave in a goal-directed *initiative* way and always consider their own requirements. [Leit15a, Hoff19]

A MAS consists of multiple autonomous agents with different purposes that are embedded in a determined environment. The system focuses on collaborations among various autonomous agents. Each agent has a different goal and pursues its requirements in a different way. Their corresponding behaviour must be coordinated in order to achieve a global objective that cannot be reached by a single agent [Zhan17]. The agents in a MAS share their knowledge via communication and interaction protocols to solve the common goal. Therefore, the information within each agent is incomplete and the knowledge base is distributed [Zhan17]. Taking all these characteristics into account, a MAS should provide three basis properties: sociability, autonomy and cooperation. Same as for a single agent, a MAS needs the characteristics of *sociability*. The agents in a MAS must communicate in their social environment to reach the global objective. In a MAS, agents receive and requests data from other agents without having the ability to force each other to act in certain way. This feature is described as *autonomy*. *Cooperation* is as aforementioned necessary to reach a common goal due to the distributed or even heterogeneous goals of every agent. [Leit15a, Hoff19]

2.2.2 Agent structure and multi-agent architecture

Agents can be distinguished into two types: deliberative and reactive agents. *Deliberative agents*, also called cognitive or proactive agents, have a complex internal structure and therefore behave reasonably sophisticated . This type of agent is mostly implemented in a belief-desire-intention structure. "The belief reflects the agent's abstract understanding" [LEIT15a] of the world, the desire of an agent is coupled with its goals, and the intention provides requirements and plans to achieve the goals. Because of this structure, deliberate agents are not fully explainable. Moreover, they predict future actions and produce high-quality solutions. They are very flexible, but can become overly complex over time, which results in a decreasing reaction time. These agents are also able to learn very well. On the other hand, *reactive agents* are the complete opposite of deliberative agents. They have an explainable structure and react in a simple situation-action manner. Moreover, they react quickly to sudden changes. Reactive agents are not flexible and have very little smartness and learning capabilities compared to deliberative agents. Even though deliberative and reactive agents are total opposites, it is possible to replace a deliberate agent with a certain amount of reactive agents without losing any quality. [LEIT15a]

A classification of different MASs can be accomplished based on different architectures. Three principal types of control architectures can be identified for MASs: centralised, hierarchical and heterarchical. A *centralised MAS architecture* (Figure 2.5) has one decisional agent at the root of the system (A1). This agent controls all planning issues, and all the other agents (A2-A7) in the system therefore have no decision power. These agents are passive nodes in this system. A centralised architecture works best in small and static systems, where short paths lead to a highly effective optimisation in a short time. A centralised approach is not optimal in complex and large systems due to increasing reaction time. Moreover, the root agent is critical for the functionality of the whole system and must never be out of order. [LEIT15a]

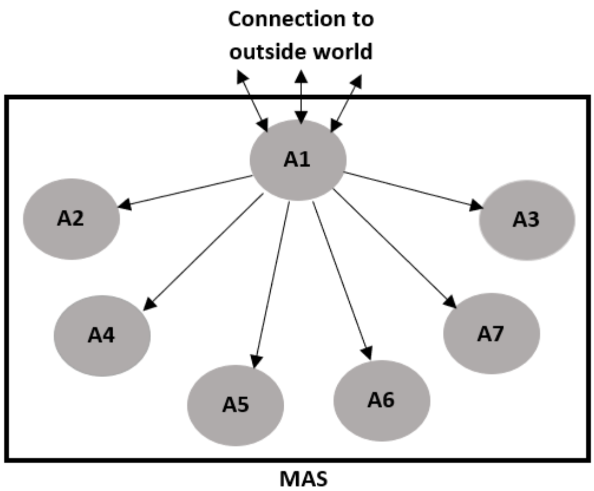

Figure 2.5: Centralised MAS control architecture with *Agents (A1-A7)*

With the first introduction of distributed systems in early 1970s, the centralised architecture was replaced with a *hierarchical MAS organisation* (Figure 2.6) which is “allowing the distribution of decision making along theses hierarchical levels” [LEIT15a]. The agents on different levels also have different autonomy levels. Higher levels (Level 1) make strategic-oriented decisions and lower levels (Level 3) focus on simple tasks. A hierarchical architecture provides higher efficiency, robustness and a better optimal solution compared to a centralised architecture. A hierarchy supports low product variety, few production changes and a low error rate. [LEIT15a]

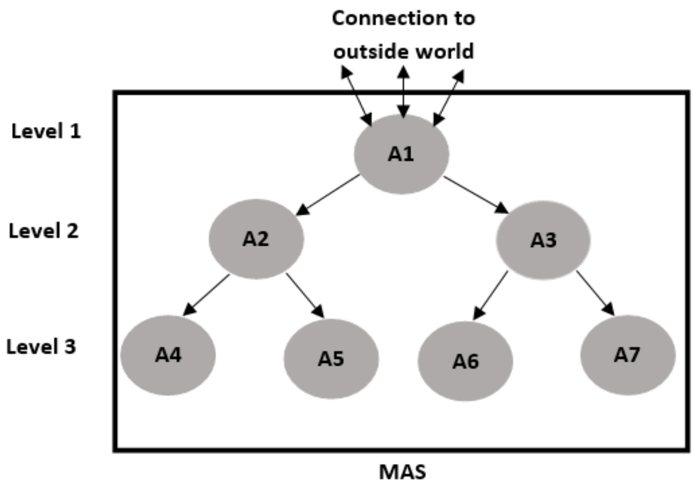

Figure 2.6: Hierarchical MAS control architecture with *Agents (A1-A7)*

Compared to hierarchical architectures, *heterarchical MAS organisations* rely on arbitrary communication and collaborations among all agents instead of strict decision dependence of higher level agents. A *full-heterarchy* (Figure 2.7 left) is defined as an architecture where no levels exist. Therefore, a hierarchy can be classified as a strict extreme of a heterarchy. Full-heterarchies are highly flexible, but short-term optimisation is not possible due to consideration of all agents' decisions. A *semi-heterarchy*, on the other hand, is defined as an architecture where a loose hierarchy exists. Low-level agents have limited intelligence and react quickly to sudden changes (reactive agents). High-level agents perform strategical long-term decisions and are mostly deliberative agents. Moreover, low-level agents are mostly organised in a hierarchical fashion, while high-level agents mostly communicate in a heterarchical way. Semi-heterarchies are very beneficial because they provide robustness on the low levels and intelligent decision-making on the high levels. [LEIT15a]

A very common semi-heterarchy is the holonic agent organisation (Figure 2.7 right). A holon can be "decomposed into a set of subordinate holons when analysed on the next lower level" [LEIT15a]. Holons are therefore always part of a larger holon and contain several other holons. This nesting can be also defined as part–wholes or holarchy. Each holarchy selects a head holon (H1, H2, H3), based on its capabilities, that communicates with the environment or other head holons. Holarchies can constantly be adapted if change is needed. A holonic architecture handles sudden changes in a robust and autonomous manner and is therefore very desirable. Moreover, holarchies can be easily implemented in a MAS because they share many principle characteristics. Consequently, autonomous agents in a semi-heterarchical holonic organisation have holonic grouping properties and represent altogether a holarchy. Hence, MASs represent an actual implementation, whereas holons represent logical units of an industrial factory. [LEIT15a]

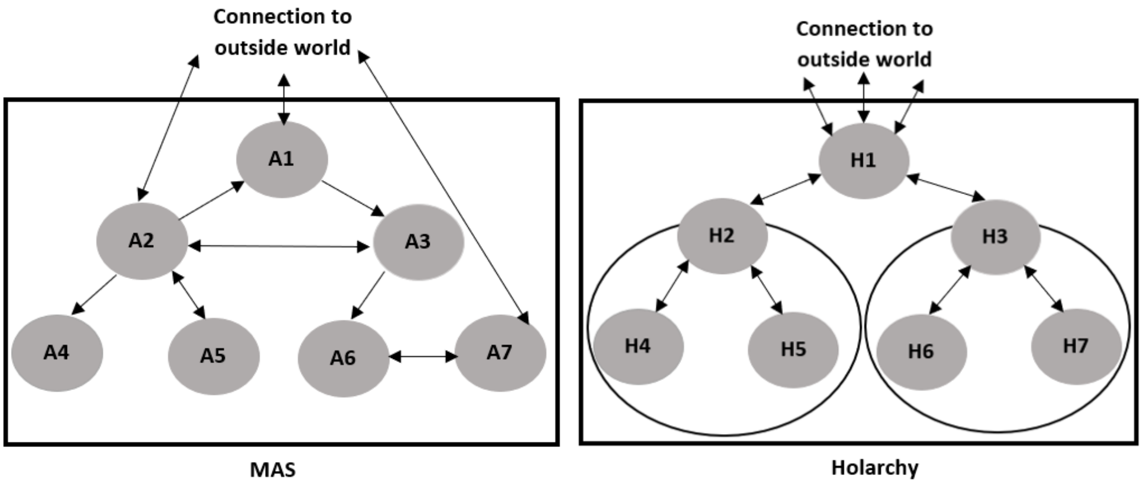

Figure 2.7: Heterarchical MAS control architecture (left) with *Agents (A1-A7)* and semi-heterarchical holonic MAS conotrl architecture (right) with *Holons (H1-H7)*

2.2.3 Communication and Interaction

One of the most important characteristics of agents is their social ability. They are able to interact with other agents and with the external environment. The communication and interaction of agents refers mostly to their interactive behaviour and is the basis of any decision making and collaborations. The communication and interaction behaviour can be separated into three levels (Figure 2.8): the transport layer, the communication layer and the interaction layer . The *transport layer* is responsible for forwarding the final message via a computer network protocol (e.g. TCP/IP, HTTP). It relies on the communication and interaction protocols in the lower layers. The *communication layer* ensures that the agents can exchange messages via Controller Area Networks (CANs) and are able to understand each other. These messages contain specific intentions (e.g. proposals, rejection, instruction) and reflect the agents' initiative . All communication languages are based on the principle of the speech-act theory which enables the agents to have a mutual understanding of the messages. Moreover, all communication languages should provide a clear syntax and semantics to ensure a high clarity of the messages. A few examples on communication languages are the Knowledge Interchange Format (KIF), the Knowledge Query Manipulation Language (KQML) and the FIPA Agent Communication Language (FIPA-ACL). *The interaction* *layer* is also often defined as indirect communication. The interaction protocol should provide a certain purpose and action in order to carry out a dialogue with other agents. The interaction protocol can be divided into the protocols that serve a certain purpose (e.g. collaboration protocol, negotiation protocol) and into the protocols that provide action-time requirements (e.g. long-term protocol, short-term protocol). The FIPA Contract Net Protocol (CNET) and the blackboard interaction protocol are two examples of a collaboration-based interaction protocol. [LEIT15a, ZHAN17]

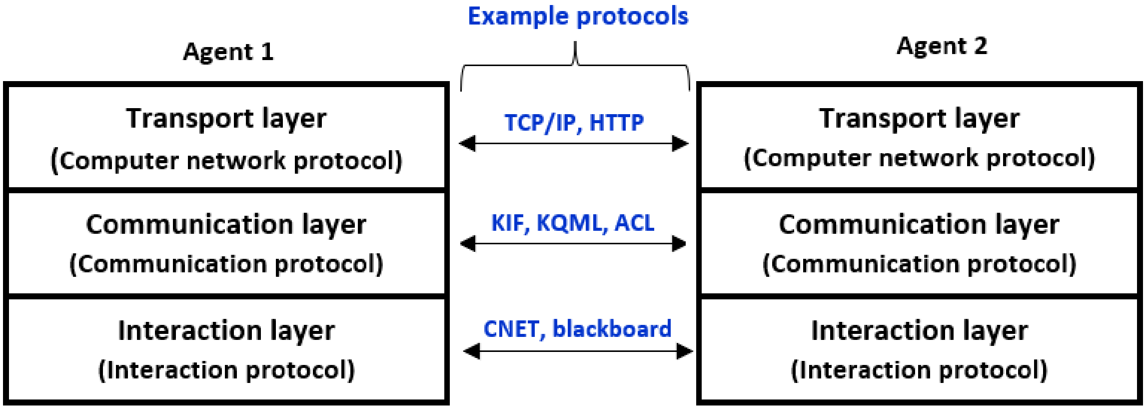

Figure 2.8: Communication and interaction between agents in a MAS [ZHAN17]

2.2.4 Decision-making and Learning

All agents within a MAS want to achieve different goals. In order to reach the global purpose of a MAS, the agents have to coordinate in order to come to a certain decision. Usually, the agents have to join special actions to maximise the outputted reward for the whole system. This strategy can be modelled with a game theoretical method. In the beginning of every negotiation, the agents choose a personal action with highest payoff. Through simultaneous execution, an optimal decision for the whole system is found. [BALA10]

The application of machine learning to optimise decision-making is very fitting in the industrial area. Agents that are enabled to have artificial intelligence features can learn in a way to improve their performance on future tasks by observing different patterns. They can learn in an autonomous way from absorbing data and can easily adopt to sudden environmental changes. Therefore, the integration of machine learning is a highly desirable state to reach within the MAS research. [HOFF19]

2.2.5 Development support and simulation environments

In order to implement agent-based systems for technical realisation, different support options can be used. The three main support systems for MAS development are agent-based development frameworks, agent-oriented programming languages and agent-based software methodologies . The *development toolkits and frameworks* for MASs are based on object-oriented programming languages. There exist several different concepts, the most widely known are the FIPA-OS, JACK and JADE. Especially JADE is in the focus of attention due to its open-source and java-based framework. Moreover, it is compliant with the FIPA standard. *Agent-Oriented Programming Languages* (AOPs) are seen as the future agent programming and should replace agent object-oriented programming one day. AOPs enable researcher to develop MASs in a high-semantic and logic-based programming language. An AOP must consists of the three following properties in order to be complete: a formal language with a clear syntax, a defining agent semantic and a conversion of neutral applications into agents. *Agent methodologies* facilitate the semantic development of a whole MAS life cycle by providing a set of models and techniques. The FIPA Agent Unified Language (AUML) was one of the first developed modelling languages and had a large impact on later developed software methodologies. Some of the most popular agent-based development methodologies are GAIA, MaSE, MESSAGE and PROMETHEUS. [Leit15a]

Especially in the case of MASs, simulation environments are a big advantage, because it is very complicated to implement a MAS in a real industrial enterprise. Simulation studies enable researchers to implement real-world and virtual instances into the system. The outcome of a simulation can be analysed for further optimisation. The outputted performance and behaviour in certain situations might be crucial to determine if a certain MAS concept should be further investigated or not. Examples for agent-based simulation tools are AGENT.GUI, MASON and MAST. [Leit15a]

3 Analysis and evaluation of multi-agent systems for digital production

Cyber-Physical Production Systems (CPPSs) in industry 4.0 make customised and adaptable production processes possible. At the same time, the requirements for production planning and control increase. This issue can be solved with the use of Multi-Agent Systems (MASs). This chapter's goal is to analyse and evaluate different approaches and requirements for the existing MASs with a focus in production planning and control. Moreover, the applicability of these system to be integrated into digital and modular production is to be examined and discussed.

To reach this goal, the following procedure takes place (Fig.3.1):

1. An analysis of the existing MAS articles is developed. The amount of approaches is limited to those which include a solution-based proposal with the focus on production planning and control.
2. In order to evaluate the resulting MAS approaches, classification criteria have to be selected. A table with 15 criteria is developed. This table mostly focus on the MAS architecture, applicability in the industry 4.0 and comparison criteria with other MASs for further evaluation.
3. Five MAS approaches are selected to be evaluated with the proposed classification criteria. The evaluation includes a detailed description of each MAS and concludes the evaluation with a graphical representation of the system.
4. The evaluated MAS are compared and further discussed in the context of applicability for digital and modular production (industry 4.0)

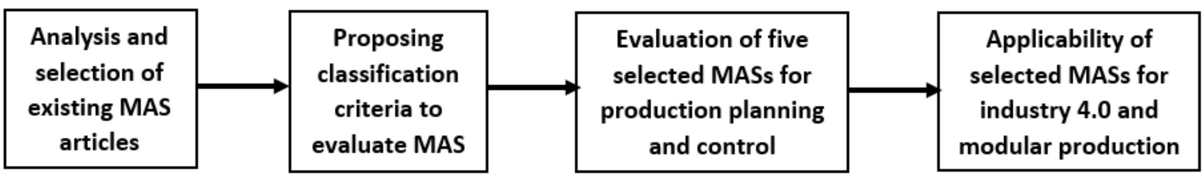

Figure 3.1: Structure of the analysis and evaluation of MASs for digital production

3.1 Analysis of multi-agent and solution-based articles for production

The amount of published articles on MASs has been rising steadily since the first documents emerged in the early 90s. As a starting point for the analysis and evaluation of different MASs throughout the years, fitting documents have to be collected. Table 3.1 shows the amount of articles that are outputted, given suitable keywords (connected with AND) on Elsevier's Scopus (a fee-based citation database) and Google Scholar (a web search engine for scholarly literature).

Table 3.1: Document results on Scopus and Scholar for MAS articles in different contexts (Keywords connected with AND)

Keywords	**Document Results**	
	Scopus	Scholar
Multi-agent systems	219.450	3.740.000
Multi-agent systems Production planning and control	24.596	85.500
Multi-agent systems Industry 4.0	5.692	175.000
Multi-agent systems Digital production	5.563	70.000
Multi-agent systems Production planning and control Digital production	2.560	44.000
Multi-agent systems Production planning and control Industry 4.0	1.279	25.100

With more than 1000 articles even in the combined search, the quantity of articles exceeds the boundaries of this thesis time and requirements. It is not possible to evaluate and analyse every single one of these to identify the suitable proposals.

Therefore, a number of already existing literature reviews is taken as a foundation to find valid approaches on MASs. Table A1.1 (see Appendix) shows and summarises six considered papers that have a collection of articles that focus on MASs for industrial application. The showcased articles on proper MAS approaches cover the years from 1998 to 2018 and include several application domains, such as energy systems, smart production, electric grids and infrastructure. The filtered citation count of the six literature review papers indicates that [LEIT16]'s article from 2016 received plenty of attention compared to other reviews. Consequently, [LEIT16]'s work can be seen as main related work to the following literature review in Table A1.2 and Table 3.2.

The individual proposals on MAS in the aforementioned literature review papers (Table A1.1) are sorted and further narrowed. Only the articles that take solution-based MAS approaches which can be applied in the manufacturing and production area are considered in the following. This reduction was taken because the inclusion of papers that only have hypotheses or frameworks without simulations are not useful for the further context. An overview of the resulting 61 articles can be found in Table A1.2 (see Appendix). The table organises the individual approaches by the published year and summarises the most important facts, containing: the associated MAS name (if given: written in capital letters) and the outlined content, the system's ISA-95 level location and lastly the citation count of Elsevier's Scopus and Google Scholar to highlight the attention and influence in research.

As already explained in section 2.1.1, the field of production planning and control can be located in the ISA-95 level 3. Table A1.2 is therefore further reduced to capture the articles that take this level into account. As a result, Table 3.2 is the final collection of 16 articles that fit the requirements of being solution-based MAS approaches and are located in the ISA-95 level 3.

Table 3.2: MAS-based and real problem-solving approaches focusing on production planning and control

Author(s) Reference	**Year**	**Content**	**ISA-95 Level**	**Citation Count** Scopus	Scholar
Pechoucek et al.[PECH02]	2002	EXPLANTECH: project-driven production planning with a MAS	L3	27	54
Lee et al. [LEE03]	2003	P-TATO: dynamic resource scheduling with a MAS for market-based control	L3	109	114
Lüder et al. [LÜD04]	2004	PABADIS: a MAS process control approach for distributing production execution systems	L1-L4	57	83
Jacobi et al. [JACO05]	2005	AGENTSTEEL: production planning and scheduling based on a MAS	L3	12	25
Lima et al. [LIMA06]	2006	Production planning and control using a MAS for distributed resources	L3	43	84
Karnouskos et al. [KARN08] [COLO15]	2007	SOCRADES: SOA-devices and MAS for industrial implementation	L1-L4	21	34
Blanc et al. [BLAN07]	2008	An holonic MAS for manufacturing execution systems focusing on control and scheduling for the AGP	L3	67	115

Author(s) Reference	**Year**	**Content**	**ISA-95 Level**	**Citation Count** Scopus	Scholar
Andreev [ANDR10]	2010	Manufacturing scheduling for adaptive networks with a MAS	L3	9	21
Badr et al. [BADR10]	2010	A MAS approach for integrated production and transport scheduling for flexible manufacturing systems	L3	7	11
Skobelev [SKOB13]	2013	KUZNETSOV: adaptive resource planning and scheduling based on a MAS	L3	17	51
Colombo et al. [COLO14] [COLO15]	2014	IMC-AESOP: industrial MAS in SOA and cloud-based architectures	L1-L4	142	290
Vogel-Heuser et al. [VOGE14]	2014	MYJOGHURT: a MAS-based prototype demonstrator for cyber-physical production systems	L1-L3	67	100
Marín et al. [MARI13]	2015	ARUM: a manufacturing support system for planning based on a MAS	L3	30	38
Lüder et al. [LÜD17]	2017	Identification of design patterns for MAS in production control	L3	11	12
Rehberger et al. [REHB17]	2017	Decoupling planning of production sequences from distributed real-time control with a MAS for reconfigurable manufacturing	L3	10	11
Ghita et al. [GHIT18]	2018	SCEMP: a MAS for manufacturing control and scheduling to predict maintenance	L3	5	3

This resulting amount of articles can now be further examined in detail. For the purpose of this thesis, only those MAS articles will be evaluated that have an in depth description of their architecture. Furthermore, the MAS approaches should include the CPPS requirements (see section 2.1.2) of flexibility, reconfigurability and adaptability, which is important for an additional examination and comparison of the evaluated MASs in the context of modular production in section 3.4. Applying these requirements to Table 3.2, five selected approaches ([PECH02], [BADR10], [SKOB13], [BLAN07] and [KARN08]) were chosen to be evaluated in detail. It has to be mentioned that some of the other 11 approaches also fit to the above mentioned requirements, but were not chosen due to overlapping with the five selected approaches.

3.2 Classification criteria for evaluating multi-agent system approaches

Before the five selected MAS approaches can be evaluated in detail, classification criteria have to be selected that can be applied universally.

Multiple works on how to categorise and evaluate certain technology systems have emerged in the last years. The approaches of [Ecke12] and [Cruz19] were selected to be used as the foundation for this work because their focus was set on architecture-related patterns and seemed to be the most fitting for this thesis' purpose. [Ecke12] developed design patterns for distributed automation systems that include general pattern information (e.g. category, type, scope), as well as advantages and disadvantages of the developed system. These classification criteria by [Ecke12] can also be applied for the evaluation of MASs. This work was extended and modified by [Cruz19], who introduces 13 design patterns to classify MAS architectures. These criteria were developed with the German FA 5.15 working group and were published in the VDI/VDE 2653 guideline paper 4, which focuses on the evaluation of MAS in the field level control (ISA-95 level 0) [VDI/21].

The proposed classification criteria in this thesis merges the work by [Ecke12] and [Cruz19] and extends the criteria by taking CPPS and RAMI 4.0 requirements into account to exhibit the applicability of the system in the context of the industry 4.0. The modified classification can be partitioned into three sections (Table 3.3):
First, a general description of the MAS is given. This includes an introduction of the MAS by listing the name, application area and purpose/scope of the system to give a broad overview of where the MAS is located in the field of technology. After that, an in depth listing of the MAS architecture with its corresponding sub-agents is introduced. This contains the amount of sub-agents in the system; its main functionality with tasks that have to be fulfilled; ranking in the ISA-95 automation pyramid; if it requires real-time execution for performance; source type information and the inner communication/interaction base with concept or protocol. Moreover, the MAS implementation (technological realisation), knowledge processing and possible learning process is identified. To conclude the first part of the evaluation, a graphic representation of the MAS with its sub-systems and it's inner connections is illustrated.
Second, the possibility of an execution of the MAS in the industry 4.0 is examined to show the applicability of an application in digital production. As already discussed in section 2.1.2, the CPPS and RAMI 4.0 play an important role in the industry 4.0 and therefore can be used to evaluate the MAS applicability in this sector. Certain CPPS and RAMI 4.0 conditions must be fulfilled by the system to fit into the specifications [Cruz19, VDI/15]. These are matching to a certain degree for the system and are therefore evaluated with either high, medium or low feasibility, depending on how correctly the following requirements can be executed or not. All of the following requirements are based of on the work of [Cruz19] and [VDI/15].

Five key requirements have to be met of a MAS to be called an agent-based CPPS [Cruz19]:

C.1 Are the MAS (regarding e.g. associated protocols) independent of a particular application? [→
;Application independence
C.2 Is the MAS applicable for all ISA-95 levels? → ISA-95 level independence
C.3 Can the MAS be implemented in all platforms? → Platform independence
C.4 Does the MAS react appropriately in error cases and dynamic conditions? → Robustness against errors
C.5 Can the MAS handle connection losses and are important data distributed in the system? → Decentralisation

MAS can be found in various domains with different purposes [Cruz19]. Therefore, all systems have a different focus which benefits they provide (see section 2.1.2). CPPS can focus on giving flexibility (FX), meaning to which extend the system can react in an efficient and satisfactory way, such as to variants and quantity of of products. Furthermore, CPPS can concentrate on reliability (RL) to enhance and maintain a specific level of performance for special conditions (e.g. error cases) for a certain period of time. CPPS that take reconfigurability (RA) and adaptability (AA) into account are designed to adjust quickly and effectively to sudden changes in either the structure (hardware and software) or environment (market). Lastly, systems that put dependability (DP) in focus relay on the the trustworthiness of a provided service. [Cruz19].

Moreover, five key requirements have to be met of a MAS to be fully integrated for an industry 4.0 (RAMI 4.0 model) concept [Cruz19, VDI/21]:

R.1 Can the MAS support different engineering disciplines? → Support of various engineering fields
R.2 Does the MAS sub-models take the relationship between the RAMI 4.0 layers into account? → System boundary report
R.3 In the case of modularisation, can an organisation concept provide a MAS component to encompass other components to act in a logical unit? → Nestability principle
R.4 Does a virtual representation (administration shell) exist? → Administration shell
R.5 Does the MAS have an externally accessible set of meta-models regarding its functional and non-functional properties? → Functional properties

In the third part of the classification table, additional information (advantages, disadvantages and additional comments from the author) are given to simplify the comparison and selection of the MASs.

Table 3.3 lists the proposed classification criteria and describes the possible content.

Table 3.3: Proposed classification criteria for evaluating MAS based on [ECKE12] and [CRUZ19]

Criteria	**Content**
Name	Name of the MAS
Area of application	Application area of the MAS (e.g smart manufacturing, energy systems, logistics)
Purpose/Scope	Description and use of MAS
Architecture	Agents' behaviour and MAS organisation (e.g. reactive agents, hierarchical MAS, based on another MAS)
Sub-agents description	Amount of sub-agents Name of each sub-agent (e.g. resource agent) ▪ Functionality ▪ ISA-95 level ▪ Real-time capability (Yes/No) ▪ Source type information (e.g. data, hardware) ▪ Communication/Interaction base (if given)
Implementation	Framework/Programming language/Methodology used for the MAS
Knowledge processing	Knowledge storage (e.g. engineering concept, ontology, meta model)
Learning processing	Methods for learning abilities (if possible e.g. machine learning, neuronal networks)
Solution	Simplified graphic representation of the MAS
CPPS Requirements	See C.1-C.5 (Levels of truth: +(high)|o(medium)|-(low))
CPPS Characteristics	FX, RL, RC/AA, DP
RAMI 4.0 Requirements	See R.1-R.2 (Levels of truth: +(high)|o(medium)|-(low))
Advantages	Advantages of the use compared to other MAS
Disadvantages	Disadvantages of the use compared to other MAS
Others	Additional comments (e.g. exceptional properties)

3.3 Evaluation of five selected multi-agent system approaches for production planning and control

As already mentioned in section 3.1, five approaches were chosen to be evaluated in detail. With the proposed classification criteria from section 3.2, the foundation is now set to be taken to the evaluation stage. The approaches of [PECH02], [BADR10], [SKOB13] are discussed first and represent conventional MASs. After that, the approaches of [BLAN07] (an holonic MAS) and [KARN08] (a SOA MAS) are examined as special cases. All MAS were illustrated graphicly at the end of each subsection. Agents that serve the same purpose within all five presented MASs have the same colour to represent the similarity or difference between the systems.

3.3.1 ExPlanTech: project-driven production planning with a MAS

[PECH02]'s MAS named "ExPlanTech" is based on the the "ProPlanT" MAS [MARI00] and supports project-driven production planning. The proposed MAS has two types of agent groups: intra-enterprise (IAE) agents and extra-enterprise (EEA) agents. Within the IAE agents, the configurator agent, the schedular agent and the database agent schedule and optimise the internal enterprise resource planning while obtaining the customers' requirements for the selected factory. The two EEA agents (resource agent and monitor agent) provide either the factories staff or the customer with relevant information about their order. Table 3.4 shows the evaluated classification criteria of the ExPlanTech MAS in detail.

Table 3.4: Evaluation of ExPlanTech MAS with proposed criteria [PECH02]

Criteria	Content
Name	ExPlanTech multi-agent system
Area of application	Production planning and application to an automobile enterprise, naming LIAZ Pattern Shop Ltd.
Purpose/Scope	ExPlanTech multi-agent system should improve strategic decision-making to reach optimal production plan (maximum processing of clients' orders for highest profit while obtaining several resource restrictions, e.g. material supply, staff availability). It should mainly support project-driven (meaning: there is a limited series of products of one type that only can be manufactured) production planning. Moreover, it should make priority categorisation decisions, meaning orders with high priority have to be processed before other ones. The system should detect production bottlenecks, communication loops and other possible inefficiencies.

Criteria	Content
Architecture	Heterarchical ProPlanT-based [Mari00] architecture ExPlanTech system + information system called ISML (caches necessary data for production planning and presents complete business solution →represents ERP)
Sub-agents description	Amount of sub-agents: five (three intra-enterprise agents (DBA, CA, SA) and two extra-enterprise agents (MA, RA))
database agent (DBA)	Functionality: Support the other agents with production data (e.g. orders, calendar) by serving as interface from communicational bridge between ExPlanTech system and ISML. ISA-95 level: L4 Real-time capability: No Source type information: Data Communication/Interaction: XML format via TCP/IP connection with ISML and FIPA specification with other agents
configurator agent (CA)	Functionality: Works like "production planning agent" and "production management agent" in ProPlanT by contracting the best possible SA and providing it with production data about order. The agent is implemented in the simplified 3bA (tri-based acquaintance) model, which reduces the communication traffic and the overall complexity by keeping precompiled information about workshops (e.g. with their load and free spaces), which would have received through communication otherwise. ISA-95 level: L3 Real-time capability: No Source type information: Data/Hardware Communication/Interaction: FIPA specification
scheduler agent (SA)	Functionality: Works like "production agent" in ProPlanT and simulates the shop floor process level by creating schedules while obtaining restrictions (e.g. priority, capacity) for several workshops (multiple SA needed). It sends DBA the computed schedule and CA the planned tasks. ISA-95 level: L3 Real-time capability: Yes Source type information: Data/Hardware Communication/Interaction: FIPA specification

Criteria	**Content**
monitor agent (MA)	Functionality: Serving customers and managers of the factory with order information and process status directly from the online agent community with an Internet browser (multiple MA possible). ISA-95 level: L4 Real-time capability: No Source type information: Data Communication/Interaction: Servlets technology (JAVA) for remote access to the ExPlanTech system
resource agent (RA)	Functionality: Status of required resources (e.g. staff, material) to provide factory staff with important information (multiple RA possible). ISA-95 level: L4 Real-time capability: No Source type information: Data/Hardware Communication/Interaction: Not given
Implementation	different from the ProPlanT architecture (mostly in C++ and running on WinNT 4.0 operation system) Here: FIPA specifications →JADE software framework (fully in JAVA)
Knowledge processing	Meta model and 3bA (tri-based acquaintance) model
Learning processing	Not possible
Solution	Example: see Fig.3.2
CPPS Requirements	C.1 (+) | C.2 (-) | C.3 (+) | C.4 (o) | C.5 (-)
CPPS Characteristics	FX, RC/AA
RAMI 4.0 Requirements	R.1 (-) | R.2 (-) | R.3 (o) | R.4 (o) | R.5 (o)
Advantages	External access to information and status on order available.
Disadvantages	No in-depth simulation presented and use of flexibility ability in production process less discussed and shown.
Others	ExPlanTech has also been applied in other factories, e.g. SKODA and BEHR, both automobile factories. "ExtraPlanT" extends the original ExPlanTech MAS by focusing and providing more EAA agents for external planninng and control [HODI05].

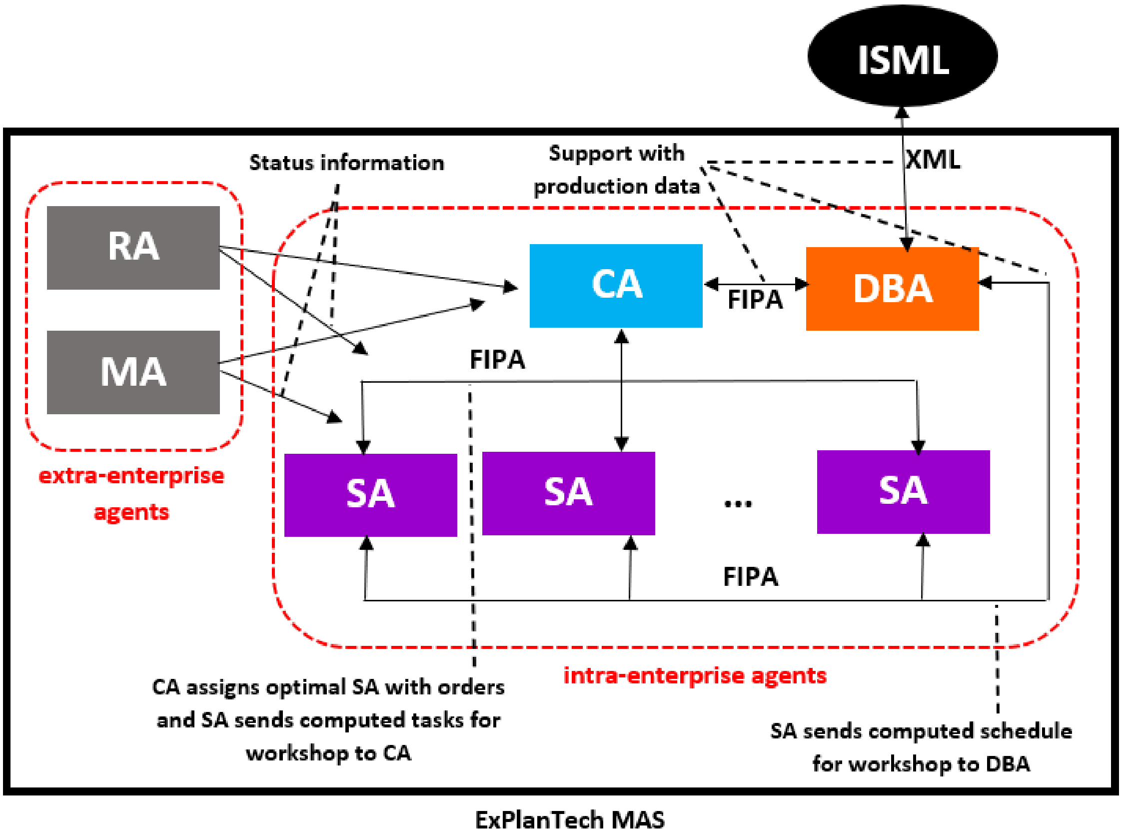

Figure 3.2: Simplified ExPlanTech MAS architecture with communication/interaction [PECH02] *database agent (DBA), configurator agent (CA), scheduler agent (SA), monitor agent (MA), resoruce agent (RA), information system (ISML)*

3.3.2 A MAS approach for integrated production and transport scheduling for flexible manufacturing systems

Flexible manufacturing systems serve the purpose to react appropriatly in changing conditions. Such conditions include sudden changes in the factories' environment (e.g. changing customer requirements, market variability) and internal resources (e.g. material shortage, staff scarcity). [BADR10]'s real-time MAS for dynamic scheduling focuses on job planning and control, and breaks down the complex task of flexible manufacturing into several sub-tasks with autonomous agents. The MAS is divided into four layers, each incorporating several sub-agents. The resource layer maximises the resource allocations for optimal sequencing and routing. This schedule is handed over to the service level, where the best allocation alternatives for jobs to resources is found. The job layer minimises the job-level execution time, like the job group layer for the job group execution time. The MAS controls errors efficiently with a disturbance handling approach. Table 3.5 shows the evaluated classification criteria of this MAS in detail.

Table 3.5: Evaluation of a MAS for flexible manufacturing systems with proposed criteria [Badr10]

Criteria	Content
Name	A MAS for flexible manufacturing systems
Area of application	Any factory that requires dynamic scheduling for flexible manufacturing
Purpose/Scope	The MAS should decompose the complexity of flexible manufacturing systems into several sub-agents which form a real-time MAS. The resource utilisation should be maximised by exploiting the accessible flexibility. The system should react in an adaptive and dynamic way to rescheduling or error cases with the use of schedular repair methods, which should include as minimal human operations as possible.
Architecture	Semi-heterarchical organization with reactive (quick reaction to the environmental changes) and deliberative (optimisation agent's decisions) architecture
Sub-agents description	Amount of sub-agents: four layers with several sub-agents (MA, AGVA, MAA, BA, OA, TA, JA, JGA)
Resource Layer (Control layer)	Functionality: Finds the best sequencing and routing alternatives while maximising the resource utilisation. This layer contains machine agents (MA: solve sub-problem of machine schedule), automatic guided vehicle agents (AGVA: solve sub-problems of transportation schedule), material allocator agent (MAA: assign material to jobs) and the buffer agent (BA: assign store space to jobs). ISA-95 level: L2-L3 Real-time capability: Yes Source type information: Data/Hardware Communication/Interaction: Extended contract net (CNET) protocol
Service layer (Control layer)	Functionality: Looks for optimal allocations of jobs to resources. An agent can provide either jobs to operation agents (OA: represent processing services and should improve machine schedule -> cooperates with MA) or transportation agents (TA: represent material handling services and should minimise transportation time from source to destination -> cooperates with AGVA, BA, MAA). ISA-95 level: L3 Real-time capability: Yes Source type information: Data Communication/Interaction: Extended contract net (CNET) protocol

Criteria	**Content**
Job layer (Planning layer)	Functionality: A job agent (JA) plans jobs with their given restrictions and requirements (e.g. quantity, deadline, priority,) and find feasible and optimal allocations by checking and calculating results from TA and OA focusing on minimal job execution time. ISA-95 level: L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Extended contract net (CNET) protocol
Job group layer (Planning layer)	Functionality: Job group agents (JGA) define a specific job type with similar constraints and focus on minimal job group execution time . These constraints and grouping depend on the factories' strategy (e.g. capacity-based factories should group by shared part types and customer) ISA-95 level: L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Extended contract net (CNET) protocol
Implementation	Whitestein LS/TS platform with the use of JAVA for implementing the sub-agents -> Integration in the self-developed GADWAL framework for realisation
Knowledge processing	Ontology/processing: each sub-agent will start a negotiation process based on extended CNET Storage space given at each workshop as an input or output buffer (either work-in-progress or local buffer) -> limits the amount of workpieces that can be processed at a certain point in time
Learning processing	Not possible
Solution	Example: see Fig. 3.3
CPPS Requirements	C.1 (+) | C.2 (-) | C.3 (+) | C.4 (+) | C.5 (-)
CPPS Characteristics	FX, RL, RC/AA
RAMI 4.0 Requirements	R.1 (o) | R.2 (-) | R.3 (o) | R.4 (-) | R.5 (-)
Advantages	Evaluation and simulation with IBM test line of MAS-based scheduling and repairing efficiency: generates optimal schedule, balances system resources and adapts dynamically to flexible requirements especially for long-term changes.

Criteria	**Content**
	Extending the MAS with internal (e.g. machine breakdown) and external (e.g. incoming of higher priority job) disturbance handling by an detailed procedure (includes identifying the problem, investigating alternatives, choosing optimal solution and repairing the schedule with appropriate efficiency).
Disadvantages	An application of this MAS on a real industrial business is left for future research and was not executed so far.
Others	This work could be extended and improved by introducing a more sophisticated optimization algorithm instead of relying on the cooperation between OA and their related resource agents.

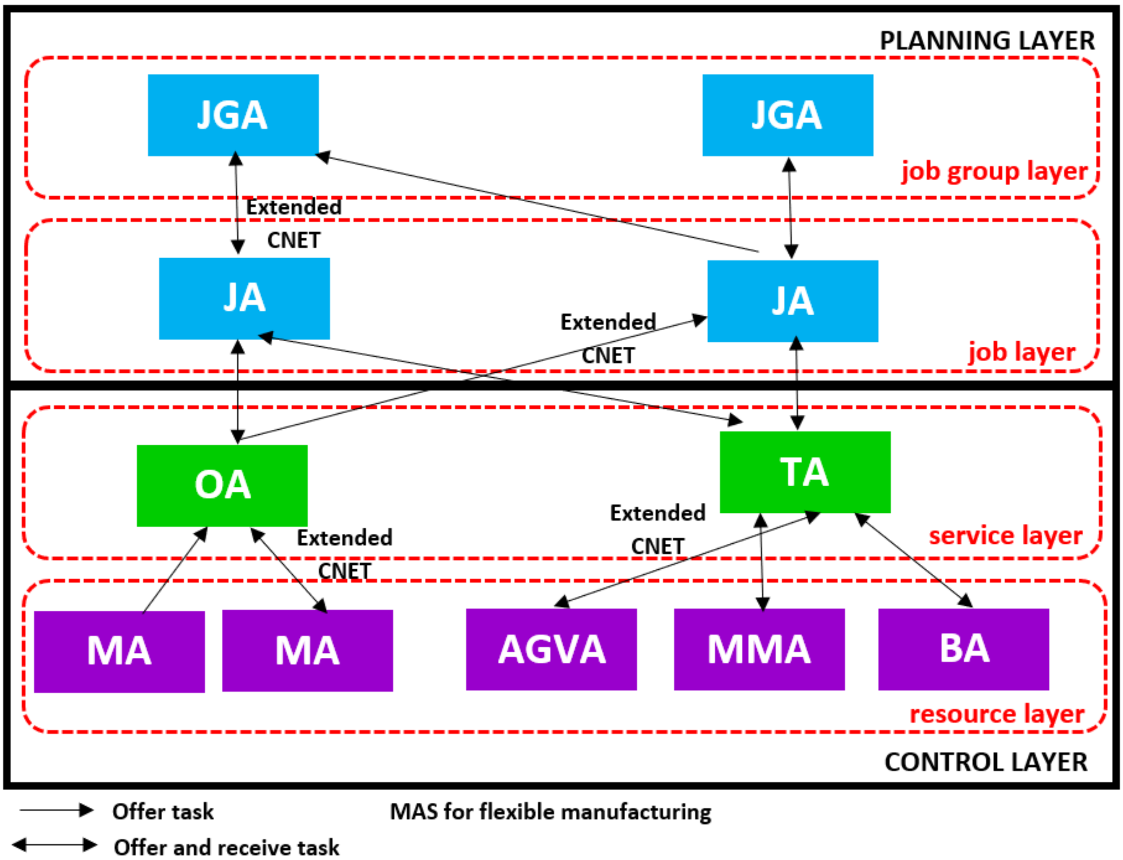

Figure 3.3: Simplified MAS architecture for flexible manufacturing systems with communication/interaction [BADR10]
machine agent (MA), automatic guided vehicle agent (AGVA), material allocator agent (MAA), buffer agent (BA), operation agent (OA), transport agent (TA), job agent (JA), job group agent (JGA)

3.3.3 KUZNETSOV: adaptive resource planning and scheduling based on a MAS

[Skob13] create a MAS for adaptive and flexible real-time resource scheduling in the manufacturing area. The system provides high efficiency in the case of machine errors and material delays. The MAS consists of several sub-agents: the organisation agent takes care of the incoming jobs at the highest planning level. The order agent is assigned to plan the optimal allocations to the product agent, which, in turn, controls the technical specifications and forwards this information to the operation agent. Finally, the optimal machine and worker agent execute the assigned job. Table 3.6 shows the evaluated classification criteria of the KUZNETSOV MAS in detail.

Table 3.6: Evaluation of KUZNETSOV MAS with proposed criteria [Skob13]

Criteria	Content
Name	KUZNETSOV multi-agent system
Area of application	Real-time resource management in manufacturing workshops
Purpose/Scope	KUZNETSOV multi-agent system provides real-time resource scheduling by reacting in a flexible and event-driven manner for increasing the productivity in a machine-production factory. This objective should be achieved by adaptive behaviour where reallocations for orders and resources must be scheduled to solve time conflicts. The result should be available on screens for the factories staff to improve communication between all work groups.
Architecture	Semi-heterarchical PROSA-based (product, resource, order, staff) architecture [Brus98]
Sub-agents description	Amount of sub-agents: six (OrgaA, OA, PA, OpA, WA, MA)
organisation agent (OrgaA)	Functionality: Coordination and scheduling of business (OA) and technical (MA and WA) jobs (decompose processes into several jobs) on upper level as "head" of agents with advisory purpose to satisfy every agent and balance resources while enhancing KPIs, to change strategies for optimal solution and harmonise the involved agents. ISA-95 level: L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Not given

Criteria	Content
order agent (OA)	Functionality: Loads information from OrgaA to analyse results and schedules best allocation for PA (e.g. shifting jobs to solve time conflicts) while obtaining minimal costs, priority setting, deadline for order execution, maximum quality and focus on minimal delivery time. The structure of the order can be displayed for the customers and factories' management members. ISA-95 level: L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Not given
product agent (PA)	Functionality: Match order specifications from OA and technical specifications from OpA to specify domain-specific product requirements (e.g. material, detail dimension). ISA-95 level: L3 Real-time capability: Yes Source type information: Data Communication/Interaction: Not given
operation agent (OpA)	Functionality: Match information from PA to plan optimal schedule with workers and machines with start/stop preferences. The OpA should be able to generate a plan that shows queue of machine events and schedule of workers that highlights errors (e.g. worker matched to machine is not be able to finish in time or does not have required qualification) if jobs cannot be handled with given requirement. ISA-95 level: L3 Real-time capability: Yes Source type information: Data Communication/Interaction: Not given

Criteria	Content
worker agent (WA)	Functionality: Plans and schedules factories' workers' time and salary with OrgA specifications by knowing key competencies for maximal workload (requirements: must be busy all working time and receives extra salary for high performance and quality of work). The WA analysis the best matching for job allocations and dynamic price for the several workers A worker can operate several machines (MA) and receives information about jobs from OrgaA. A list of tasks for all or individual workers can be generated with the WA. ISA-95 level: L3-L4 Real-time capability: Yes Source type information: Data/Hardware Communication/Interaction: Not given
machine agent (MA)	Functionality: Maximise possible resource workload on machine while obtaining restrictions (e.g. capacity, order priority, energy consumption) with OrgA specifications and paying attention to machines' maintenance. A machine can require the operation of several workers (WA) and receives information about jobs from OrgaA. ISA-95 level: L3 Real-time capability: Yes Source type information: Data/Hardware Communication/Interaction: Not given
Implementation	Implementation process was still in progress at the time of publishing the paper/ Today: no implementation on this MAS was published (no further details were given on programming, but implementation on p2p platform proposed)
Knowledge processing	Manufacturing ontology based on ISA-95 standards
Learning processing	Not possible
Solution	Example: see Fig. 3.4
CPPS Requirements	C.1 (+) | C.2 (-) | C.3 (o) | C.4 (+) | C.5 (-)
CPPS Characteristics	FX, RL, RC/AA
RAMI 4.0 Requirements	R.1 (-) | R.2 (-) | R.3 (o) | R.4 (-) | R.5 (-)

Criteria	Content
Advantages	Compared to a production system without a MAS organisation: ▪ Staff can simulate new orders to examine how existing orders must be reallocated or postponed to fulfil new order (high potential of the adaptive scheduling) ▪ Increase of workshop productivity by 10-15% ▪ Reduction of planning and scheduling effort by 3-4 times ▪ Increase of resource efficiency to 15% ▪ Reduction of unexpected events by 2-3 times ▪ Increase of the percentage of the business orders completed within the timeframe by 15-30%
Disadvantages	No in depth implementation details on platform or language use given, no communication or interaction base discussed.
Others	Key ideas are also used and presented in the ARUM [MARI13] approach and were also already applied as a simulation for flight scheduling in the ISS (International Space Station).

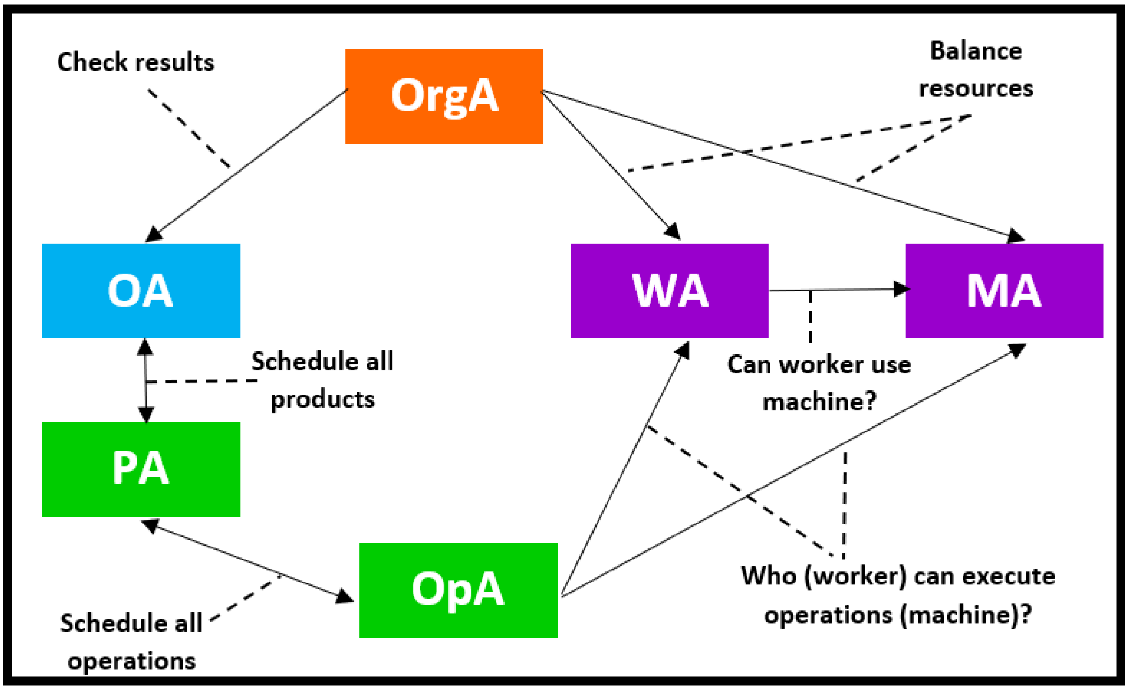

Figure 3.4: Simplified KUZNETSOV MAS architecture [SKOB13]
organisation agent (OrgaA), order agent (OA), product agent (PA), operation agent (OpA), worker agent (WA), machine agent (MA)

3.3.4 An holonic MAS for manufacturing execution systems focusing on control and scheduling

[Blan07]'s work focuses on the application of holons for manufacturing execution systems. As already discussed in section 2.2.2, holons serve the purpose to describe whole-part constructs. The presented holonic system consists of four holons (product, resource, order, staff) and should support the flexibility of a production system while optimising the resource, productivity and time consumption. The system is implemented in a MAS framework to simulate the application. Table 3.7 shows the evaluated classification criteria of the holonic MAS in detail.

Table 3.7: Evaluation of an holonic MAS with proposed criteria [Blan07]

Criteria	Content
Name	Holonic MAS for manufacturing execution systems
Area of application	Manufacturing area for discrete-event driven execution systems and applied to the American Glass Production (AGP) company
Purpose/Scope	Holonic MAS characteristic is to maintain the stability of hierarchy while providing the dynamic flexibility of heterarchy. Therefore, the aim of this product-centred and distributed manufacturing execution system is to minimise material consumption and maximise productivity while considering the time requirements. Moreover, the system should support reconfigurability for production control systems.
Architecture	Semi-heterarchical and PROSA-based (product, resource, order, staff) architecture [Brus98] Reactive and deliberative behaviour
Sub-agents description	Amount of sub-agents: four (PH, RH, OH, SH)
product holon (PH)	Functionality: Define the characteristics' of a certain product with product (e.g. shape, property) and process specifications. Products can be either bought, manufactured or sold (e.g. material, intermediate products). A PH may consist of other PH. They behave as information base for other holons' questions and answer queries. ISA-95 level: L3 Real-time capability: No Source type information: Data/Hardware Communication/Interaction: Not given

Criteria	Content
resource holon (RH)	Functionality: Each physical device (e.g. machine, transport device) is connected with a resource holon. It is responsible for optimal lot-sizing, scheduling, and organisation of the given tasks. The RH takes the dynamic conditions of machine failure and rescheduling into account. The RH can be separated into four classes: supplier, assembling, disassembling, and transformation holons. They use the process specifications from the PH and the allocated tasks from the OH to execute the given work. A single RH may be subscribed by several OH for its service (resource holarchy). RH are considered to be runtime static elements. ISA-95 level: L2-L3 Real-time capability: Yes Source type information: Data/Hardware Communication/Interaction: Not given
order holon (OH)	Functionality: Each OH is associated to a PH that matches the same requirements to assure the quality specifications. This feature increases flexibility, because products that did not fit the initial requirements of an order might fit a different order with another purpose. The OH ranks the orders by importance with the use of priority specifications and deadlines. An OH may consist of other OH. A proposed mechanism synchronises the execution of manufacturing tasks to guarantee the availability of components while retaining time constraints. They subscribe tasks to a RH which is able to execute the allocated work. The whole system depends on the lifecyle of the OH (product-centred). A single PH may be used by several OH for its specifications (order holarchy). OH are considered to be runtime dynamic elements. ISA-95 level: L4 Real-time capability: No Source type information: Data Communication/Interaction: Not given

Criteria	Content
staff holon (SH)	Functionality: The SH has a global view of the system and helps other holons to perform their tasks by analysing the optimal functionality and providing an advisory feature. In this holonic MAS execution system, the SH acts as facilitator agent/interface to connect the holonic system with the discrete-event driven simulator. ISA-95 level: L4 Real-time capability: No Source type information: Data Communication/Interaction: XML format via TCP/IP connection with simulator
Implementation	FIPA specifications: JADE software framework (fully in JAVA) Discrete-event simulation with ARENA software
Knowledge processing	Meta heuristics, BOM (bill of material), routing
Learning processing	Not possible
Solution	Example: see Fig.3.5
CPPS Requirements	C.1 (+) | C.2 (-) | C.3 (+) | C.4 (+) | C.5 (+)
CPPS Characteristics	FX, RL, RC/AA, DP
RAMI 4.0 Requirements	R.1 (-) | R.2 (-) | R.3 (o) | R.4 (-) | R.5 (-)
Advantages	This holonic MAS is partially implemented and still in use in the AGP: a program called KD performs the production supervision. Therefore, human errors due to information misapplication in the production process are not possible anymore. A detailed disturbance handling is discussed. Moreover, the system is compatible with the similar HCBA approach.
Disadvantages	Space and time transformations (stock and transport) are not discussed. No communication or interaction base is given.
Others	Future work should focus on task allocations when different resources match the process requirements. This might be possible to solve with a negotiation process between the holons. Moreover, space transformation (transport) should be taken into account.

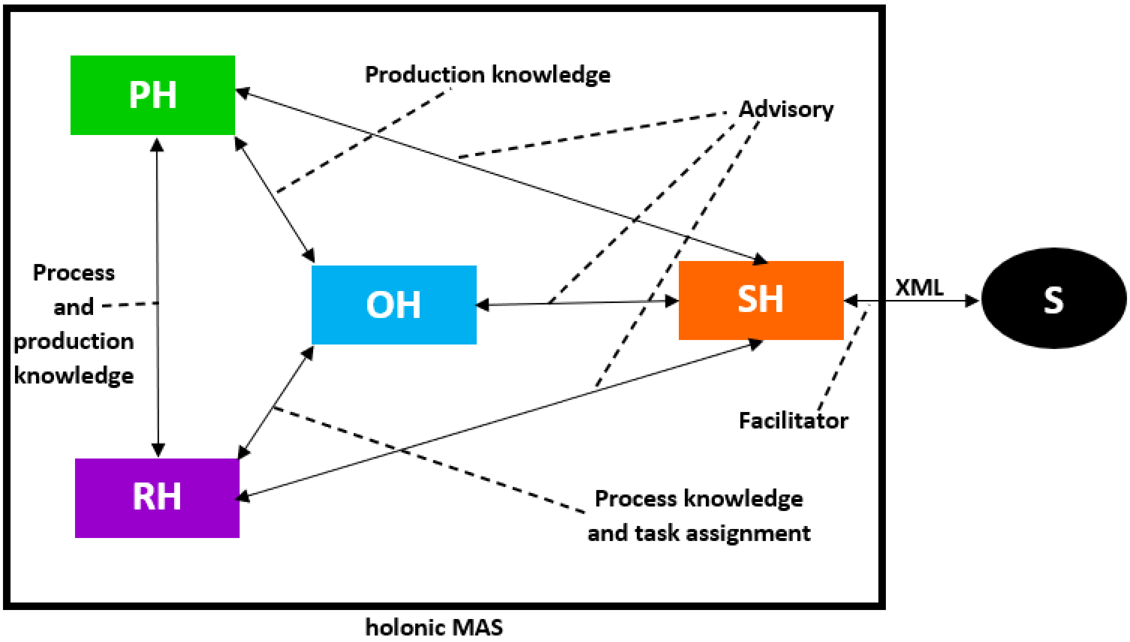

Figure 3.5: Simplified holonic MAS architecture [Blan07]
product holon (PH), order holon (OH), resource holon (RA), simulator (S)

3.3.5 SOCRADES: SOA-devices and MAS for industrial implementation

[Karn08] and [Karn09]'s work differs massively from other presented MAS systems. Factories' applications that take diversified infrastructures into account, should be able to connect directly from the enterprise layer to the devices in the shop layer. This can be realised with web services which are able to provide high interoperability. Therefore, [Karn08]'s approach puts a service-oriented architecture (SOA) in focus. This approach is implemented in a MAS to simulate the dynamic infrastructure and create a flexible production system. The network is based on modular entities that provide their functionality via device profiles for web services (DPWS). The systems focus in not set on production planning and control. Regardless, simulations in this area are possible. Table 3.8 shows the evaluated classification criteria of the SOA MAS in detail.

Table 3.8: Evaluation of a SOA MAS with proposed criteria [Karn08] and [Karn09]

Criteria	**Content**
Name	SOCRADES: a service-oriented MAS
Area of application	Industrial automation systems for modular factories and applied in a dynamic assembly system, named Prodatec/FlexLink DAS 30.

Criteria	Content
Purpose/Scope	This approach should couple all ISA-95 levels. The physical devices (e.g. robots, programmable logic controllers (PLCs), sensors) on the shop floor level should provide digitalised services via a DPWS gateway or are part of a virtual DPWS device simulation for behaviour testing. The execution/simulation layer should host several agents that cooperate in an arbitrary order and control the devices on the shop floor level via the DPWS connection. The users' request from the outside world should be received via the DPWS from the agents, and scenarios that are demanded should be executed. At the enterprise level, applications and business processes should be able to communicate with the shop floor level via the DPWS.
Architecture	Service-oriented and fully-heterarchical MAS architecture The agents with MES functionality can be located in the simulation environment
Sub-agents description	Amount of sub-agents: five (MA, DEA, DGA, ScA, SeA)
management agent (MA)	Functionality: Mostly management function, e.g. process evaluations of user arguments, logging. Moreover, it is responsible for the creation of other agents. ISA-95 level: L3-L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Communication with the "outside" world via web services (DPWS) and within the MAS with agent communication language (ACL).
device explorer agent (DEA)	Functionality: Also called "DPWS client agent". This agent should discover and expose all DPWS devices and their service/data in the whole system to other applications. It does not have a public interface and therefore is not used for any service for the outside world. ISA-95 level: L3-L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Communication with the "outside" world via web services (DPWS) and within the MAS with agent communication language (ACL).

Criteria	Content
device generator agent (DGA)	Functionality: Receives and executes user requests and forwards them to the SeA. ISA-95 level: L3-L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Communication with the "outside" world via web services (DPWS) and within the MAS with agent communication language (ACL).
scenario agent (ScA)	Functionality: Specific to each scenario and the execution of its strategy/logic. ISA-95 level: L3-L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Communication with the "outside" world via web services (DPWS) and within the MAS with agent communication language (ACL).
service agent (SeA)	Functionality: Also called "DPWS service agent". It is visible as an interface to the outer world via DPWS communication and handles all client's requests. The DPWS is not part of the MAS environment (JADE). Therefore, either a direct implementation or a bridging implementation of the DPWS into the agent is developed. ISA-95 level: L3-L4 Real-time capability: Yes Source type information: Data Communication/Interaction: Communication with the "outside" world via web services (DPWS) and within the MAS with agent communication language (ACL).
Implementation	FIPA specifications: JADE software framework (fully in JAVA) DPWS (Devices Profile for Web Services) for web integration
Knowledge processing	Ontology services, data transformation services and life-cycle management to share knowledge
Learning processing	Not possible
Solution	Example: see Fig.3.6

Criteria	Content
CPPS Requirements	C.1 (+) | C.2 (+) | C.3 (+) | C.4 (o) | C.5 (+)
CPPS Characteristics	FX, RC/AA, DP
RAMI 4.0 Requirements	R.1 (o) | R.2 (+) | R.3 (+) | R.4 (+) | R.5 (+)
Advantages	Several simple scenarios were already tested and evaluated. With 2000 devices, the system simulation is fully functional and covers most of the existing infrastructures today. At a higher device number, the system fails due to increasing CPU usage and non-responsiveness. With 1000 devices, the system executes in a comparatively short time. The Prodatec/FlexLink DAS 30 (Figure 1.1) is a flexible production system with two workstations. The presented SOA MAS architecture is implemented into this transfer system to navigate and control palettes between the two work stations.
Disadvantages	The system was implemented for a proof of concept and no optimisation features were included to calculate optimal resource planning.
Others	Future work should concentrate on larger scale infrastructures, more difficult scenarios, cooperation of agents, proper real-time communication and transparent enterprise integration.

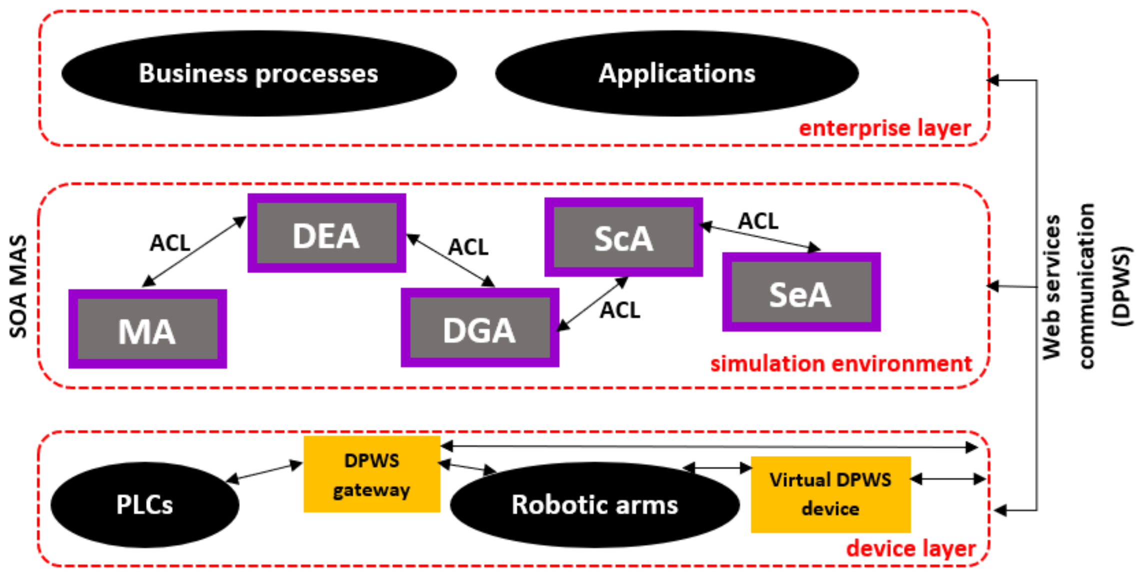

Figure 3.6: Simplified SOA MAS architecture with communication/interaction [Karn08] *management agent (MA), device explorer agent (DEA), device generator agent (DGA), scenario agent (ScA), service agent (SeA)*

3.4 Discussion of the selected multi-agent system approaches in the context of digital and modular production

The approaches of ([PECH02], [BADR10], [SKOB13], [BLAN07] and [KARN08]) were individually evaluated in section 3.3. In this section, a comparison of all five MASs and their applicability for digital and modular production shall be discussed. In this context, the similarities and differences of the individual MAS architectures and their implementation, simulation and application in the real world are examined. Moreover, the suitability of an integration of each MAS into the industry 4.0 is to be evaluated.

Considering all MAS architectures, it is noticeable that several agent types occur repeatedly. Their given names may be different in every individual MAS approach, but their functionality and purpose for the whole system are for the most parts the same. In section 3.3, the graphic colour illustrations of the MAS approaches indicate the similarities of the systems sub-agents. The following five sub-agent patterns can be highlighted:

- **Support agent:** this type of agent can be positioned at the highest level of the planning layer. Like the given name already suggests, the support agent has an advisory and supporting behaviour towards the other agents by providing production data and analysing the optimal behaviour of each agent. Moreover, it is responsible for balancing the interests and interactions of the other agents.
- **Order agent:** this agent provides specific production data (e.g. deadlines, priority) about the order. It is responsible for forwarding this information to the agents that control and schedule the devices on the shop floor level to find the optimal allocation for the execution.
- **Product agent:** this agent holds all detail specifications of the products or services which the factory produces (e.g. material composition, volume, transportation details). Same as the above-mentioned order agent, it is responsible for forwarding this information to the agents that control and schedule the devices on the shop floor level to find the optimal allocation for the execution.
- **Resource agent:** this agent is responsible for controlling the shop floor processes by assigning different physical devices or human staff members to execute the subscribed products of each individual order, while obtaining the restriction from the order and product agent. Therefore, the resource agent must schedule the optimal working plan for maximal resource use while minimising the time consumption.
- **External agent:** this agent serves users from the outside world to connect to the factory's production system. It can be used as a status basis for the progress of the order, or for simulating future orders.

In Table 3.9, a summary of the availability of the above-mentioned sub-agent patterns with their colour coordination from the graphic illustration can be found for the individual MAS approaches. The existing sub-agents were listed and named with their given acronym from their MAS evaluation in section 3.3 for further detailing. It has to be mentioned that the MAS approach by [KARN08] does not fit accurately into this classification, because this proposal focuses more on the service-oriented implementation of connecting physical devices with the cyber-physical world, than on the conventional MAS architecture.

For every approach, the agent communication, interaction and linking was implemented differently. Therefore, no further comparison can take place on this basis. However, it has to be stressed that some MAS approaches were giving detailed description about the agents' communication/interaction protocols and linking; others did not mention this fact at all. Therefore, in Table 3.9 a summary of the existing or non-existing explanation of the agents' communication/interaction can be found. A "+" indicates the availability and a "-" the absence of this feature. The same principle is also applied to indicate the MASs' real-time capability.

Table 3.9: Architecture details on sub-agent and communication availability

Criteria	**MAS approach**				
	[PECH02]	[BADR10]	[SKOB13]	[BLAN07]	[KARN08]
Support agent	DBA	-	OrgA	SH	-
Order agent	CA	JGA, JA	OA	OH	-
Product agent	-	OA, TA	PA, OpA	PH	-
Resource agent	SA	MA, MMA, BA, AGVA,	WA, MA	RH	MA, DEA, DGA, ScA, SeA
External agent	RA, MA	-	-	-	MA, DEA, DGA, ScA, SeA
Communication/ Interaction	+	+	-	-	+
Real-time capability	-	+	+	-	+

For an appropriate judgement of the applicability of the five discussed MAS, not only the architecture description has to be taken into account, but most important might be their execution details. This implies the existence of a fully implemented system, an evaluated simulation and the attempts that have been made to integrate the MAS into a real industrial enterprise. As already discussed in section 2.1.2, the industrial application of MASs is very difficult. Therefore, a focus is set on the implementation and simulation execution, rather than the integration into an enterprise which can only be seen as an advantage. In table 3.12, an overview of the execution details can be found. A "+" indicates the availability, a "-" the absence, and additionally an "o" for an upgradable implementation, simulation or industrial application.

Table 3.10: Execution details on MAS approach

Criteria	**MAS approach**				
	[PECH02]	[BADR10]	[SKOB13]	[BLAN07]	[KARN08]
Implementation report	+	+	o	+	+
In depth simulation	o	+	+	+	+
Industrial application	+	-	-	+	+

For all evaluated MAS proposals, a detailed description of their architecture was given, which was already defined as a main criterium in section 3.1 for a MAS to be even considered to be evaluated in detail in section 3.3. Putting the communication, real-time capability and execution details in focus, it becomes clear that the approaches of [BADR10] and [KARN08] can be considered to fulfil the given criteria best, compared to the other MAS. Nevertheless, [BLAN07], [PECH02] and [SKOB13] can not be classified as non-functional, even though they are all missing multiple criteria. [PECH02] does not provide a in depth simulation and cannot act in a real-time manner. [BLAN07] is missing real-time capability and the communication/interaction base. [SKOB13] does not give details about the implementation and communication/interaction process.

The current industrial trend is shifting towards applications in the industry 4.0 area. The challenging switch from conventional automation systems towards cyber-physical production systems (CPPS) can be the supported with use of smart entities, mainly agent-based systems, that enable an industrial enterprise to make the leap towards industry 4.0 [CRUZ19]. Moreover, the industry must meet the reference architectural model for industry 4.0 norm (RAMI 4.0) to approach the industry 4.0 field in a structured manner where every technical aspect and participant is considered [CRUZ19]. Taking the requirements for an agent-based CPPS and full integration into the RAMI 4.0 norm from section 3.2 into account, the five selected approaches can be compared regarding their individual applicability for an application into industry 4.0. In Table 3.11, a summary of the evaluated CPPS and RAMI 4.0 requirements can be found with the same ranking as described in section 3.2. The approaches of [BLAN07] and [KARN08] satisfy the requirements of an agent-based CPPS almost completely. This outcome might not be surprising especially for the [KARN08] proposal, because the approach provides a service-oriented and complete ISA-95-integrated architecture which implies an intense use of web services and capability to handle all ISA-95 levels. The other approaches can be mostly located in the ISA-95 level 3 and are therefore failing the requirement of being level independent. It must be highlighted that a massive advantage of [BADR10], [SKOB13] and [BLAN07]'s proposals is a detailed error handling. The only mentionable approach for fulfilling the RAMI 4.0 requirements is the proposal of [KARN08], which can also be explained by the service-oriented architecture that supports the main aim of industry 4.0, namely digital production. It has to be mentioned that the other approaches could likely be expanded and integrated into a digital framework without much of an issue, but the given descriptions do not make an effort to discuss the integration of the MASs into a fully developed industry 4.0 environment. Moreover, all discussed MAS approaches were developed in a time when the concept of industry 4.0 was not the centre of attention, and the development of MASs was mainly supposed to support distributed automation systems.

Table 3.11: Feasibility of MAS for industry 4.0 application

Criteria	**MAS approach**				
	[Pech02]	[Badr10]	[Skob13]	[Blan07]	[Karn08]
C.1 **Application independence**	+	+	+	+	+
C.2 **ISA-95 level independence**	-	-	-	-	+
C.3 **Platform independence**	+	+	o	+	+
C.4 **Robustness against errors**	o	+	+	+	o
C.5 **Decentralisation**	-	-	-	+	+
R.1 **Various engineering fields**	-	o	-	-	o
R.2 **System boundary report**	-	-	-	-	+
R.3 **Nestability principle**	o	o	o	o	+
R.4 **Administration shell**	o	-	-	-	+
R.5 **Functional properties**	o	-	o	-	+

The concept of a dedicated manufacturing line seems to be outdated in the current ever-changing world with more-than-ever-demanding customer requirements. The ability of reacting flexible and effectively in a dynamic environment is a main property of every MAS. Because of this fact, MASs are highly feasible to be integrated into modular production. MASs are normally designed to serve in different domains and for distinct purposes and therefore, they all have a different focus. Four behaviour characteristics were discussed for agent-based CPPSs in section 3.2. The five selected MASs were chosen according to the criteria of having a detailed architecture description, under the CPPS circumstance that they all have a high reconfigurability and adaptability feature.

Especially for modular production, the ability of being reconfigurable when sudden changes in the hardware, software and structure system of a factory occur is going to be convenient. For example, these sudden changes might happen because the production capacity changes due to machine overloading or non-availability of materials. Moreover, adaptable reactions to environmental changes are necessary in modular production, mainly due to overcompetitive markets or customer related order changes. As seen in Table 3.12, a "+" indicates the availability and a "-" the absence of a particular CPPS characteristic. All five MAS approaches are applicable in a modular production environment. It must be emphasised that the proposals of [BADR10], [SKOB13] and [BLAN07] have the additional advantage of being a highly reliable system. They maintain a high level of performance while exceptional failure cases might occur and are proven to have an exceptional high fault tolerance. This behaviour is not only very desirable in modular production, but preferable for all profit oriented enterprises.

Table 3.12: Feasibility of MAS in modular production with CPPS characteristics

Criteria	**MAS approach**				
	[PECH02]	[BADR10]	[SKOB13]	[BLAN07]	[KARN08]
Flexibility	+	+	+	+	+
Reliability	-	+	+	+	-
Reconfig./Adapt.	+	+	+	+	+
Dependability	-	-	-	+	+

To summarise, all MASs have a detailed architecture and are applicable in modular production. For future use, it would be useful to further develop the approaches of [PECH02], [BADR10] and [SKOB13] to be able to reach an full integration of these MASs into digital production. In Table 3.13, a personal assessment of the MAS presentation can be found. A "+" indicates a high, a "o" a medium and a "-" a low performance on the individual criteria. Overall, the MAS approaches by [BLAN07] and [KARN08] had the best performance based on a subjective assessment.

Table 3.13: Overall performance of the MAS

Criteria	**MAS approach**				
	[PECH02]	[BADR10]	[SKOB13]	[BLAN07]	[KARN08]
Execution details	o	o	-	+	+
CPPS	o	o	o	+	+
RAMI 4.0	-	-	-	-	+
Modular production	o	+	+	+	o

4 Conclusion and Outlook

In this work, a detailed literature review on MAS proposals with a focus on production planning and control was accomplished. With more than 60 fitting articles in this research area, the selection of agent-based systems had to be further reduced. 13 classification criteria were proposed in order to set an equal foundation for the MASs. Five different approaches were selected and evaluated in detail. Through a comparison of all systems, the MASs' applicability for digital and modular production was assessed. It's noticeable that all selected MASs are applicable in modular production, but neither is implemented as a standardisation in an real industrial enterprise.

Therefore, several future challenges and trends that can be pointed out:

- More *demonstrators* in the industry would help industrial enterprises and future customers to understand the advantages and benefits that come along if an agent-based system is implemented in an industrial environment. Most work on MASs did not leave the stage of running in simulators and are therefore hard to trust for outsiders. It is important to demonstrate that these systems are able to handle real-life production planning and control in order to adapt this technology to an actual enterprise.
- *Real-time control* is one of the most radical changes that has to take place in order to exploit the whole potential of modular systems. Nowadays, the major technological barrier is the incompetence of manufacturers to understand the need for real-time capability to have more robust and flexible systems.
- The trend towards *service-oriented and cloud-applicable architectures* must be further supported. These architectures are very desirable, because they enable customers and factory staff members of running status reports and applications on a web browser which increases user-friendliness.
- The area of intelligent *learning* in a MAS environment should be further investigated in order to improve agents' behaviour and performance. The capability of learning would enable an agent-based system to exceed its already flexible reaction to an even more optimal solution in sudden changes.
- More *standardisation and mature development support* would simplify the implementation of agent-based systems. They are crucial for quality and safety aspects. Moreover, they are necessary for MASs to be even accepted in the industrial area.

A1 Appendix

A1.1 Literature overview for Multi-Agents Systems

Table A1.1: Recent work focusing on MASs for industrial application (literature reviews)

Author(s) Reference	**Year**	**Content**	**Citation Count** Scopus	Scholar
Adeyeri et al. [ADEY15]	2015	Literature review from 2003 to 2014 of agent and MAS used in several manufacturing application domains: ▪ (Virtual) manufacturing enterprise ▪ Enterprise integration ▪ Supply chain management ▪ Supply chain management ▪ Planning, control and scheduling ▪ Reconfigurable System ▪ Infrastructure Introduction of a framework for MAS in Industry 4.0	33	22
Leitão et al. [LEIT16]	2016	Literature review from 1995 to 2015 of MAS applications for several industrial cyber-physical systems: ▪ Smart production ▪ Smart electric grids ▪ Smart logistic ▪ Smart healthcare Proposing design principles, standards and key challenges for integrating MAS in cyber-physical systems	238	333
Lüder et al. [LÜD17]	2017	Literature review from 2006 to 2014 of MAS and identification of two multi-agent design patterns for production control	11	12

Author(s) Reference	Year	Content	Citation Count Scopus	Scholar
Salazar et al. [CRUZ19]	2019	Literature review from 1998 to 2018 of german MAS design pattern applications for several cyber-physical production domains: ▪ Smart grids ▪ Material flow systems ▪ Energy system ▪ Image processing application ▪ Smart manufacturing Proposing in depth classification criteria for MAS patterns and evaluation of selected MAS applications	31	32
Vogel-Heuser et al. [VOGE20]	2020	Literature review and analysis from 2006 to 2018 on MAS approaches for different industry 4.0 application areas	1	1

Table A1.2: 61 articles that describe MAS-based and real problem-solving approaches in the manufacturing and production area || 5 discussed articles marked in bold

Author(s) Reference	**Year**	**Content**	**ISA-95 Level**	**Citation Count** Scopus	Scholar
Brussel et al. [Brus98]	1998	PROSA: an holonic MAS for shop floor control in manufacturing	L2	1009	1712
Wada et al. [Wada00]	1998	Flexible manufacturing machinery control based on a MAS software prototype	L1	8	1
Brückner et al. [Brü00]	1999	MASCADA: a MAS manufacturing process control approach	L2	-	54
Bussmann et al. [Buss01]	2001	Flexible adaptation for manufacturing control systems based on a MAS	L2	95	157
Pechoucek et al. [Pech02]	**2002**	**EXPLANTECH: project-driven production planning with a MAS**	**L3**	**27**	**54**
Djurdjanovic et al. [Djur03]	2003	WATCHDOG AGENT: prediction on machinery life expectancy based on a controlling MAS	L1	255	408
Fletcher et al. [Flet03]	2003	An holonic MAS manufacturing software control system	L2	4	32
Kornienko et al. [Korn03]	2003	A software model for MAS in dynamic manufacturing process planning	L2	11	28
Lee et al. [Lee03]	2003	Dynamic short-term resource scheduling with a MAS for market-based control	L3	109	114
Mönch et al. [Mön03]	2003	FABMAS: a MAS manufacturing process control approach	L2	27	59
Rabelo [Rabe03]	2003	HOLOS: an implemented framework for dynamic scheduling and shop floor control with an agile and reconfigurable MAS	L2	6	23
Sadeh et al. [Sade03]	2003	MASCOT: a MAS decision support environment for the control of dynamic enterprise supply chain management	L4	63	100
Lüder et al. [Lüd04]	2004	PABADIS: a MAS process control approach for distributing production execution systems	L1-L4	57	83
Jacobi et al. [Jaco05]	2005	AGENTSTEEL: production planning, scheduling and observation based on a MAS	L3	12	25

Author(s) Reference	Year	Content	ISA-95 Level	Citation Count Scopus	Scholar
Lastra et al. [MART05]	2005	ABAS: MAS software simulation tools for manufacturing assembly control operations	L2	10	18
Marík et al. [MARI05]	2005	A MAS for industrial real-time process control	L1	23	75
Tang et al. [TANG05]	2005	A reactive MAS prototype model for manufacturing system control	L2	28	47
Colombo et al. [COLO06]	2006	Realization of an holonic MAS for process control and scheduling in industrial shop floor manufacturing systems	L2	116	198
Mönch et al. [MÖN06]	2006	MANUFAG: a PROSA-based MAS for process control in manufacturing systems	L2	24	43
Lima et al. [LIMA06]	2006	Production planning and control using a MAS for distributed resources	L3	43	84
Wong et al. [WONG06a]	2006	oHAN: an hybrid-based MAS for integrated process planning and scheduling	L2	85	116
Wong et al. [WONG06b]	2006	Evaluation of two (simple and hybrid) MAS architectures for dynamic manufacturing processes planning and scheduling	L2	128	184
Cândido et al.[CÂND07]	2007	NovaFlex: a MAS for manufacturing control of an agile shop floor assembly cell	L2	49	91
Karnouskos et al. [Karn08] [Colo15]	**2007**	**SOCRADES: SOA-devices and MAS for industrial implementation**	**L1-L4**	**21**	**34**
Blanc et al. [Blan07]	**2008**	**An holonic MAS for manufacturing execution systems focusing on control and scheduling for the AGP**	**L3**	**67**	**115**
Leitão et al. [LEIT08a]	2008	ADACOR-FMS: an holonic MAS for flexible manufacturing control and reconfiguration with software and hardware redundancy	L2	60	95
Leitão et al. [LEIT15b] [LEIT08b]	2008	GRACE: process and quality control for factory automation and self-adaptation with an holonic MAS	L2	71	105

Author(s) Reference	**Year**	**Content**	**ISA-95 Level**	**Citation Count**	
				Scopus	Scholar
Srivastava et al. [SRIV08]	2008	A MAS for flexible manufacturing with automated guided vehicles	L2	64	97
Guo et al. [GUO09]	2009	Scheduling strategies for manufacturing systems with a MAS	L2	69	94
Merdan [MERD09]	2009	Process Planning, Scheduling and Transportation within manufacturing locations	L2	-	39
Lepuschitz et al. [LEPU09]	2009	High and low level control with a MAS for manufacturing systems	L2	22	28
Wang et al. [WANG09]	2009	An agile manufacturing planning and control system with RFID techniques and a MAS	L2	54	87
Andreev [ANDR10]	2010	Manufacturing scheduling for adaptive networks with a MAS	L3	9	21
Badr et al. [Badr10]	**2010**	**An MAS approach for integrated production and transport scheduling for flexible manufacturing systems**	**L3**	**7**	**11**
Chen et al. [CHEN10]	2010	Production control based on a MAS for flexible manufacturing systems	L2	33	47
Vrba et al. [VRBA10]	2010	Dynamic reconfiguration of MAS-based control system for material flow systems	L2	61	84
Folmer et al. [FOLM11]	2011	Process control of production plants with MAS to increase flexibility	L2	-	11
Schütz et al. [SCHU11]	2011	Real-time production planning and execution for flexible manufacturing system based on a MAS	L2	12	15
Erol et al. [EROL12]	2012	Dynamic machine process scheduling and automated guided vehicles with a MAS-based approach	L2	87	139
Park et al. [PARK12]	2012	Swarm intelligence of cognitive MAS for autonomous manufacturing systems	L2	38	49
Ribeiro et al. [RIBE13]	2013	IDEAS: a MAS architecture for plug-and-produce focusing on control, reconfiguration and fast deployment	L2	12	18

Author(s) Reference	Year	Content	ISA-95 Level	Citation Count Scopus	Scholar
Ulewicz et al. [Ulew13]	2013	Increasing flexibility with a MAS for automated manufacturing plants	L2	5	6
Skobelev [Skob13]	**2013**	**KUZNETSOV: adaptive resource planning and scheduling based on a MAS**	**L3**	**17**	**51**
Barenji et al. [Bare14]	2014	A MAS- and RFID- based process control system for flexible manufacturing systems	L1-L2	79	100
Colombo et al. [Colo14] [Colo15]	2014	IMC-AESOP: industrial MAS in SOA and cloud-based architectures	L1-L4	142	290
He et al. [He14]	2014	Process planning and scheduling for make-to-order manufacturing system with a MAS	L2	49	74
Legat et al. [Lega14]	2014	A MAS to handle unforeseen failures on field level control	L1	9	14
Vogel-Heuser et al. [Voge14]	2014	MYJOGHURT: a MAS-based prototype demonstrator for cyber-physical production systems	L1-L3	67	100
Barbosa et al. [Barb15]	2015	ADACOR2: an holonic MAS architecture for self-organised manufacturing control	L2	157	239
Marín et al. [Mari13]	2015	ARUM: a manufacturing support system for planning and scheduling based on a MAS	L3	30	38
Rocha et al. [Roch15]	2015	PRIME: a MAS implementation for manufacturing plug-and-produce	L2	17	53
Cala et al. [Cala16]	2016	A MAS approach for flexible manufacturing control	L2	6	6
Regulin et al. [Regu16]	2016	A MAS-based control system for material flow systems	L2	16	25
Ryashentseva [Ryas16]	2016	A MAS control architecture for production systems	L2	-	7

Author(s) Reference	**Year**	**Content**	**ISA-95 Level**	**Citation Count** Scopus	Scholar
Lüder et al. [LÜD17]	2017	Identification of design patterns for MAS in production control	L3	11	12
Rehberger et al. [REHB17]	2017	Decoupling planning of production sequences from distributed real-time control with a MAS for reconfigurable manufacturing	L3	10	11
Theiss et al. [THEI17]	2017	A real-time Java control MAS platform	L2	-	4
Cruz et al. [CRUZ18]	2018	Production control for independent cyber-physical systems with a MAS	L2	10	14
Fischer et al. [FISC18]	2018	A MAS-based control system for material flow systems	L2	9	11
Ghita et al. [GHIT18]	2018	SCEMP: a MAS for manufacturing control and scheduling to predict maintenance	L3	5	3
Shukla et al. [SHUK18]	2018	A MAS for integrated process planning and scheduling in job-shop manufacturing systems	L2	8	7

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