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Confidential: no

Supervisor: Dr. ir. Y. Pang

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Agent technology offers the approach to monitor and control complex distributed systems. Agent technologies create autonomous decision makers which communicate their explorations, negotiate their preferences and coordinate their intentions to achieve the operational goals on both individual and system levels. Such distributed artificial intelligent approach makes agent systems especially suitable for manufacturing where the system complexity can be controlled with respect to local problem-solving instead of centralized approaches.

The application of agent technologies is booming nowadays in the field of manufacturing control. This assignment is to provide a state of the art literature review of such applications. The survey of this literature assignment should cover the following:

- to understand the concepts of agent and agent system and the link with manufacturing
- to summarize the possible application fields of agent technology in manufacturing
- to investigate the characteristics, general architectures, basic interaction protocols and intelligent abilities of agent in the domain of manufacturing and manufacturing control
- to explore the current applications of agent technology in manufacturing control
- to indicate the future development of agent technologies in manufacturing

This report should be arranged in such a way that all data is structurally presented in graphs, tables, and lists with belonging descriptions and explanations in text.

The report should comply with the guidelines of the section. Details can be found on the website.

The mentor,

Dr. ir. Y. Pang

Application of agent technology in manufacturing control

D.S. de Boer

Literature Survey

TU Delft Delft University of Technology

Transport Engineering and Logistics

Application of agent technology in manufacturing control

Literature Survey

D.S. de Boer

November 15, 2016

Faculty of Mechanical, Maritime and Materials Engineering (3mE) · Delft University of Technology

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Abstract

Manufacturing systems are changing a lot, especially in recent years. The main reason is the shifting from a supplier's to a customer's market. This transition is caused by fluctuations in the market due to globalization, more choices for customers, increasingly complex products and continuous changes in technologies to produce them. This results in the demand for manufacturing (control) systems which are adaptable, flexible and capable of dealing with complex problems. Traditional hierarchical and centralized control approaches are not sufficient enough. Agent-based systems on the contrary allow distributed and heterarchical approaches, which are capable of controlling the required systems. Agent-based systems therefore allow further development of manufacturing control systems in order to stay competitive and future proof.

An agent is an autonomous entity that can adapt to and interact with its environment. Together, agents form multi-agent systems which are capable of dealing with complex manufacturing problems. Agent-based systems are a relatively new concept. Its development started after the use of computerized systems with programmable logic controllers became standard. Since then, many agent architectures, different interaction protocols and control approaches have been proposed. Applications for agent technologies can be found in every step of a manufacturing process. From the design of a product until the assembly. What all these steps have in common is the fact that (part of) a manufacturing system is of few utility without the presence of an appropriate control system. Manufacturing control systems are concerned with managing and controlling the physical activities in the factory. With the correct use of agent-based distributed and intelligent control solutions, the systems are adaptable, flexible and capable of dealing with complex problems. Despite these advantages and that there are already a number of industrial applications, a wide spread adoption of the industry lagging behind.

Reasons for the lack of adoption are: manufacturers wait for the technology to mature more, the industry is reluctant to change and companies are not always able or willing to do major investments that are required. However, with continuous development of agent systems and complementary technologies many of these road-blockers are already of will be overcome. Hence completing the transition towards widely use of agent-technologies.

Keywords: multi-agent systems, agent technology, manufacturing control, distributed and heterarchical systems.

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Chapter 1

Introduction

1-1 General introduction

Mass production with centralized decision making and planning was once considered an efficient way to run a manufacturing organization. However, globalization and continuous change in demands have resulted in fluctuating markets. These fluctuations in combination with products becoming more and more complex and rapid changes in technologies to produce them require transformations in the way of running a manufacturing process in order to stay competitive. Companies that cannot adapt fast enough to cope with these changes will be left behind [Odell, 2010]. The main result of these market changes is that the manufacturing industry is shifting from a supplier's to a customer's market. Where the customer is demanding more choices of different types of complex products and at the same time is becoming less loyal to a certain brand. "Therefore, companies must reduce the time-to-market, instantly satisfy demand, increase product variety, shorten product-life cycles, while maintaining quality and reducing costs" [Bussmann and Schild, 2000]. Next to these challenges, the manufacturing process must be robust as well as scalable, which is difficult in traditional centralized manufacturing processes. All these changes thus require a new approach in designing and operating manufacturing systems, where the high need for complexity, adaptability and agility plays an important role. These factors make agent technologies particularly suitable. A multi-agent system for example, which is a computerized system consisting of multiple interacting agents within an environment. An agent within a such a system is an autonomous entity that can adapt to and interact with its environment [Odell, 2010]. Due to these properties, multiple agents can form a functioning complex dynamical system and make manufacturing systems more suitable for the future.

1-2 Goal of the literature survey

The use of information technology (IT) in manufacturing is became a standard. Where the use was limited at first, it is currently taking over manufacturing. Especially with processes becoming more distributed and highly dynamical, in which real time logistics, intelligent control and transportation are important factors. These distributed processes require new approaches in IT, for example with the use of artificial intelligence (AI). Key elements in AI are "learning" and "problem solving". The part of AI that focuses on the interaction of intelligent agents is called distributed artificial intelligence (DAI). DAI can be categorized into three areas: multi-agent systems (MASs), parallel artificial intelligence (PAI) and distributed problem solving (DPS) [Nwana, 1996]. One way to deal with distributed dynamical systems in manufacturing is with the use of agents and these MASs. Therefore, the use of agent technologies in the field of transport engineering and logistics (TEL), especially in manufacturing, is getting more and more attention. Consequently, the goal of this literature survey is to provide a overview of agent technologies in manufacturing and in particular the application in manufacturing control. This is done with a study in different literature in order to make a survey that summarizes the application of agent technology in manufacturing control. The following aspects are discussed in this survey: the concepts of agents in general with its characteristics, possible fields of applications in manufacturing, manufacturing control, the applications in manufacturing control, the key elements of wide scale implementation of agent-based manufacturing systems and current and future trends.

1-3 Structure of the report

This paper will be structured as follows: after the introduction, the report starts in Chapter 2 with agents and agent systems in general. In that chapter the concept of agents, the characteristics, general architectures, basic interaction protocols and intelligent abilities are discussed. The general use of agent technologies in different manufacturing steps are explained in Chapter 3. In Chapter 4 the focus will be on agent technologies in manufacturing control. Followed by a few industrial applications in Chapter 5. In Chapter 6 is discussed why agent applications are not yet fully adopted by the manufacturing industry and what current and future trends in the manufacturing industry are. The last Chapter, Chapter 7, is the conclusion of the literature survey.

Chapter 2

Agents and agent systems

To properly understand the use and advantages of agent technologies in manufacturing, a general understanding of the concept of an agent and agent systems is necessary. Therefore, this Chapter gives an introduction to agent and agent systems. Firstly the general concept of an agent and multi-agent systems are explained. Thereafter, the anatomy of an agent, general architectures, interaction protocols and intelligent abilities are discussed. At last, the reasons for the use of agent technologies in manufacturing are discussed.

2-1 The concept of an agent and agent technologies

The concept of agents, multi-agent systems (MASs) and agent technology has its roots in computer science. In computer science, agents existed for a longer time and are commonly used. Before the use of agents, things were programmed centrally. The communication was through a central exchange of data and commands with the use of conventional objects which were passively waiting. Once invoked, they do their task or method and go back to being passive. These are know as passive objects. However, then the use of objects that react to events and are proactive became more popular. These are known as active objects, in other words known as agents [Odell, 2010]. Agent technology creates autonomous decision makers in order to solve problems locally, instead of through a central system. The use of agent systems further evolved with development of computer science and information technology (IT). Especially in combination with a branch of distributed artificial intelligence (DAI), which is devoted to MAS [Nwana, 1996].

2-1-1 What is an agent

An agent can be almost anything, for example: a person, a machine or a piece of software. The most basic definition is:

something that acts.

A more specific definition was found in [Odell, 2010]:

An agent is an autonomous entity that can adapt to and interact with its environment

Another more comprehensive definition was found in [Leitão, 2009], which states that an agent is:

An autonomous component that represents physical or logical objects in the system, capable to act in order to achieve its goals , and being able to interact with other agents, when it does not possess knowledge and skills to reach alone its objectives.

Although different sources give different definitions of an agent, most of them define about the same properties. The properties mostly listed as important ones are the same as the ones listed below according to [Monostori et al., 2006]. Especially the first 3 or 4.

- **Autonomous** - Agents are autonomous and therefore capable of acting without direct external intervention. Thus they control their internal state and behaviour within their environment.

- **Interactive** - Agents interact with their environment, and in a community, with other agents. The interaction can be conversational in nature, for example: marketplace-style bidding, making a query or negotiating contracts.

- **Adaptive** - Agents are adaptive, which means that they are capable of adjusting their behaviour to changes of the environment or other agents without intervention of a third party.

- **Intelligence** - Agents display some kind of intelligence, from planning, to reasoning with fixed rules and learning capabilities.

- **Purpose** - Agents act on the behalf of the user or their designer in order to meet a particular purpose.

An example of an agent with its properties and its environment is schematically shown in Figure 2-1. In the Figure can be seen that the agent is interacting with its environment through actions and observations. Therefore, it can adapt its behaviour to changes in its environment. The intelligence is displayed by the agent through reasoning (with keeping objectives, prior knowledge etc. in mind) and the evaluation that is done. Its purpose is formed by its goals. The agent does this all without external intervention and is therefore autonomous.

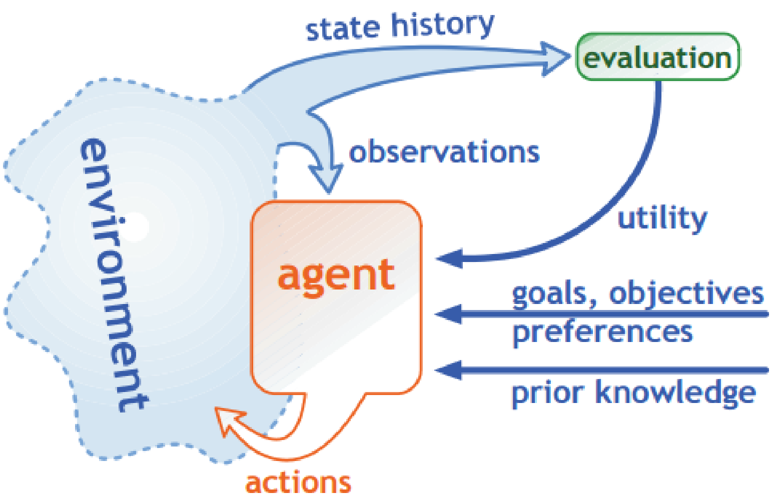

Figure 2-1: An agent and its environment - [Monostori et al., 2006]

All the listed properties are not all or nothing propositions. An agent can be for example autonomous, intelligent, interactive, and adaptive to some degree depending on the use of the agent.

Next to the most important properties, agents may possess various combinations of other properties whose usefulness is dependent on the application of the agent. These characteristics may include being [Odell, 2010]:

- **Sociable** - interaction that is marked by friendliness or pleasant social relations, that is, where the agent is affable, companionable, or friendly.
- **Mobile** - able to transport itself from one environment to another.
- **Proxy** - may act on behalf of someone or something, that is, acting in the interest of, as a representative of, or for the benefit of some other entity.
- **Rational** - able to choose an action based on internal goals and the knowledge that a particular action will bring it closer to its goals.
- **Temporally continuous** - is a continuously running process.
- **Credible** - believable personality and emotional state.
- **Transparent and accountable** - must be transparent when required, yet must provide a log of its activities upon demand.
- **Coordinative** - able to perform some activity in a shared environment with other agents. Activities are often coordinated via plans, workflows, or some other process management mechanism.
- **Cooperative** - able to coordinate with other agents to achieve a common purpose; non-antagonistic agents that succeed or fail together. (Collaboration is another term used synonymously with cooperation.)

- **Competitive** - able to coordinate with other agents except that the success of one agent implies the failure of others (the opposite of cooperative).
- **Rugged** - able to deal with errors and incomplete data robustly.
- **Trustworthy** - adheres to Laws of Robotics and is truthful.

There are currently many single-agent based systems. However, systems are distributed or becoming too complex for single agents, for that reason multi-agent systems are becoming increasingly popular.

2-1-2 Multi-agent systems

"A MAS is a set of agents that interact to solve problems that are beyond the individual capacities or knowledge of each individual agent" [Potiron et al., 2013]. Hence, often the agents themself have only a partial model of the environment and limited intelligence, but they can communicate. Due to this interaction, MASs are capable to solve problems which are too complex for individual agents or monolithic systems. Therefore MASs may exhibit emergent behaviour [Monostori et al., 2006].

A everyday life example of this is an ant colony. When modelling a simple version of an ant colony, it can be done with giving each ant (agent) the following three simple rules:

1. Wander randomly.
2. If food is found, take something back to the colony and leave a trail of pheromones, then go back to rule 1.
3. If a trail of pheromone is found, follow it to the food and go to rule 2.

By doing this, all the relatively dumb ants together form an efficient and successful working community. This example of emergence in nature forms the basis of *swarm intelligence*, which now forms the basis for inspiration to make new intelligent systems [Hadeli et al., 2004] [Leitão et al., 2012]. This is called stigmergy, see section 4-3-1.

MASs are systems that can make use of machines, automated guided vehicles (AGVs), humans or other aspects of a system, which can interact with software programs, which on their turn have access to physical sensors to detect all changes in a distributed business environment. Therefore, MASs promise the most for companies that operate in environments that are open and distributed and that have complex problems [Sycara, 1998]. Companies that have the greatest advantages of agent-based, event-driven architectures have the following characteristics according to [Odell, 2010]:

1. Large and heterogeneous environments.
2. Many kinds of changes can occur frequently within the environment.
3. The need to deliver and respond appropriately to complex exceptions and state changes in real time.

Thus many companies can have advantages from MASs. However, MASs are not always useful. For example, a company that makes one simple product which is always the same and where there is a steady demand does not need a extensive agent-based network.

2-2 Anatomy and general architectures

The most simple way to display an agent is as a black box, where the agent only has an input and an output to its environment. This concept is shown in Figure 2-2. The input can be whatever the agent perceives, such as messages, sensor inputs, requests, commands etc. Based on this input, the agent autonomously decides how to act. This normally results in some kind of an output.

Figure 2-2: A basic model of an agent

In order for an agent to work properly, the agent must be able to do more than detect and react. It must understand what it is detecting and response properly to that. To function properly the agent has a form of memory, in other words its state. This state contains the data that is needed to operate the agent. For example, an inventory agent has certain information about the reorder point of a particular product. However, when it understands its input and current state, the agent still must react properly. Therefore [Wooldridge et al., 1999] notes: "the key problem facing an agent is that of deciding which of its actions it should perform in order to best satisfy its design objectives". To solve these decision problems, several models and architectures have been proposed. The following three main architectures taken from [Bussmann et al., 2004] are shortly reviewed: reactive agents, deliberative agents and hybrid agents.

2-2-1 Reactive agents

In case of an reactive agent, the designer of the agent specifies for each possible input an direct action the agent has to take. Thus the agent only has to match its input signal to the conditions for each action. There is however a problem when multiple conditions match the same sensory input and the actions belonging to these conditions are in conflict. Therefore [Brooks, 1986] proposed the subsumption architecture. Where the conditions are listed on priority and some actions inhibit others. So only actions are executed if no other action inhibits this action. The main disadvantages of this architecture is that it is difficult to implement goal-directed behaviour, because reactive architectures only look at the current situation. In Figure 2-3, a schematic view of a subsumption architecture is shown.

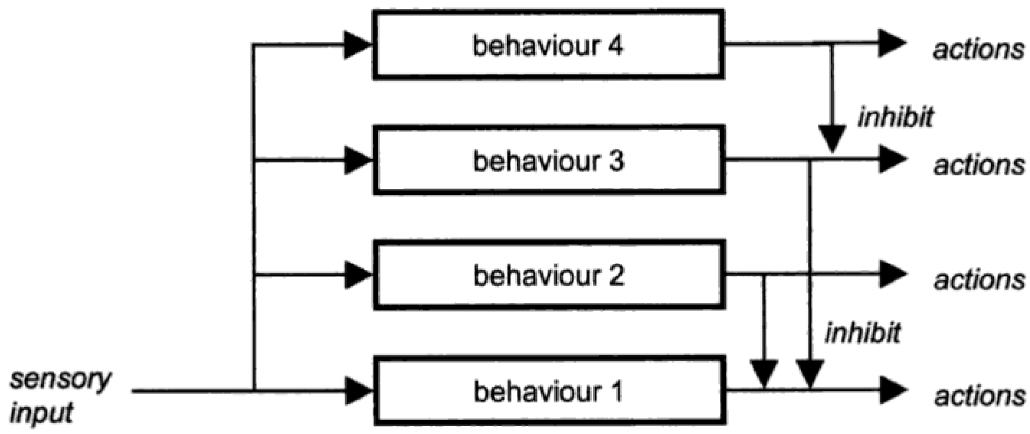

Figure 2-3: Subsumption architecture - [Bussmann et al., 2004]

2-2-2 Deliberative agents

"The deliberative agent architectures explicitly represent goals and forms plans about how the agent wants to behave in the future in order to achieve its goals" [Bussmann et al., 2004]. The most known deliberative agent architecture is the belief-desire-intention (BDI) architecture of [Rao and Georgeff, 1992]. Such a structure is shown in Figure 2-4. Here the beliefs are its inputs accumulated over time and the desires are its goals, with these two its intentions are formed. The intentions are what it is going to do in the future. A set of intentions determines which actions the agent should perform. Therefore, BDI agents can follow their goals pro-actively and at the same time react to their environment. The problem with these agents is, however, that when the agents are complex, the steps of forming an intention can take a long time. Therefore, these architectures are not suited for highly dynamical environments.

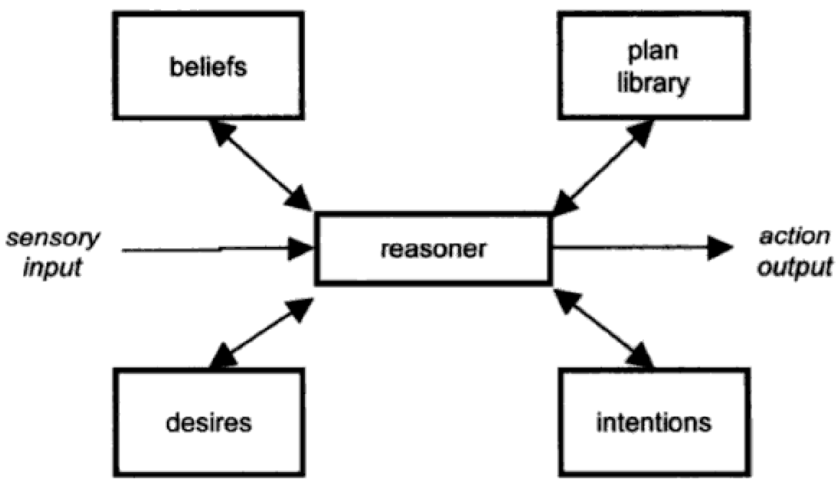

Figure 2-4: A BDI architecture - [Bussmann et al., 2004]

2-2-3 Hybrid agents

To avoid the problem of deliberative agents, hybrids agents were proposed. Hybrid agent architectures integrate reactive and deliberative mechanisms into one architecture. An example is the InteRRap architecture [Müller, 1996], shown in Figure 2-5, which consists of three layers. A behaviour layer for the reactive aspects, an plan layer for goal-directed planning and a co-operation layer to interact with other agents. Interaction with the environment starts with inputs at the behaviour layer, when this layer cannot handle the input it goes to the plan layer, when this layer cannot handle the input it goes to the top layer. A certain action decided by a layer goes the other way around. Due to this structure, hybrid agents are autonomous, reactive, pro-active and capable of social behaviour. The only disadvantage of this architecture is the complexity for the designer to let the layers co-operate correctly to produce coherent behaviour.

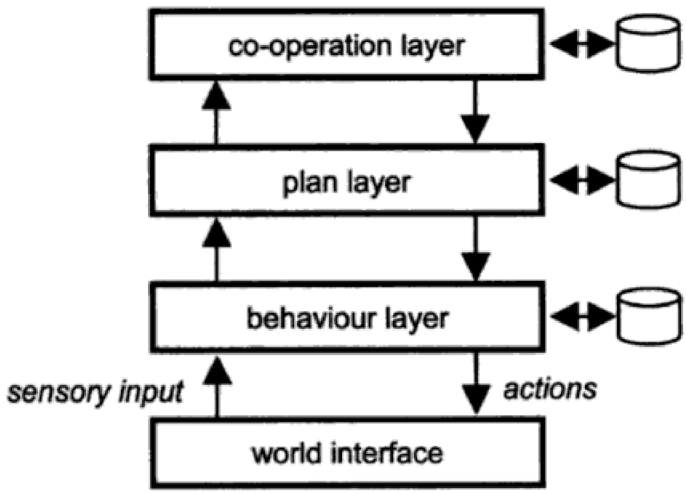

Figure 2-5: InteRRaP architecture - [Bussmann et al., 2004]

2-3 Agent interaction

As stated in the beginning of this chapter, interaction is one of the key elements which defines an agent. The environment an agent is operating in, is often an environment where multiple agents are autonomously operating in. Therefore, and sometimes to meet its goals, agents may have to interact with other agents. Certainly when an agent is not capable of meeting its goals on its own. Interaction is any kind of information exchange that somehow influences the actions of another agent [Bond and Gasser, 1988]. This means that interaction can take place in many different forms. Co-ordination and negotiation are the most important ones for manufacturing control [Bussmann et al., 2004] and will therefore be discussed in this section.

2-3-1 Co-ordination

"Coordination is the process by which an agent reasons about its local actions and the (anticipated) actions of others to try and ensure the community acts in a coherent manner" [Jennings, 1996]. In a well run organization or event, co-ordination itself is nearly invisible. However, no co-ordination is directly noticeable. Co-ordination is especially difficult in a MAS, where there is no central control. In such systems, co-ordination is not an inherent system property and can only be achieved through effort of the agents. [Bussmann et al., 2004] gives three reasons why coordination may be difficult to achieve:

1. The actions of the agents may interfere.
2. There may be global constraints to be met.
3. No individual agent has sufficient capabilities or resources to achieve its or the system's goals.

All of the above points have in common that there is some kind of dependency between the agent. So to achieve system co-ordination, it is necessary to understand these dependencies. Several studies on these dependencies have distinguished the following dependencies:

- Unilateral dependence, the dependence is one way.
- Mutual dependence, the dependence is two way.
- Reciprocal dependence, the dependence is two way but for different reasons.

Next to these classifications, more were made for modelling co-operation. Such as: task/resource dependencies, goal relationships and domain dependencies, which can all be controlled with different co-ordination techniques [Bussmann et al., 2004]. However, these make agents more complex. Therefore social laws, attempt to avoid interaction at the first place. They define conventions, which makes some of the co-ordination obsolete. For example AGVs who always ride on the right side, will not have a frontal collision. Therefore, social laws will significantly reduce the co-ordination requirements [Bussmann et al., 2004]. In applications, most relationships are quite clear and will not be comprehensively discussed, but for designing MASs it is important to understand all the relationships.

2-3-2 Negotiation

Negotiation is a common form of interaction between human beings. Negotiation is defined by [Pruitt, 1981] as follows: "Negotiation is a process by which a joint decision is made by two or more parties. The parties first verbalize contradictory demands and then move towards agreement by a process of concession or search for new alternatives". Conflicts are a natural part of our own life, because everyone has their own goals and interests. The same happens in systems with autonomous agents. When each agent has its own goals and interests, conflicts are inevitable. Therefore, one of the key elements in multi-agent research are negotiations to resolve conflicts. Many of the possible solutions come from existing human solutions, e.g. auctions, general equilibrium market mechanisms, service negotiation and conflict resolution techniques. Auctions are trade mechanisms for exchanging commodities [Friedmann, 1991]. There are three types of auctions: one-sided (where there is one auctioneer who only does bids or asks), two-sided (where the auctioneer matches different bids and asks from agents) and continuous actions (where the auctioneer matches different bids and asks from agents over time) [Bussmann et al., 2004]. All of these auction methods have in common that they match buyers and sellers, but not take into account constraints or global optimization. General equilibrium market mechanisms on the contrary are able to do that. Such mechanisms are able to allocate the goods and resources among agents through identification of market clearing prices. The concept works as a normal market: the higher the price, the less consumers will consume and the more producers will wish to produce and vice versa. One of the drawbacks of these two methods is that they only can negotiate prices. Therefore, more sophisticated negotiation techniques are required where it is also possible to alter other aspects of negotiation subjects in order to find solutions. [Faratin et al., 1998] developed such a sophisticated technique. In this case an interaction model for bilateral negotiation of services, which means two agents basically exchange new proposals until one of them accepts or withdraws. This whole proposal process is supported by a certain set of tactics and strategies for generating new proposals. Another technique is proposed by [Hollmann et al., 2000], which is a technique for resolving conflicts between agents that are supposed to find a common proposal. Here, the agents must find a proposal that satisfies all agents by passing their given threshold. This is done by new proposals given by agents which are unsatisfied until one proposal is found that satisfies all. The disadvantage of this technique is that it can only be applied if there is a solution that fits all.

2-4 Intelligent abilities

Intelligence is an important property of an agent as stated in the beginning of this chapter. However what is an intelligent agent? [Wooldridge and Jennings, 1995] define an intelligent agent as one that is capable of flexible autonomous action to meet its design objectives. Flexible in this definition means:

- *reactivity* a level of adaptivity as described in section 2-1-1
- *pro-activeness* described in section 2-1-1 as purpose
- *social ability* described in section 2-1-1 as interactive

So an agent is intelligent as it has these characteristics and the level of intelligence is defined by the level of these characteristics. The incentive of intelligent agents is the amount of available data which has to be processed. This available data is continuously growing and cannot be processed in conventional ways. Therefore intelligent agents are critical. E.g. finding an Italian restaurant through Google Now, which filters the right information for you and gives you a list of Italian restaurants nearby in stead of manually going through all the restaurants. The key issue in designing intelligent agents is that the designer tells an agent what to do, but not how to do it. Otherwise if the designer simply tells the agent what it should execute in which situation, the agent will not be able to react to unforeseen circumstances [Rudowsky, 2004]. However, the capacity of an intelligent agent is limited by its knowledge, its computing resources, and its perspective. By forming MASs the intelligent abilities increase.

Therefore, MASs can deal with complex, realistic and large-scale problems which are beyond conventional systems. So the intelligent abilities of MASs systems are promising and a good way to deal with certain manufacturing problems, especially in the future.

Chapter 3

Agent systems in manufacturing

Manufacturing nowadays can be one of the most complex processes in the world. As stated in the introduction, markets are prone to sudden changes in demand and have been globalized in the last years. Which have major influences on manufacturing. Such as the shifting from a supplier's to a customer's market. Customers are becoming less loyal to a certain brand and are asking high quality products for a low price. This has led to the the fact that manufacturing companies must reduce the time-to-market, instantly satisfy demand, increase product variety, shorter product-life cycles in order to stay competitive. The manufacturing process must also be robust and scalable. These factors increase the complexity, the need for adaptability and agility of the manufacturing process.

Multi-agent systems promise the most for companies that operate in environments that are distributed and open and have complex problems. As listed in section 2-1-2 companies with the greatest advantages of agent systems have the following characteristics: large and heterogeneous environments, frequent changes within the environment and the need to deliver appropriately to complex exceptions and changes in real time. When looking at manufacturing companies nowadays, they almost all have these traits and therefore are well suited for agent technologies. The way of building manufacturing systems has been revolutionized with the possibility of information exchange, distributed coordinating, adjustability and especially the ability of multi-agent system (MAS) to solve dynamical complex problems. Therefore, this Chapter will consist of possibilities for applications of agent systems throughout the different steps of a manufacturing process. Starting with the design of a product, until the last step of production, the assembly. This categorization is based on the following paper [Monostori et al., 2006]. Thereafter, another categorization is made based on [Shen et al., 2006].

3-1 Engineering design

Engineering design has changed a lot the past 100 years. For example in the car industry, where Ford started with building only one type of car for many years in a row. The development of a new design, what they did totally by themselves took many years. When the new design was finished, the whole factory setup switched to building that new car. In the years that followed the cars became more and more complex and at a certain moment consisted of more than 10.000 parts. Therefore, it became almost impossible to design everything on your own in a few years. Especially because some design processes could only start when others were finished. For example, the seat designer had to wait until the complete body design was finished in order to get the required dimensions of the seats. Therefore, Toyota came up with the idea of collaborative designing and engineering, where they for example told to a seat maker: we want a seat and these are roughly the constraints. Then the seat maker could already start thinking about possible designs within the constraints [Womack et al., 2007]. "This approach promotes interaction instead of iteration and makes the conflicts between different stakeholders in the design process explicit and strives to achieve acceptable trade-offs in negotiation". This negotiation can even extend towards customers, "where design specifications and customized products are developed in the course of an iterative give-and-take process" [Monostori et al., 2006]. Because of the many parts and different parties all around the world these developments require some sort of computational support, where negotiations can take place. These negotiations make decomposition and parallel execution of the design possible. This method naturally lends itself for an agent-based approach. Next to the advantage of having a modular system, the agents could work with current used tools such as simulators and CAD systems. It can also bring together all kinds of engineering fields with a shared set of concepts, terminology and a common language. Due to the communications and a set of constraints, one can see collaborative engineering as trading incomplete knowledge against interest. "A trade like this can be very fruitful: rational, interest-seeking behaviour on the part of autonomous agents can result in successful overall performance in cases when the agents have limited capabilities" [Monostori et al., 2006]. These negotiations can be the key to creative designs and innovative solutions.

3-2 Process planning

Process planning is basically planning discrete manufacturing operations within the constrained production environment. This is already too complicated to do by hand, therefore it is done with the use of computers. This is called computer-aided process planning (CAPP). The normal way of handling complex CAPP problems is by de-structuring its world into manageable micro worlds or by decomposing the planning problem into sub-problems. However, solving these CAPP problems efficiently will mostly come down to distributed negotiations. Just as in the example of the previous section, MAS concepts are particularly well suited for this type of problems.

3-3 Production planning and resource allocation

Production planning is selecting and sequencing activities, within a set of constraints and in this way achieving the goals of the organisation. This production planning is of bigger scale then the production scheduling discussed in the next section. Here for instance it is about a plan: product X has to go from station A to station B, where part C is added so at the moment product X arrives at B there must be a part C ready to use. These kind of problems are also about negotiation, part C can arrive on time but it comes with certain costs, therefore these can also be solved by e.g. market systems. This concept of decomposition of manufacturing objectives and the allocation of tasks by agent-based market systems is already proven to be successful.

3-4 Production scheduling and control

"Scheduling is the process of selecting from alternative plans and assigning resources and times to the activities in the plan" [Monostori et al., 2006]. These assignments must be within certain constraints. "Manufacturing control relates to strategies and algorithms for operating a manufacturing plant" [Monostori et al., 2006]. Including taking certain experiences and expectations into account. There are some strategies of agent-based production scheduling and control. Examples are: collaborative coordination control (CCC) and Real-Time Decision making in manufacturing (RIDER).

3-5 Process control, monitoring and diagnosis

Monitoring is observing and processing signals and in this way detecting abnormal conditions. Diagnosis is generating plausible causes that led to these abnormal conditions. Process control is controlling conditions with the information of the monitoring and diagnosis in order to prevent abnormal conditions. Therefore, all three are closely related. All three apply to physical processes (signals which are e.g. force, vibrations, temperature) and business processes (e.g. material movement, process times). There are many developed control and monitoring processes, many come down to modularity were to accomplish sensor integration and achieve appropriate computing power. Modularity can be seen as a step towards agent-based systems. Taking this agent-based approach, many subsystems and sub-subsystems follow with agent interaction and negotiation mechanisms. Nowadays, with advanced communication technologies, remote monitoring and maintenance is very common.

3-6 Enterprise organization and integration

"Enterprise integration is aimed at providing an information technology infrastructure for all business, engineering, operational and administrative functions of an enterprise that can be used for information exchange, decision making, coordination and collaboration" [Monostori et al., 2006]. Key ideas here are: enterprise modelling, distributed planning and information system modelling. "Decentralized agents permits local parts to continue operation during temporary lapses in connectivity" [Monostori et al., 2006]. Also all other benefits from MASs such as modularity, scalability and capable of making local decisions apply here. In despite of all the advantages, one issue which remains here is how to integrate agent-based solutions into existing systems.

3-7 Production in networks

"A production (or supply) network is a network of suppliers, factories, warehouses, distribution centres and retailers through which raw materials are acquired, transformed and delivered to customers" [Monostori et al., 2006]. It is clear that in a supply chain network, the inflow of all different type of goods must meet the internal flow of materials. Currently there are supply chain management (SCM) systems for integrating data of all major business functions in a network, but these systems do not really support decision making. Supply chain networks are unique and complex, therefore there is not a "one size fits all" solution. But basically there are two main types of research in applying agents to SCM according to [Monostori et al., 2006]:

- The general approach which handles SCM as a problem of designing and operating a MAS.
- Specific problems such as collaborative inventory management, bidding decision, material handling and inventory planning.

There are different types of solutions for agent-based systems in supply chain networks. A general example of an agent-based supply chain is show in Figure 3-1.

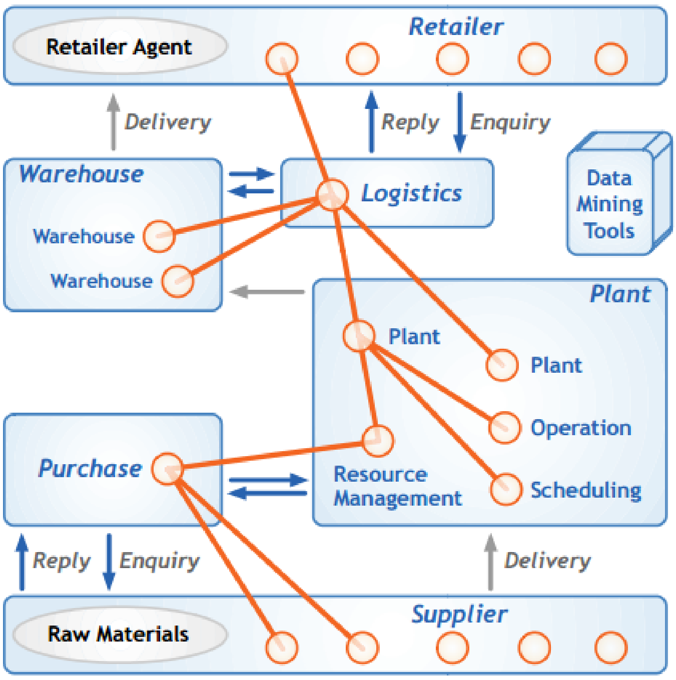

Figure 3-1: A multi-agent-based supply chain - [Monostori et al., 2006]

3-8 Assembly and life-cycle management

"Assembly, usually represents the last technical step in the product creation process" [Monostori et al., 2006]. In modern companies, the value adding chain is a combination of world wide network of suppliers, transport agencies, manufacturers, retailers, distributors and recyclers. There are examples where an agent-based approached is used to avoid large lead times and capital-intensive stock and make the assembly process less sensitive for disturbances. Such an agent society is shown in Figure 3-2.

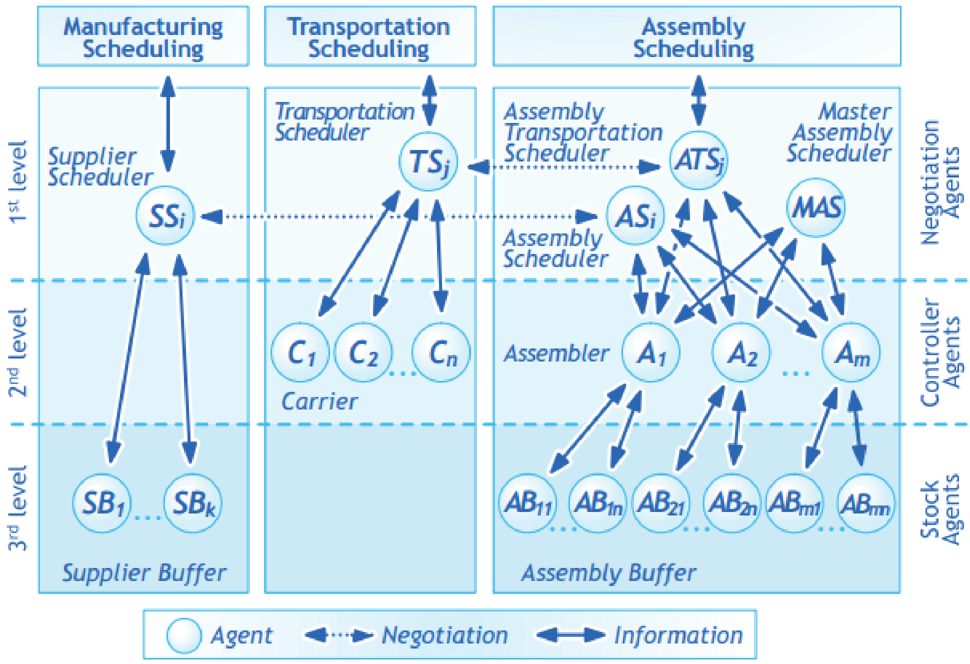

Figure 3-2: An agent society for assembly control - [Monostori et al., 2006]

3-9 Another manufacturing classification

Other resources use different categories to divide the different agent-based approaches. For example [Shen et al., 2006] in *Applications of agent-based systems in intelligent manufacturing: An updated overview.* Their categorization is a broader categorization than the one given by [Monostori et al., 2006]. The categories of [Shen et al., 2006] are more vertical levels of controlling an enterprise than the chronological sequence of manufacturing steps. The categories are:

- **Enterprise integration** means that each unit of the organisation will have access to the information relevant to its tasks and will understand how its actions will impact other parts of the organization thereby enabling it to choose alternatives that optimize the organization's goals.
- **Enterprise collaboration** Coexistence of competition and cooperation is a dichotomy governing today's enterprises. Enterprises collaboration vertically among a supply chain

and horizontally among peers (even competitors) becomes more and more significant for enterprises to survive in the increasingly competitive global market.

- **Manufacturing process planning and scheduling** Manufacturing process planning is the process of selecting and sequencing manufacturing processes such that they achieve one or more goals and satisfy a set of domain constraints. Manufacturing scheduling is the process of selecting among alternative plans and assigning manufacturing resources and time to the set of manufacturing processes in the plan.
- **Manufacturing shop floor control** relates to strategies and algorithms for operating a manufacturing plant, taking into account both the present and past observed states of the manufacturing plant, as well as the demand from the market.
- **Holonic manufacturing systems** Holonic manufacturing comes from the word "Holon", which combines "holos"(the whole) and "on"(a part). This means that an autonomous part of the system, can be its own system and at the same time be part of a bigger system. A more comprehensive explanation can be found in Section 4-3-1.

Agent technologies can be used in different manufacturing steps and in overlapping processes. What all the manufacturing systems have in common is the fact that a manufacturing system is of few utility without the presence of an appropriate control [Leitão, 2009]. Therefore, the focus will be on manufacturing control in the rest of the literature survey.

Chapter 4

Manufacturing Control

In the end of Chapter 3 is stated that a manufacturing system is of few utility without the presence of an appropriate control system. Next to that, the reliability and flexibility of a manufacturing system are not only determined by its components (such as machines, employees, transport systems) but also by their control system [Leitão, 2009]. Therefore, the main focus in this chapter will be on manufacturing control. Where in Chapter 5 some industrial applications of agent systems in manufacturing control will be discussed.

4-1 What is manufacturing control

According to [Leitão, 2009] traditional manufacturing control is defined as follows:
"the manufacturing control is concerned with managing and controlling the physical activities in the factory aiming to execute the manufacturing plans, provided by the manufacturing planning activity, and to monitor the progress of the product as it is being processed, assembled, moved, and inspected in the factory. Algorithms at this level are used to decide what to produce, how much to produce, when production is to be finished, how and when to use the resources or make them available, when to release jobs into the factory, which jobs to release, job routing, and job/operation sequencing".
As stated in the introduction, traditionally manufacturing systems have a centralized control approach. Such a traditional approach to manufacturing control systems is shown in Figure 4-1. Each of the components has its own tasks and operates in a certain set of constraints and within a certain time horizon. Planning has for example the highest time horizon, which can be days, weeks or months. It gives a production plan to the scheduling, which has a smaller time span. This can go on until an order reaches e.g. the machine control, which can have a time span of seconds. The monitoring component on his turn, can pass signals from the manufacturing system to the planning or to the diagnosis, e.g. in case of an error detection. This way planning can make adjustments or the diagnosis can pass the problem to error recovery. These processes must be done during operation and that makes the manufacturing control interesting and complex.

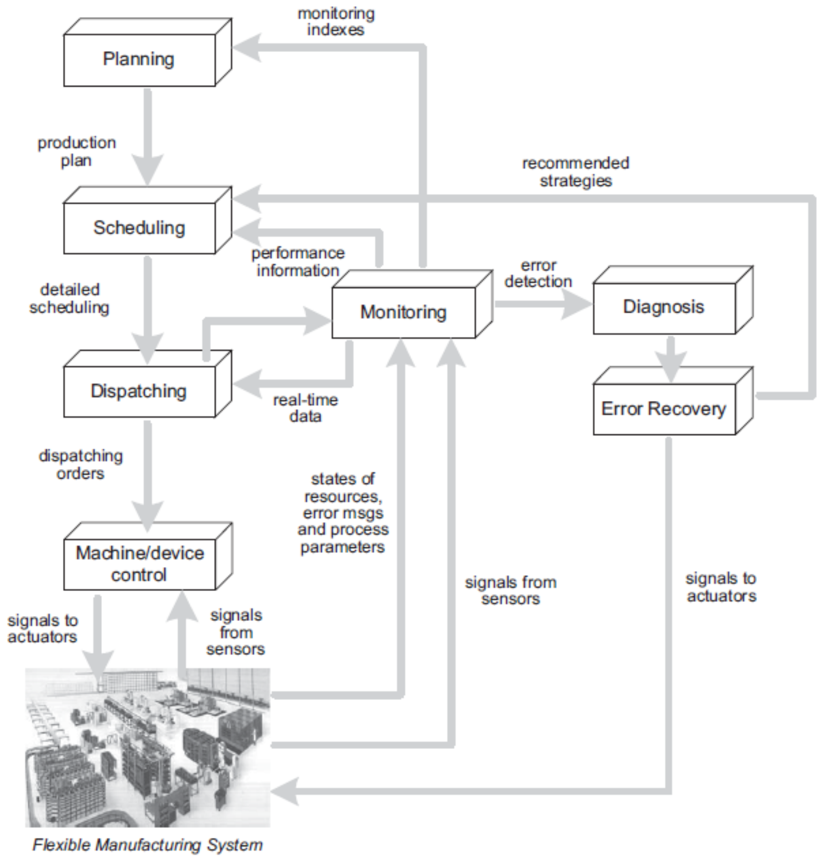

Figure 4-1: Traditional approach to manufacturing control systems - [Colombo, 1998]

These centralized and hierarchical control structures are good in terms of productivity. However, adaptivity, flexibility, re-configurability of these systems, which normally come with large specialized software packages, are small and not in line with the current market requirements. On the contrary, systems that can be in line with the current market requirements are multi-agent based control systems, which address distributed and intelligent manufacturing control. Multi-agent control system technologies are capable to respond promptly and correctly to change without external intervention.

4-2 Multi-Agent-based manufacturing control

As explained in Chapter 2, the advantages such as modularity, decentralization, dynamically and capability to deal with complex problems and the simpler software also apply on manufacturing control. In manufacturing systems agents can represent physical resources as well as logical objects. Some examples are: machine tools, robots, automated guided vehicles (AGVs), products, schedulers and orders. When an multi-agent system (MAS) is implemented in the right way, the individual components of the manufacturing system can make decisions on their own. Another key benefit of this is that if there is an error in the system or a shift in market demands, it can be solved locally and the system can continue to operate. This makes the system relatively robust to change. A schematic view of conventional and distributed approaches for decision making is given in Figure 4-2. All the decisions are divided between three control functions, which require less calculation power and time.

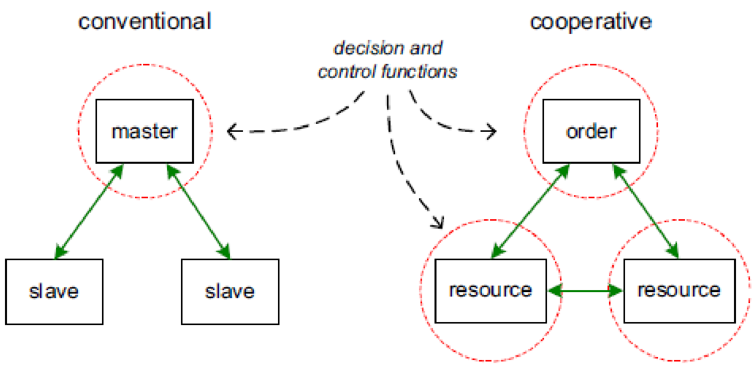

Figure 4-2: Conventional and distributed approaches to decision-making - [Marik and McFarlane, 2005]

In Figure 4-3 a simple example of the application of agents for manufacturing control is given. Here, the part agent asks to the other agents who has the right set of tools in combination with a certain set of skills and who is available. In other words: who can drill this part? Then the other agents reply, where agent 3 replies positive. After this negotiation, the part is assigned to machine 3 and the negotiation with the transport agent starts. Here the agents representing the machines are developed with the same software and the part agent does not notice it if there comes an extra machine agent in the system or one disappears. Next to the agents, the corresponding controllers are given with matching colours which are: An industrial personal computer (IPC), computer numerical controls (CNC) and a programmable logic controller (PLC).

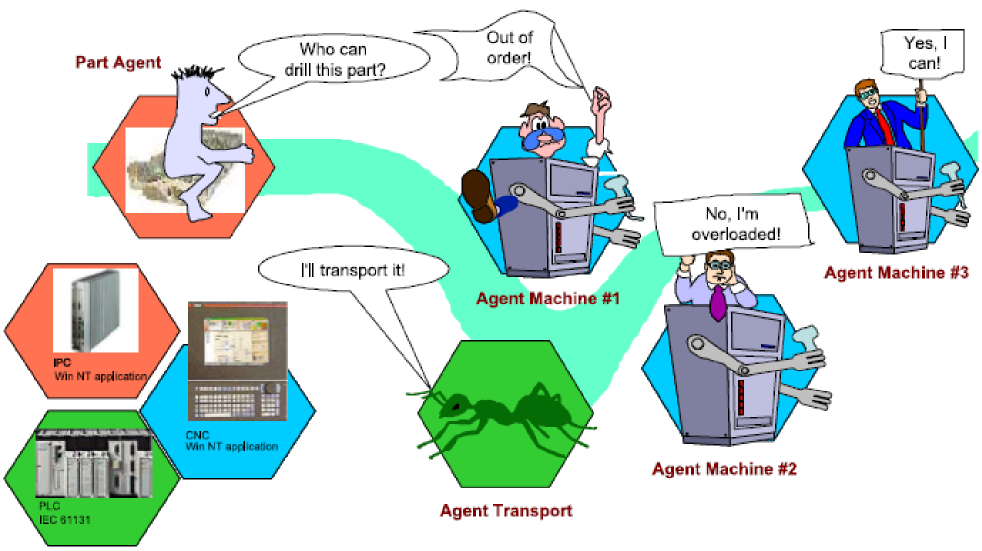

Figure 4-3: An example of the application of agents for manufacturing control - [Colombo, 2005]

One of the first examples of the use of a MAS in the industry was at General Motors, where it was used to paint trucks. As in all the factories at that time, the assembly line was scheduled and controlled centrally. However, with continuous colour changes in the painting booths, sick personnel and work station breakdowns it became almost impossible to schedule efficiently. Dick Morley, founder of the floppy disc and the programmable controller, though of this problem and found out that he had to schedule the non-schedulable. Namely the situation at the paint booths, were there were almost as many paint changes as trucks produced and such a paint change costs about somewhere between a sixth to eight of the paint needed for one single truck. This constant change was due the fact that the colour of the truck was only known once it came of the production line. Also there were constantly people sick or paint booths broken down. So the schedule had to be created dynamically. In stead of the classical way of assigning each truck to a certain paint booth randomly, his solution was to let the paint booths bid on the paint job of the truck. For this reason he equipped each paint booth with a bidding software, which task was to keep the booth busy and bid on the trucks. The height of the bid was dependent on factors such as the current paint colour in the booth compared to the colour of the truck, how busy the paint booth was and whether the booth was functioning properly. To coordinate this process, a scheduler agent was installed which told the painting booths which colour truck was next and then did the auctions. This approach of Dick Morley, reduced the lines of the computer code from hundreds to four and saved GM nearly a a million dollar in the first nine months [Cicirello and Smith, 2003].

These were a theoretical example and a practical example of agent-based systems in manufacturing control. The next section will give some extra information about control approaches for manufacturing control. Therefore, table 4-1 firstly summarizes the most important differences between classical control solutions and agent-based control solutions according to [Leitão, 2009].

Table 4-1: Comparison between traditional and distributed approaches

Traditional control solution	**Distributed and intelligent control solution (Agent-based)**
Centralized solution for each individual control function	Distributed solution with cooperation between nodes and focusing on more than one control function
Rigid and static architecture	Flexible, programmable and dynamic architecture
Intelligence centred in the top levels	Intelligence distributed by the control levels
Efficiency through the specialization Weak response to disturbances Operators are replaced by automation technologies (removed from production process)	Efficiency through the flexibility High response to disturbances Operators are complemented with automation technologies (increasing the skills of the operators that stay in the production process)
More efficient for high volume and low variability	More adequate for high-low volume and medium-high variability

4-3 Agent-based control approaches

Although the goal of this report is not evaluating all the different control approaches and trends in agent-based manufacturing control, some points are important to mention for manufacturing control.

4-3-1 Trends

The general architectures and interaction protocols of agents are discussed in Chapter 2 the focus here lies more on manufacturing control approaches. The most used interaction is negotiation. The contract net protocol (CNP) was and is mostly used for agent negotiation. After the first uses, different CNP based control approaches were developed. However, most of the early control approaches were limited. These limitations, in combination with newly developed hardware possibilities, have motivated the development of other approaches. Three trends which are most relevant are discussed in this chapter: heterarchical control architectures, stigmergy-based coordination and control, and holonic manufacturing. In the newest agent-based approaches, multiple control architectures can be used at the same time.

Heterarchical control

In centralized and hierarchical controlled architectures they centralize distributed information. Therefore, larger structures become too complex and their information exchange becomes slow. Also they were difficult to modify and had a low fault tolerance. Therefore, distributed control was needed in the form of heterarchical control. Heterarchical control was motivated by these limitations [Dilts et al., 1991]. Heterarchical control eliminates the central elements, see Figure 4-4 , making the agents more autonomous and responsible for their own "neighbourhood". However, to make heterarchical architectures work, there must be a sort of overall production goal. Otherwise each agent will only fulfil its own goals.

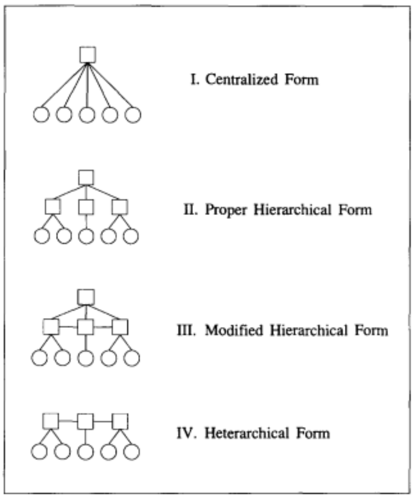

Figure 4-4: The evolution of the four basic forms of control architectures - [Dilts et al., 1991]

Stigmergy-based coordination and control

Stigmergy is a relatively new approach for MASs. It is based on indirect coordination and communication, this way individual agents do not have to deal with the complexity of the whole situation. This way the communication burden is lower compared to other approaches. An example of such a system, is an ant colony. Where the ants just follow simple rules and do not know and cannot communicate with the whole system.

Holonic manufacturing systems

Holonic manufacturing looks at the whole manufacturing process instead of only the control. The motivation for holonic manufacturing was the manufacturing market becoming more and more agile. A holonic manufacturing system consists out of autonomous units, called holons. A holon can be a part and a whole simultaneously, thus a holon can be made up of holons. The conventional parts as machines, AGVs and humans can be holons, but also e.g. orders can be holons. Therefore, [Christensen, 1994] foresees three major interfaces to an artificial holon: a physical processing interface, an inter-holon interface and a human interface (see Figure 4-5). Although holonic manufacturing is promising and there is a lot of attention for and researches done into holonic manufacturing, the report will focus on MAS in manufacturing control specific and therefore not comprehensively discuss holonic manufacturing.

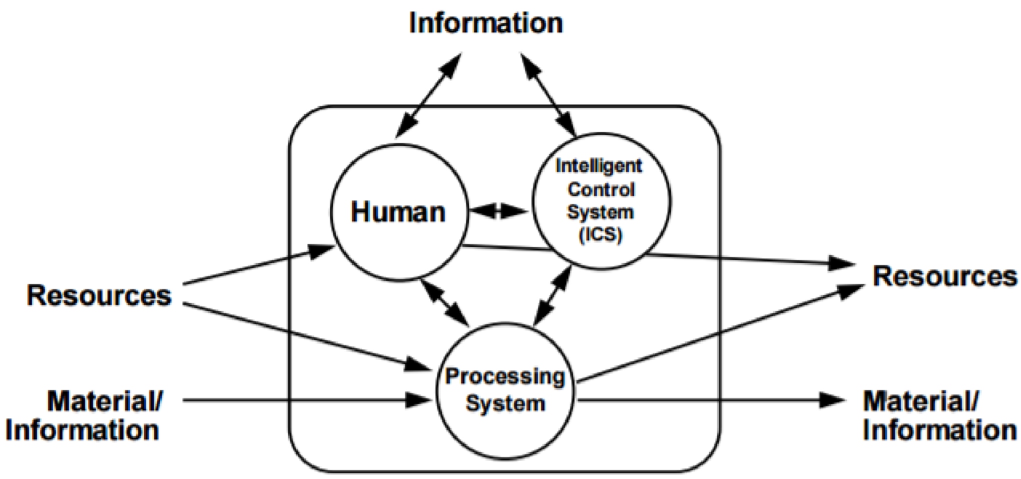

Figure 4-5: Holon interface - [Christensen, 1994]

4-3-2 Ontologies

One of the goals in MASs are "plug and play" capabilities, where systems can be easily adjusted or extended. One of the mayor issues for this which will be found in the next Chapter is the communication of different elements with different "languages" in a MAS. In order for the elements to understand each other and to increase the "plug and play" capabilities, some steps are necessary. The first step for existing MASs is a modular representation of the manufacturing system components, where after the parts can be agentified. Coalition Based Approach for Shop-floor Agility (CoBASA) and actor-based assembly systems (ABAS) are examples for such a modular based architecture. The next step in flexibility of agent-based control systems is the application of ontologies for knowledge representation, sharing and high-level reasoning [Terzic et al., 2009]. An ontology is a data model of the types, functions, properties, and interrelationships of the entities in a certain domain, so it is possible to reason. These ontologies are necessary to enable reconfiguration in an extensive way. Different ontologies for different domains are described in different sources, but the MASON ontology can be seen as a draft of an overall ontology for the manufacturing domain (Lemaignan et al., 2006). With these ontologies, production systems can be configured directly in stead of reconfiguring agents or the whole control system in order to adapt to new situations. Implementations of system wide ontologies are given in the next Chapter.

Chapter 5

Applications of agent technologies in manufacturing control

In the previous chapters agents, agent systems, agent systems in manufacturing in general and agent-based control approaches are described. Although many researches are done in these fields, most of them have not led to industrial applications. However, some of them have, a few of those will be discussed in the this chapter. Starting with one of the first applications and ending with a state of the art application.

5-1 Production 2000+

The cylinder head manufacturing system Production 2000+ (P2000+) of DaimlerChrysler is probably the first full scale industrial agent-based production system [Bussmann and Schild, 2001] [Bussman, 2016]. At DaimlerChrysler they concluded that in order to deal with the current market situation, the production process must be flexible and robust for any disturbances in order to maximize the total use of the manufacturing system. To achieve this, they developed a new production system called P2000+, which addressed three important aspects:

1. Flexible machines who are capable of doing multiple different operations
2. The ability do adjust the NC programs in order to process different products
3. A flexible transportation system which is able to move any workpiece to any machine in any order

In classical manufacturing processes, one product often moves along a transfer line, where it passes a certain set of machines. When one machine has a breakdown, the whole manufacturing line stops. Such a transfer line is not capable of making different types of products at the same time. Therefore, the P2000+ system consists of flexible computer numerical controls (CNC) machines among a flexible transport line. The CNC machines are capable of doing multiple handlings so that each handling of the workpiece can be performed by at least two CNC machines. In case of normal operations each machine is fully utilized, in chase of a machine breakdown the system still can function on at least 50% of its capacity. Which is quite good compared to transfer lines which have no throughput in case of a breakdown. To make the flexible transportation possible they designed a transfer line as shown in Figure 5-1. Where the forward and backward conveyor can move workpieces around between machines and the shifting table. The supply conveyor can move the pieces into the CNC machines. The configuration also consisted of a certain load and unload station where the workpieces can be loaded and unloaded.

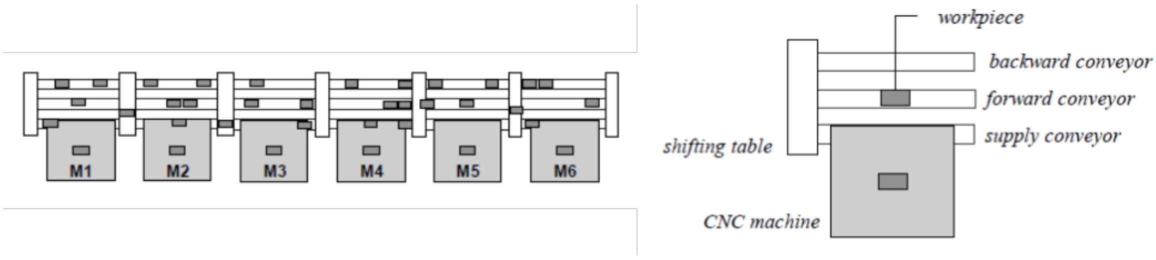

Figure 5-1: The configuration of the P2000+ and its system components - [Bussmann and Schild, 2001]

This configuration only consisted of standard hardware, in order to get it working a whole new control approach is required where workpieces should be assigned to machines at the latest moment possible. Therefore, DaimlerChrysler developed a decentralized approach called West (Werkstücksteuerung in German). Where the hardware part consists of the following agents: workpiece agents, machine agents and shifting agents. The machine agent controls the machine and the material flow through the machine with a so called virtual buffer, which cannot be exceeded. The workpiece agent manages the processing state of the workpiece. The shifting agent controls the direction of the workpieces. In order to let these processes work parallel proper coordination through negotiation procedures is needed. This is achieved by the following negotiation procedures.

- **Controlling buffer sizes** Each machine agent manages its own input and output buffer, which together form the virtual buffer. Each machine has its own buffer limit and may only accept new workpieces if its virtual buffer is smaller then its buffer limit. This way the number of workpieces in the system never exceeds a global limit.

- **Dynamic task allocation** Each workpiece agent is responsible for the processing state of a workpiece. Each workpiece has a certain sequence of tasks. The state of the workpiece is determined by its sequence of tasks already performed. The current task is the current operation that has to be performed and the machine needed therefore is allocated as late as possible to keep flexibility in the system. This allocation is carried out by an auction, which has the following three steps:

    1. **The call for bids** The workpiece determines its current task and sends an invitation to all the machines capable of performing that task.
    2. **The bidding itself** If a machine gets an invitation, its checks whether it can perform that task and places a bid.

3. **The awarding** The workpieces evaluates all the bids and awards the bid to the machines who scores the best in: current size of virtual buffer and number of subtasks that machine can perform on that workpiece. If there is no bid, the workpiece starts again with the first step.

- **Avoiding deadlocks** To prevent deadlocks in the allocation process, the idea is that most workpieces follow the forward direction (Figure 5-1). So only in certain situations the workpiece can follow a backwards direction.

- **Dynamic routing** The shortest path for the movement of a workpiece is preferred. However the avoidance of congestion is more important. These jams can be avoided by separating the actual routing from the transportation goal itself. This is done through bilateral communications. Here, the workpiece with the highest priority is always served first.

These procedures were installed in a industrial prototype at a DaimlerChrysler plant and evaluated. One of the observations was that whenever a machine breaks down, the auction mechanisms automatically diverts the material flow to other machines and thus levelling out the workload. Due to the awarding of machines with a forward successor, if possible, the main manufacturing direction keeps intact and still the flexibility is available if needed. Next to that, the transportation system is not overloaded, because the loading station only feeds as many workpieces as the system can handle at that time. When tested, the West was capable of achieving 99.7% of its theoretical optimum. Hereafter, the system was installed as bypass to an existing manufacturing line. After a series of performance tests, the system still matched its simulation results. Therefore the system proved its benefits and the industrial feasibility of agent-based control approaches.

5-2 ProVis

Another early adapted application is also found in the car manufacturing industry. This application's main focus is manufacturing monitoring, which is also an important part of the manufacturing control. Its origin started with production globalization. This resulted in a market with original equipment manufacturers (OEMs) and suppliers where the latter one became more important and thus the OEMs had to focus more on logistics and supply chain management on shop floor control level [Sauer, 2004]. So production monitoring and control systems (PMC) became more important. "The PMC main function is to gather signals produced by production facilities and their programmable logic controllers (PLCs), to combine them to control relevant contexts, to visualize them and to provide functionalities to operate them" [Sauer, 2006]. People then use PMC to control manufacturing processes. However, in case of a breakdown or quality errors these systems could only tell that a certain number of vehicles was affected. "They can neither identify the customer orders related to these vehicles nor their options, e.g. colour, right or left hand drive, sun roof, etc. due to the fact that PMC do not hold any product or order related information" [Sauer, 2006]. Another problem with car manufacturers is that the PMC operate in a highly distributed soft- and hardware environment. Therefore, there is no common communication language, signal types, plant specifications etc. The challenge therefore was to integrate them, operate them in real time and at the same time making each aspect more autonomous (coupling them to manufacturing execution systems (MES)), thus eventually creating a sort of "plug and play" assembly line, which can be monitored and controlled. Thus creating some sort of integration platform for PMC and MES, with a level of standardization. In figure 5-2 are three options given for integrating these systems.

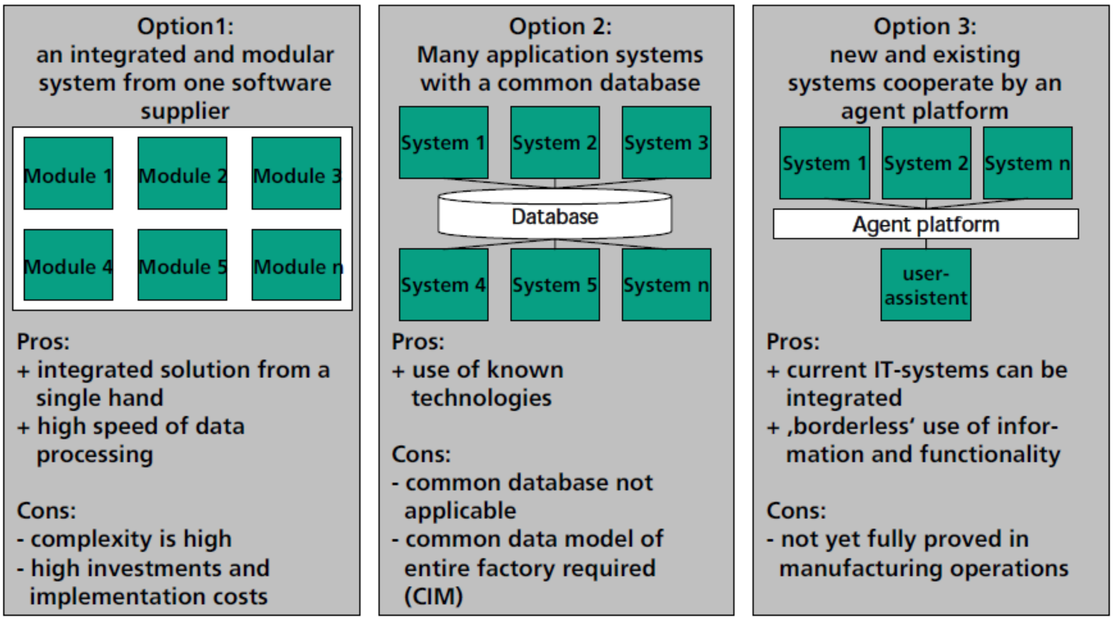

Figure 5-2: Options to integrate different software systems - [Sauer, 2004]

Although there are companies working on the first and second option, those have major disadvantages. Fraunhofer IITB therefore used the third option and used software agents for integration. In Figure 5-3 such an software agent is shown, called ProVis.Agent. Which consists of a monitoring server, with different software agents for different functionalities such as an alarm agent. The visualization agents are developed to have a uniform look at all the different signals by the different systems. Also a real-time visualization tool was developed by Fraunhofer, called ProVis.Visu. An operating agent gives the operator all the information it needs to operate the process. All the agents in the system communicate through a certain communication ontology, this ontology is open for other systems to access all the data.

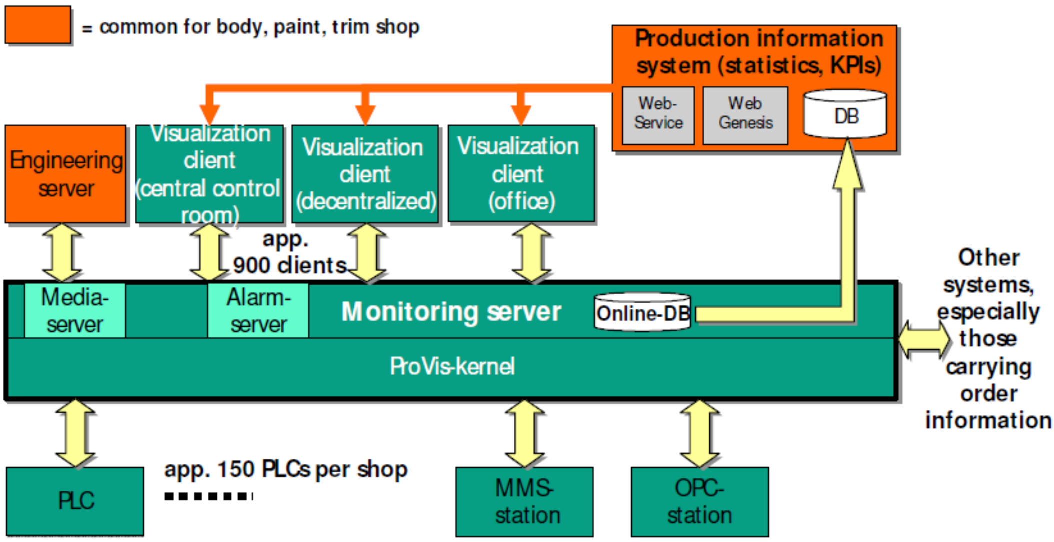

Figure 5-3: Production monitoring architecture using agent technology (ProVis.agent) - [Sauer, 2006]

This method of connecting all the manufacturing monitor and control systems must be linked to the product flow. Therefore, Fraunhofer IITB launched a new software component, called 'idle monitoring system'. This component could: identify products to see certain options or manufacturing orders and distribute this data to different levels e.g. PLCs or planning systems and provide the product status. This tool made it therefore possible to connect the real time monitoring tool (the ProVis.Agent) to an existing system to prove it benefits. This application was one of the first steps towards the use of ontologies for manufacturing control systems.

5-3 NovaFlex

An application of an ontology based multi-agent system to control a shop floor system is NovaFlex [Cândido and Barata, 2007]. The application consists of an industrial assembly cell, with certain chosen approaches to increase the plug and play capacities. Which means that components can enter or leave the system with minor changes in the production process and that the system can be updated during run-time by a small reconfiguration, without having to reconfigure the agents separately and the total control system. The NovaFlex manufacturing system was installed at the Intelligent Robotic Centre in UNINOVA and consists of two assembly robots. It started as a proof-of-concept implementation, however the application actually runs on a real shop floor cell. The layout of the NovaFlex is shown in Figure 5-4. It consists of two assembly robots with an tool exchange device and a storage for four different grippers. The one is a 5-axis robot and the other one a 3-axis robot. The other parts of the system are a transport system and an automated warehouse.

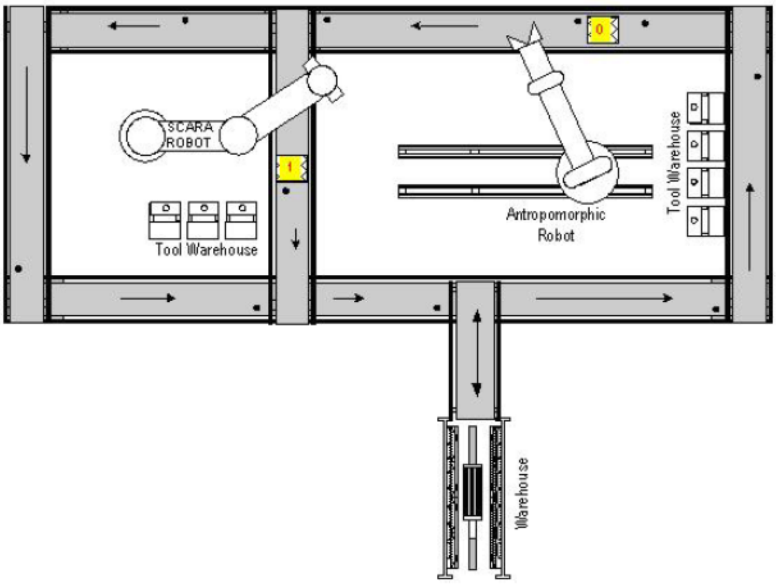

Figure 5-4: The NovaFlex layout - [Cândido and Barata, 2007]

The system overview is shown in Figure 5-5. Where according to the approach of Coalition Based Approach for Shop-floor Agility (CoBASA), each component is abstracted by an agent. Each shop floor component is represented by a manufacturing resource agent (MRA). A MRA can adapt at any moment by asking the ontology about its configuration parameters. To keep them independent, they interact with a agent-machine interface (AMI). An AMI is sort of a translation software, which translates an generic request described in agent communication language (ACL) to the corresponding agents actuators. The broker agent can decide actions it wants to aggregate and launches the coalition leader agent (CLA) to coordinate those between different agents.

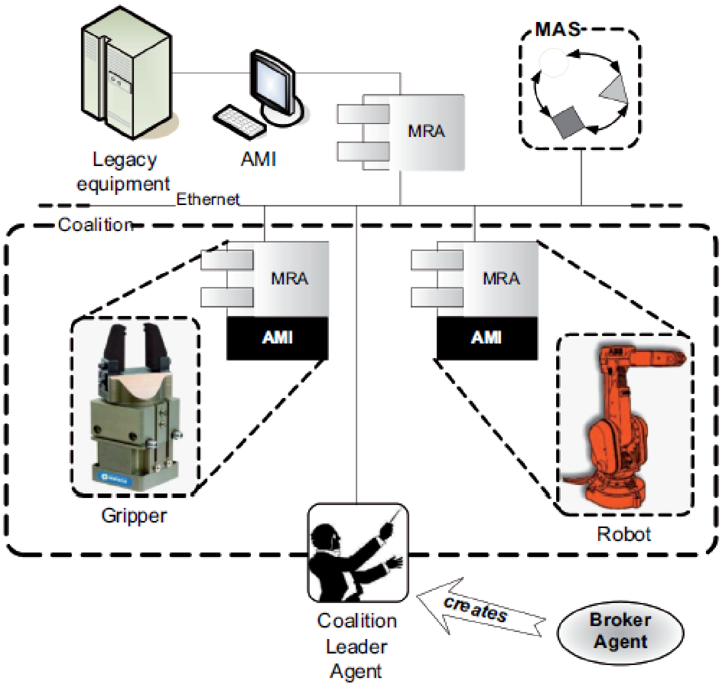

Figure 5-5: The NovaFlex Multi agent basic architecture - [Cândido and Barata, 2007]

The key issue is that agents understand each other, therefore the ontology of this shop floor domain defines the interaction parameters and vocabulary used by the agents during interactions. "All the agents enclose this ontology in order to create and understand ACL messages content" [Cândido and Barata, 2007]. In order to invoke a particular sequence of actions to manufacture a product, physical pallets with products or raw materials, represented by a pallet agent know how to execute their own process. If the process has to be changed, the integrator simply updates the data file of the pallet agent. Therefore, no extensive programming or major reconfiguration is needed.

For developing ontologies, generating corresponding Java files and visualization of these ontologies, different tools and programs can be used. However, those will not be described. An important aspect of an ontology what will be described is the definition of skills. Skills are actions that are needed to support the manufacturing process. They can have different abstraction levels, basic ones or complex ones which can be generated through the aggregation of other skills [Cândido and Barata, 2007]. Each skill represents an action model which defines the parameters that need to be exchanged for an execution request. Each agent has its own message template, which are also defined in the ontology. These message templates act as "translators" and can automatically convert data and files to be interpreted by agents. A total operation consists of the aggregation of actions, which are coordinated by the CLA. By combining these methods, a system is created which has increased plug and play possibilities and can function in a real environment.

5-4 Washing machine manufacturing line

In the previous application, a multi-agent system (MAS) was used for a dynamic production line which could be reconfigured easily. The following application is about the implementation of a MAS in a manufacturing line producing washing machines. The MAS application hereby aims to integrate the process and quality control and to provide adaption capabilities to the system operation [Rodrigues et al., 2013]. This project is carried out under the scope of the InteGration of pRocess and quAlity Control using multi-agEnt technology (GRACE) project [GRACE, 2013]. In contrast to most other applications, here the MAS principles are used in a rigid manufacturing structure, "where the benefits are in terms of product quality and production performance by adapting the process and quality control parameters" [Rodrigues et al., 2013]. The manufacturing line is shown in Figure 5-6, each station performs a single task. The washing machine enters the line with a specific set of operational parameters and preferences, among the line there are several inspections which are compiled for posterior analysis. The goal here was to implement GRACE for process and quality control in order to create feedback loops for parameter adjustments. Thus reducing process time, correcting earlier the deviations or quality problems, skipping unnecessary tests along the line and customizing the final product [Rodrigues et al., 2013].

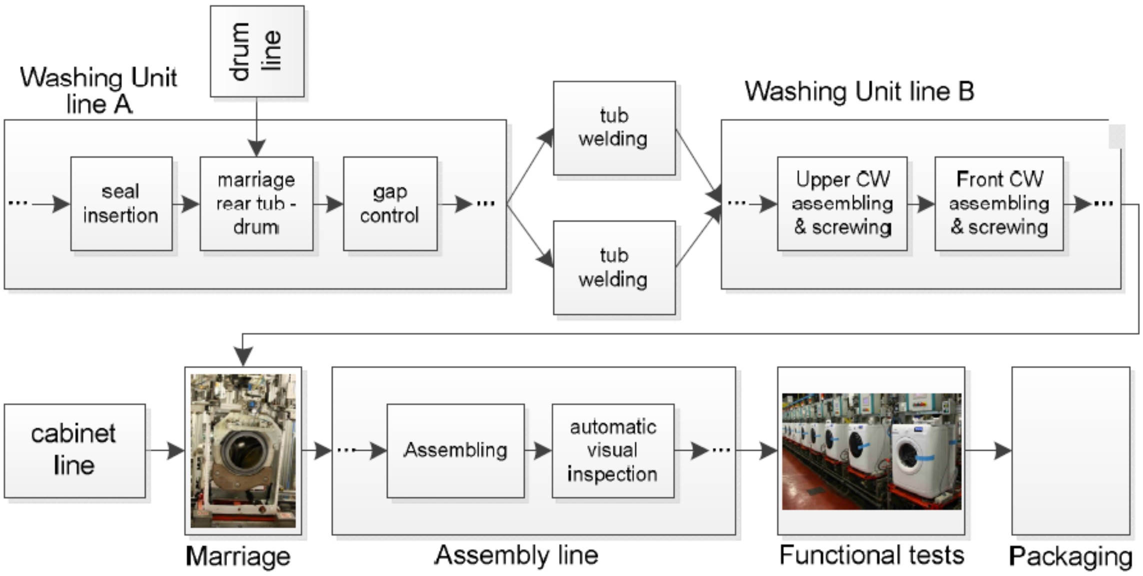

Figure 5-6: Layout of the production line - [Rodrigues et al., 2013]

For this implementation, the whole system is agentified. In this case the java agent development framework (JADE) was used as agent development platform, since it has several advantages such as: open source, compliant with foundation for intelligent physical agents (FIPA) specifications, low programming efforts and features to support the management of agent based solutions. In this GRACE system, the GRACE agents extend the agent class provided by the JADE. Such as: inheriting basic functionalities, capabilities to send and receive ACL messages and execute several actions. Next to these agents, with the use of LabView several quality control stations were developed. Also graphical user interfaces (GUIs) were developed to provide a user interface supporting the management and monitoring of the system. The right ontology plays an important role in the communication between all the elements in this manufacturing system. Therefore, a proper ontology was designed. The integration of this GRACE ontology with the GRACE MAS is done using the Ontologybeamgenerator. After this, the system was ready to be launched. Where it was, after a series of tests, implemented in the real manufacturing line. Figure 5-7 shows the system in practice.

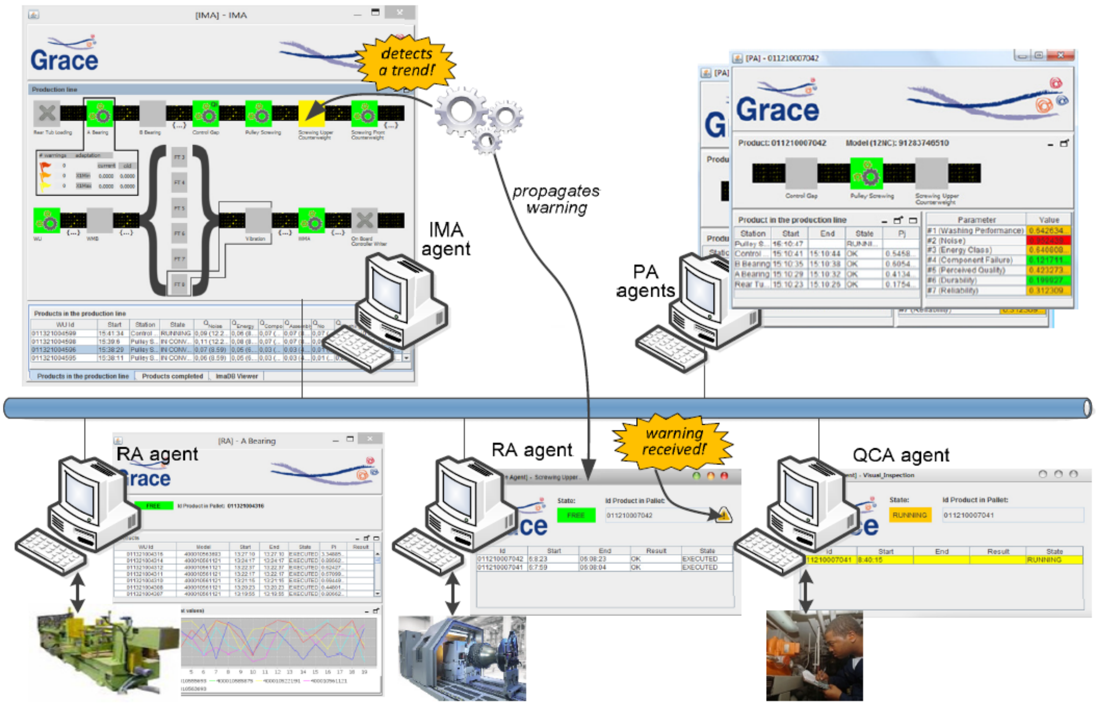

Figure 5-7: GRACE multi-agent system working in practice - [Rodrigues et al., 2013]

The results were improvement of the product quality and reduction of the production time. The product quality is mainly improved due to the adaption of parameters according to the production history and environmental parameters. The production time was mainly reduced due to selective quality controls and thus leaving out the unnecessary ones.

5-5 Digital factory

Another extending approach of dealing with the current market requirements is the concept of "service-orientated architectures (SOAs)". Although there is not a consensus for the definition of SOA, it can be described as an architecture, with a set of architectural tenets for building autonomous yet interoperable systems [Jammes and Smit, 2005]. Thus integrating advanced computing capabilities in processes to facilitate and automate manufacturing and manufacturing control [Wermann et al., 2015]. "SOA is an architecture that defines instruments to publish, find and bind services, thus enabling device interoperability in complex collaborative automation systems, which are subject to frequent changes" [Wermann et al., 2015]. SOA is based on web service technology and is characterized by message-based communication, loose coupling and open standards. Different service requesters (agents) are able to request service from different manufacturing services (other agents) without the interaction of a centralized controller or a human. Such a cloud based network is sometimes called a "service bus", which is shown in Figure 5-8. Basically, here the hierarchical structure is broken apart and in theory every part is able to interact with each other part.

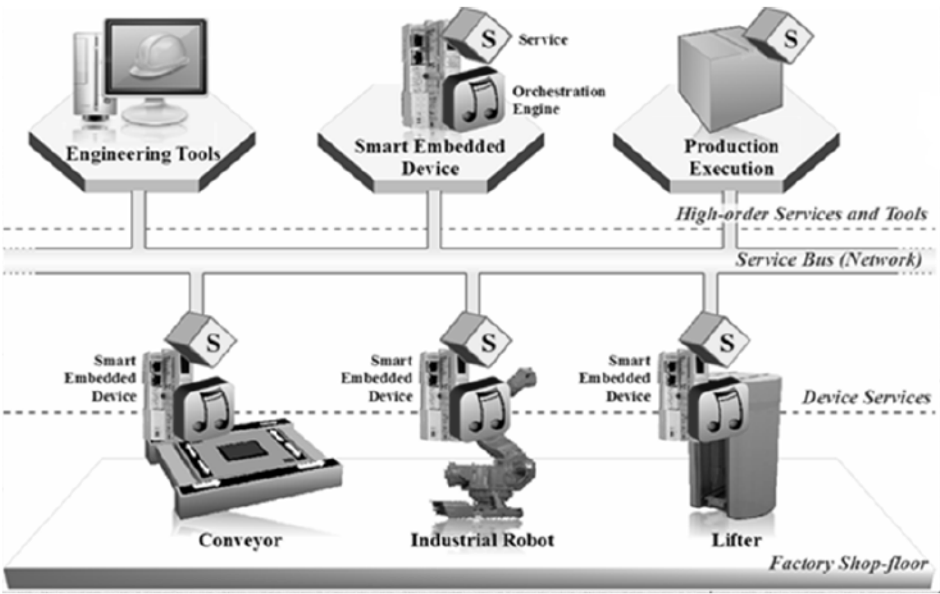

Figure 5-8: Service Bus connecting different components - [Wermann et al., 2015]

A successful implementation of such a system can result in more plug and play capabilities and [Wermann et al., 2015]:

- Installation time/cost reduction, due to the easy set up and configuration of devices
- Interoperability and reduced complexity for the suppliers, due to communication in provided services in stead of internal specifications of a device
- Cost reduction, due to increased utilization

- Reduction of waste and energy due to manufacturing efficiency.

The university of Emden/Leer has been building a "Digital Factory" following the SOA, to demonstrate and evaluate its capabilities in an industrial environment. It is sort of a small factory consisting of different industrial devices and machines, which offer a big set of functionalities. The physical layout is shown in Figure 5-9. The system follows a modular approach, consisting of different workplaces. Each has overlapping capabilities and individual capabilities. For testing, the material used are LEGO bricks, which can be used to build different structures.

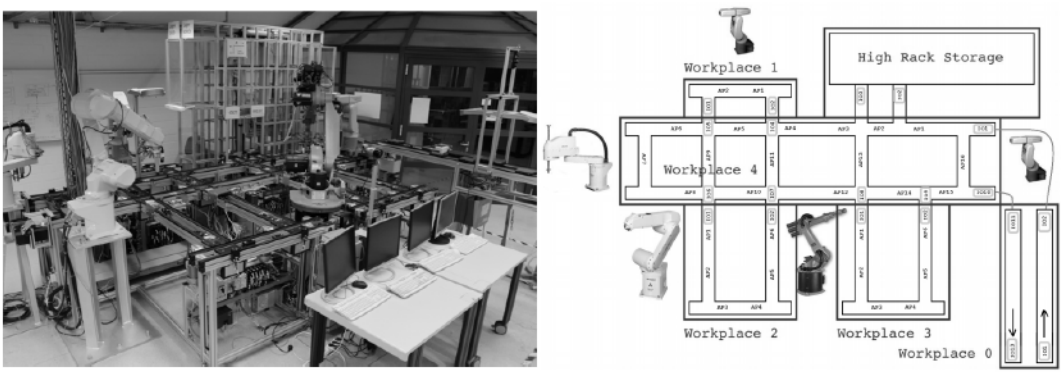

Figure 5-9: The digital factory and a schematic view - [Wermann et al., 2015]

To achieve the implementation of a web-based SOA, different functions that could be exposed as services were detected. Then the system is split into different functional modules, partly based on the physical modules. Then these modules were implemented as web services using the right standards. This implementation results in real time control, monitoring and integration into the enterprise system. Through a discovery system, new services are directly recognized when added to the system, thus enabling plug and play mechanisms. To run a whole production process, orchestration capabilities were added to the SOA as a control layer. The only disadvantage of such a web based system is security, which needs to be looked into.

As seen is this setup, most of the things from MASs come together, such as flexibility, autonomy, real time control and a certain ontology. Therefore, this set up forms the basis for more real "plug and play" factories, which is a goal in agent-based manufacturing systems. Also with such a basic setup, many systems can be tested in the future. Such as mobile devices for remote access, higher levels of implementations on enterprise levels and setting benchmarks to test more improvements.

Chapter 6

Discussion

The previous Chapter discussed some industrial applications since the first researches into agent-based systems were done. Although the number of applications increased in the last years, high levels of adoption by the manufacturing industry is lagging behind. The possible reasons for this are discussed in the first section of this Chapter. In the second section, actions to overcome these barriers are discussed. Where after trends and the future of manufacturing control are discussed. Possibilities for further research is given in section 6-5.

6-1 The lack of adoption by the industry

Although many paper have been written about multi-agent systems (MASs), MAS approaches and the use of MASs in manufacturing control, the implementation in the manufacturing industry is still limited. There is not a clear and unique answer for this. However, according to [Monostori et al., 2006], [Leitão, 2009] and [Leitão and Vrba, 2011] the barriers for large adoption are:

- In industrial applications, proven concepts are wanted by customers. However, not the first try applications. Thus MAS requires more maturity and proof of real applications and merits. Although this changes fast, most test applications have hundreds of agents, in practise systems consist of thousands or more agents. Also these laboratorial applications mostly use software agents, where real applications require a lot of integration in physical systems which requires a lot of time and money. Due to this immaturity, also the lack of software developers with the right programming skills plays a part.
- Another big issue in the industry is the required capital for MASs, which is higher than for centralized approaches. In the industry investments are done when there is a positive return on invest, where MASs will only pay itself off in the future when the need for reconfigurability due to fluctuating markets occurs.
- Not having a centralized control approach, causes an obstacle for managers and directors.

- Having the right ontologies. Making a certain standard ontology for a specific domain is hard. Because in a certain domain, different equipment is used with different properties. Also people with different backgrounds and points of views can have conflicting interests and different solutions for certain problems .
- The industry is also reluctant to things as ontologies, self organization, learning capabilities. The industry is also reluctant to unpredictable behaviour of MASs and related security issues.
- There must be a standard methodology, that formalizes structure and behaviour in order to simplify systems and create understanding of these systems.
- The absence of small industrial controllers which enables agents to run directly, without a separate computer.

Some of the barriers listed above are already overcome, some still exist. Therefore the next section explains actions which should be taken.

6-2 Actions for further implementation

More important than to know what the exact reasons for the limited numbers of implementations are, is to determine the actions to overcome the main road-blockers. Therefore, [Leitão, 2013] determined the following main actions to be considered to convince the industry:

- **The conviction of the industry people** of the benefits of MASs. This can be achieved by giving demonstrations of the maturity, flexibility and robustness of MAS solutions.
- **Standardization** is a major challenge for the acceptance of agent technologies. This includes a methodology and standard ontologies.
- **Resilience and security** especially an issue in developed systems with a service bus or cyber physical systems. This is also an key issue for the trustfulness of the systems and thus the acceptance in the industry.

Implementation of these actions may lead to further development and more MAS solutions that are better accepted by the industry.

6-3 Trends

The barriers and actions, in combination with the still promising aspects of MASs, have led to more developers, developed approaches and solutions. The industry is starting to "believe" in the concepts and technologies, as can be seen from the different interests and efforts devoted by several software development companies, e.g., Magenta Technology, Smart Solutions, NuTech Solutions and Whitestein Technologies, and by several automation technology providers, e.g. Rockwell Automation, Schneider Electric and Siemens [Leitão, 2013]. By these companies and in other researches, more standards were developed. The major trend here is the use of service-orientated architectures (SOAs) in combination with MASs. This integration allows to combine the best of both and thus overcome some limitations associated to MASs alone, such as interoperability. Other steps taken nowadays for the development of truly distributed, developing, large-scale complex systems are cloud-computing, wireless sensors and the ability of the system to evolve using learning algorithms. This combination make the agent systems suited for widespread implementations. An example of such a 3-layer engineering framework is shown in Figure 6-1. Such a structure results in a service-orientated multi-agent system (SoMAS) [Leitão, 2013].

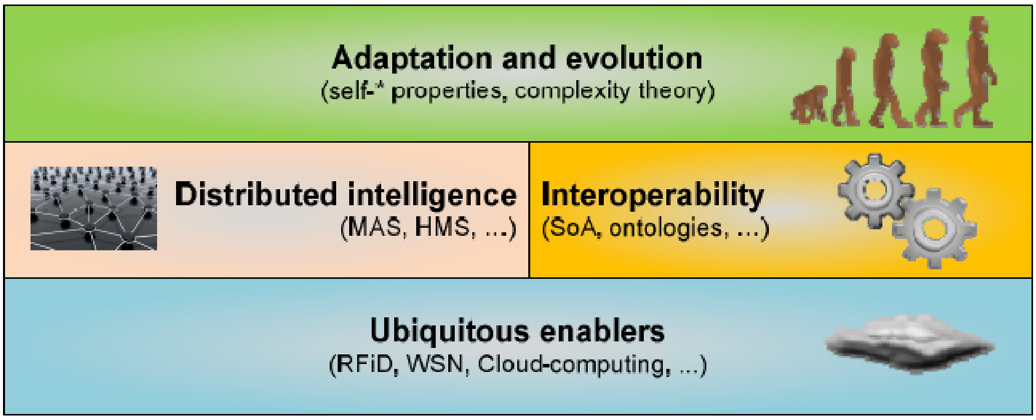

Figure 6-1: 3 layer engineering framework - [Leitão, 2013]

Another trend, which is also build on SOA foundation is the enterprise service bus (ESB). At shop floor control, an adaption of the ESB concept, called manufacturing service bus (MSB) is used to enable the data flow.

Most industries, especially the manufacturing industry, are now striving to achieve SOAs for the integration of agents. Some starting from scratch and others by slowly migrating the legacy applications and legacy processes towards this goal. The most important standards from a manufacturing perspective can be found in [Morariu et al., 2013]. A combined solution as shown in Figure 6-1 is the basis for cyber physical systems (CPSs) and these form the basis for future applications which are discussed in the next section.

6-4 The future of manufacturing

All the research in agent technologies, approaches, different ontologies, SOAs in combination with the evolution of soft- and hardware have led to more and more CPSs. "CPSs integrate the dynamics of the physical processes with those of the software and networking" [Systems, 2012]. CPSs are leading to a new industrial revolution: Industry 4.0 (see Figure 6-2) as it is called in Germany, where it is founded. In the Netherlands the name Smart Industry is preferred [Industry, 2016].

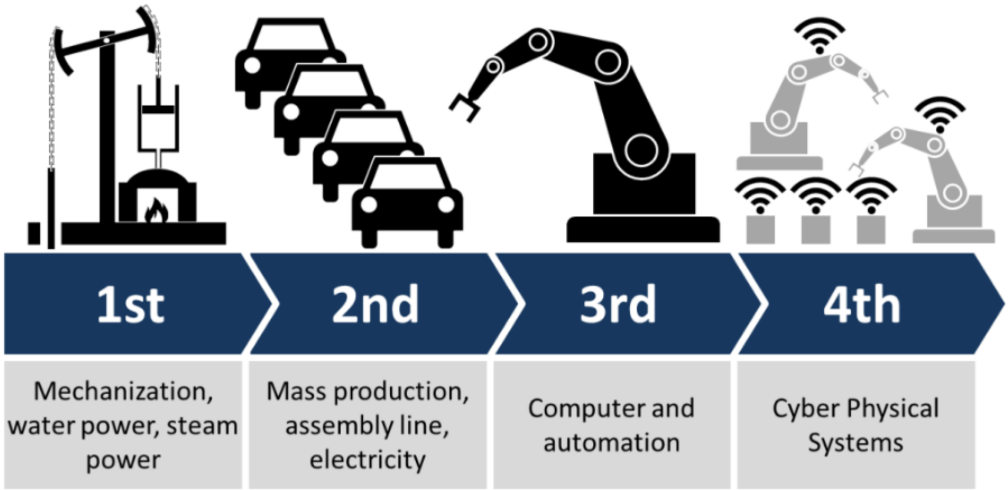

Figure 6-2: Industry 4.0 - [Roser, 2015]

The industry 4.0 includes CPSs, the Internet of Things, big data and cloud computing. It is defined by the following design principles: interoperability, virtualization, decentralization, real-time capability, service orientation and modularity [Hermann et al., 2016]. These principles match with the principles of MASs. "MASs will play an important role in CPSs by providing a new and alternative approach design of intelligent and adaptive systems based on the decentralization of control functions for flexibility, robustness, adaptation and reconfigurability". "The complete achievement of CPSs will therefore require the integration of MASs with complementary technologies" [Leitão et al., 2016]. Although there are already some examples of Industry 4.0 in some factories, for the full potential and future flexible manufacturing is a wider integration with MASs required.

6-5 Further research

A goal of this literature survey is to provide an overview of agent technologies in manufacturing, in particular in manufacturing control. To do this, a general introduction of agents and agent systems in manufacturing control is given were all the different names of interaction protocols, standards and ontologies mostly were left out. To get an overview of all these protocols, standards and ontologies and which are current standards and are outdated a further research is recommended. A goal of this survey is also to explain agent technologies in general and not only make a summation of applications, therefore only 5 applications, which had something unique or something that started a new approach, were chosen in Chapter 5. Although papers with summations of older applications were made, making a new summation can be a goal for a new research when focusing on for example applications of the last 3 years. Due to the focus on MASs, other approaches and techniques are not comprehensively discussed. Such as holonic manufacturing. However, a lot of other research is done and applications were made, in combination with MASs, using approaches such as holonic manufacturing. Thus more research for approaches as such can be a useful addition. In extension to the above point of the holonic approach, for a total overview of state of the art applications and future applications and potentials, more research in the direction of integration with CPSs is recommended. At last, some challenges continue to exist even in Industry 4.0, such as IT security issues, standardization, reluctance of stakeholders and the maintenance of integrity of the manufacturing process. A further research can also be focused on these issues alone.

Chapter 7

Conclusion

Since the start of the first industrial revolution, manufacturing companies have faced some massive changes. The globalisation of manufacturing has led to a fluctuating market where customers' demand plays a central role. Thus in order to stay competitive, manufacturing systems have to be able to function in a highly dynamical, flexible and agile environment and at the same time be robust and scalable. Controlling these manufacturing systems with traditional centralized hierarchical approaches is almost impossible. Therefore the transition towards de-centralized heterarchical systems must be made. Multi-agent systems have revolutionized the building of intelligent and de-centralized systems and is one of the solutions for a full transition. As a result, many researches have been done on different types of agents, agent interaction protocols, different agent-based approaches and even on proof-of-concept studies. Despite big numbers of researches, the number of industrial applications was lagging behind at first. As in any industrial revolution, multiple reasons can be pointed out. E.g. manufacturers wait for the technology to mature, the industry is reluctant to change and companies are not always able or willing to do major investments that are required. Despite these road-blockers, development of uses of multi-agent systems goes on. In recent years different approaches and techniques, such as: service-based approaches, ontologies, improved self learning, cloud-computing and big data, in combination with more investments from companies and governments have massively improved the use of multi-agent systems, especially in cyber physical systems. Which on their turn form a solid basis for transition towards a new industrial revolution, Industry 4.0, and thus the basis for a wide spread use of multi-agent systems.

Bibliography

[Bond and Gasser, 1988] Bond, A. H. and Gasser, L., editors (1988). *Readings in Distributed Artificial Intelligence*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA.

[Brooks, 1986] Brooks, R. A. (1986). A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automation*, 2(1):14–23.

[Bussman, 2016] Bussman, S. (2016). Production 2000+. http://www.stefan-bussmann.de/en/agents/p2000p.html. Accessed: 2016-10.

[Bussmann et al., 2004] Bussmann, S., Jennings, N. R., and Wooldridge, M. (2004). *Multiagent Systems for manufacturing Control*. Springer.

[Bussmann and Schild, 2000] Bussmann, S. and Schild, K. (2000). Self-organizing manufacturing control: an industrial application of agent technology. In *MultiAgent Systems, 2000. Proceedings. Fourth International Conference on*, pages 87–94.

[Bussmann and Schild, 2001] Bussmann, S. and Schild, K. (2001). An agent-based approach to the control of flexible production systems. In *Proceedings of the 8th IEEE international Conference on Emergent Technologies and Factory Automation (ETFA 2001)*, pages 481–488.

[Cândido and Barata, 2007] Cândido, G. and Barata, J. (2007). *A Multiagent Control System for Shop Floor Assembly*, pages 293–302. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Christensen, 1994] Christensen, J. H. (1994). Holonic Manufacturing Systems: Initial Architecture and Standards Directions.

[Cicirello and Smith, 2003] Cicirello, V. A. and Smith, S. F. (2003). *Distributed Coordination of Resources via Wasp-Like Agents*, pages 71–80. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Colombo, 1998] Colombo, A. W. (1998). *Development and implementation of hierarchical control structures of flexible production systems using high level Petri nets*. PhD thesis, Uni Erlangen-NÃijrnberg.

[Colombo, 2005] Colombo, A. W. (2005). Industrial agents: Towards collaborative production-automation, -management and-organization. *IEEE IEs Newsletter*, 52(4):17–18.

[Dilts et al., 1991] Dilts, D., Boyd, N., and Whorms, H. (1991). The evolution of control architectures for automated manufacturing systems. *Journal of Manufacturing Systems*, 10(1):79 – 93.

[Faratin et al., 1998] Faratin, P., Sierra, C., and Jennings, N. R. (1998). Negotiation decision functions for autonomous agents. *Robotics and Autonomous Systems*, 24(3):159 – 182.

[Friedmann, 1991] Friedmann, D. (1991). The double auction market institution: A survey.

[GRACE, 2013] GRACE, G. (2013). Grace project. http://grace-project.org/. Accessed: 2016-10.

[Hadeli et al., 2004] Hadeli, K., Valckenaers, P., Zamfirescu, C., Van Brussel, H., Germain, B. S., Hoelvoet, T., and Steegmans, E. (2004). *Self-Organising in Multi-agent Coordination and Control Using Stigmergy*, pages 105–123. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Hermann et al., 2016] Hermann, M., Pentek, T., and Otto, B. (2016). Design principles for industrie 4.0 scenarios. In *2016 49th Hawaii International Conference on System Sciences (HICSS)*, pages 3928–3937.

[Hollmann et al., 2000] Hollmann, O., Ranze, K. C., Müller, H., and Herzog, O. (2000). Conflict resolution in distributed assessment situations. In *Computational Conflicts*, pages 181–201. Springer.

[Industry, 2016] Industry, S. (2016). Smart industry. http://http://www.smartindustry.nl/. Accessed: 2016-10.

[Jammes and Smit, 2005] Jammes, F. and Smit, H. (2005). Service-oriented paradigms in industrial automation. *IEEE Transactions on Industrial Informatics*, 1(1):62–70.

[Jennings, 1996] Jennings, N. R. (1996). Foundations of distributed artificial intelligence. chapter Coordination Techniques for Distributed Artificial Intelligence, pages 187–210. John Wiley & Sons, Inc., New York, NY, USA.

[Leitão, 2009] Leitão, P. (2009). Agent-based distributed manufacturing control: A state-of-the-art survey. *Engineering Applications of Artificial Intelligence*, 22(7):979 – 991. Distributed Control of Production Systems.

[Leitão, 2013] Leitão, P. (2013). *Towards Self-organized Service-Oriented Multi-agent Systems*, pages 41–56. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Leitão et al., 2012] Leitão, P., Barbosa, J., and Trentesaux, D. (2012). Bio-inspired multi-agent systems for reconfigurable manufacturing systems. *Engineering Applications of Artificial Intelligence*, 25(5):934 – 944.

[Leitão et al., 2016] Leitão, P., Karnouskos, S., Ribeiro, L., Lee, J., Strasser, T., and Colombo, A. W. (2016). Smart agents in industrial cyber x2013;physical systems. *Proceedings of the IEEE*, 104(5):1086–1101.

[Leitão and Vrba, 2011] Leitão, P. and Vrba, P. (2011). *Recent Developments and Future Trends of Industrial Agents*, pages 15–28. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Marik and McFarlane, 2005] Marik, V. and McFarlane, D. (2005). Industrial adoption of agent-based technologies. *IEEE Intelligent Systems*, 20(1):27–35.

[Monostori et al., 2006] Monostori, L., VÃąncza, J., and Kumara, S. (2006). Agent-based systems for manufacturing. *{CIRP} Annals - Manufacturing Technology*, 55(2):697 – 720.

[Morariu et al., 2013] Morariu, C., Morariu, O., Borangiu, T., and Raileanu, S. (2013). *Manufacturing Service Bus Integration Model for Highly Flexible and Scalable Manufacturing Systems*, pages 19–40. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Müller, 1996] Müller, J. (1996). *The Design of Intelligent Agents: A Layered Approach*. Lecture Notes in Artificial Intelligence. Springer.

[Nwana, 1996] Nwana, H. S. (1996). Software agents: An overview. *Knowledge Engineering Review*, 11:205–244.

[Odell, 2010] Odell, J. (2010). Agent technology: An overview.

[Potiron et al., 2013] Potiron, K., El Fallah Seghrouchni, A., and Taillibert, P. (2013). *Multi-Agent System Properties*, pages 5–10. Springer London, London.

[Pruitt, 1981] Pruitt, D. G., editor (1981). *Negotiation Behavior. Organizational and Occupational Psychology*. Academic Press.., New York, USA.

[Rao and Georgeff, 1992] Rao, A. S. and Georgeff, M. P. (1992). An abstract architecture for rational agents. In Nebel, B., Rich, C., and Swartout, W. R., editors, *3rd International Conference on Principles of Knowledge Representation and Reasoning (KR '92)*, pages 439–449, Cambridge, MA, USA. Morgan Kaufmann. Proceedings.

[Rodrigues et al., 2013] Rodrigues, N., Pereira, A., and Leitão, P. (2013). *Adaptive Multi-Agent System for a Washing Machine Production Line*, pages 212–223. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Roser, 2015] Roser, C. (2015). A critical look at industry 4.0. http://www.allaboutlean.com/industry-4-0/. Accessed: 2016-10.

[Rudowsky, 2004] Rudowsky, I., editor (2004). *Intelligent Agents*.

[Sauer, 2004] Sauer, O. (2004). Modern production monitoring in automotive plants. In *Proceedings of the FISITA World Automotive Congress*.

[Sauer, 2006] Sauer, O. (2006). Production monitoring linked to object identification and tracking: a step towards real time manufacturing in automotive plants. In *Assembly of the CIRP*.

[Shen et al., 2006] Shen, W., Hao, Q., Yoon, H. J., and Norrie, D. H. (2006). Applications of agent-based systems in intelligent manufacturing: An updated review. *Advanced Engineering Informatics*, 20(4):415 – 431.

[Sycara, 1998] Sycara, K. P. (1998). Multiagent systems. *American Association for Artificial Intelligence.*

[Systems, 2012] Systems, C.-P. (2012). Cyber-physical systems. http://cyberphysicalsystems.org/. Accessed: 2016-10.

[Terzic et al., 2009] Terzic, I., Zoitl, A., Rooker, M., Strasser, T., Vrba, P., and Mařík, V. (2009). *Usability of Multi-agent Based Control Systems in Industrial Automation*, pages 25–36. Springer Berlin Heidelberg, Berlin, Heidelberg.

[Wermann et al., 2015] Wermann, J., Moraes, E. C., and Colombo, A. W. (2015). *A Service-Oriented Architecture Implementation in the Digital Factory of the University*, pages 73–83. Springer International Publishing, Cham.

[Womack et al., 2007] Womack, J. P., Jones, D. T., and Roose, D. (2007). *The Machine That Changed The World*. Free Pr.

[Wooldridge and Jennings, 1995] Wooldridge, M. and Jennings, N. R. (1995). Intelligent agents: Theory and practice. *Knowledge Engineering Review*, 10:115–152.

[Wooldridge et al., 1999] Wooldridge, M., Jennings, N. R., and Kinny, D. (1999). A methodology for agent-oriented analysis and design. In *Proceedings of the Third Annual Conference on Autonomous Agents*, AGENTS '99, pages 69–76, New York, NY, USA. ACM.

Glossary

List of Acronyms

IT	information technology
AI	artificial intelligence
DAI	distributed artificial intelligence
PAI	parallel artificial intelligence
DPS	distributed problem solving
TEL	transport engineering and logistics
MAS	multi-agent system
BDI	belief-desire-intention
AGV	automated guided vehicle
IPC	industrial personal computer
CNC	computer numerical controls
PLC	programmable logic controller
CAPP	computer-aided process planning
CCC	collaborative coordination control
RIDER	Real-Time Decision making in manufacturing
SCM	supply chain management
CNP	contract net protocol
P2000+	Production 2000+
OEM	original equipment manufacturer

PMC	production monitoring and control systems
MES	manufacturing execution systems
CoBASA	Coalition Based Approach for Shop-floor Agility
ABAS	actor-based assembly systems
MRA	manufacturing resource agent
AMI	agent-machine interface
ACL	agent communication language
CLA	coalition leader agent
GRACE	InteGration of pRocess and quAlity Control using multi-agEnt technology
JADE	java agent development framework
FIPA	foundation for intelligent physical agents
GUI	graphical user interface
SOA	service-orientated architecture
SoMAS	service-orientated multi-agent system
ESB	enterprise service bus
MSB	manufacturing service bus
CPS	cyber physical system