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Effective Monitoring and Control with Intelligent Products

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To Zheng

Preface

The Ph.D. thesis currently in front of you marks the end of a valuable and important period of my life, both academically and personally speaking. Academically, as this thesis is the result of almost five years of doctoral research which I conducted at the University of Groningen. Personally, not just in terms of self-development, but mainly because I met and married the love of my life. Therefore, I am looking back on a great period of my life, for which I am more than grateful to all the people who took part in that.

In this thesis, I describe the research conducted to investigate the applicability of intelligent products for monitoring and control purposes. Many organisations face difficulties with operational monitoring and control, and it is argued that intelligent products are promising in overcoming these difficulties. Therefore, the first part of this thesis analyses the difficulties faced, and presents an overview of intelligent products. Afterwards, part II and III analyse and evaluate the application of intelligent products in the contexts of production and transportation, respectively. Finally, part IV provides a discussion on the research findings and contributions.

The process of writing and finalising a Ph.D. thesis is something which cannot be accomplished alone. Therefore, I would like to express my appreciation to everybody who contributed to this thesis and everybody who supported me in writing it. First of all, I would like to thank my co-promoter Nick Szirbik, as his contribution to this thesis has been crucial. His encouragement for me to pursue a Ph.D., the various papers we have written together, the numerous discussions we had, his countless digressions, it all proved to be extremely valuable to the completion of this thesis. Next to

that, I would like to thank my promoter Hans Wortmann, in the first place for providing me the opportunity to pursue a Ph.D. Moreover, especially his guidance and his critical reflection on my work were more than valuable during the whole process. Furthermore, I would like to thank the members of the reading committee, prof. dr. D.C. McFarlane, prof. ir. A.J.M. Beulens, and prof. dr. I.F.A. Vis, for assessing this thesis and providing constructive comments.

Several people who contributed to this thesis deserve special mention. Gijs Roest and Wilrik Mook developed software which was key for conducting my research. Paul Buijs assisted in conducting a case study which resulted in a critical part of this thesis. Collaboration with Marco Stuit, Nick van Beest, Cees de Snoo, Marco Hoogenraad, Fred van Blommestein, Tommi Tervonen, Chee-Wee Tan, Kary Främling, Jan Holmström, and both planners and managers of the case company also led to various valuable contributions to this thesis. I am more than grateful for all these contributions. Moreover, I would like to thank all other colleagues of the department of Business and ICT, in particular the secretaries, for the provided support and working atmosphere.

Finally, I would like to thank my family and friends for all their support. I am especially grateful to my parents, for always believing in me and always supporting me in pursuing my dreams. But above all, I would like to thank my wife, Zheng. Zheng, it is impossible for me to describe how much I appreciate the endless love and support I have received from you during these years. One thing is clear: without you always being there for me, it would have been impossible for me to finish this thesis. For that, I will always be grateful to you!

Gerben G. Meyer

Groningen, The Netherlands
May 2011

Contents

Part I

Introduction

Chapter 1

Monitoring and Control

Monitoring and control is an important aspect of planning and control, as disturbances happen during plan execution, which in turn require intervention. Many companies however have difficulties in monitoring and controlling their activities. One main reason for this is the lack of timely and accurate information on the plan execution. Without this information, planners cannot effectively perform monitoring and control activities, which makes responding to disturbances troublesome. This chapter analyses the issues which occur in monitoring and control, and divides them in three categories, namely issues in information availability, problem detection, and decision making. Furthermore, it is discussed how the research as described in this thesis contributes to solving these issues. This chapter ends with an overview of the content of this thesis.

1.1 Introduction

Many companies have difficulties in monitoring and controlling their activities, for example due to the lack of appropriate information available to their planners, which in turn often results in disturbances not being detected in time. This thesis analyses these difficulties, and, in order to contribute in solving them, investigates the possibility to apply intelligent products for supporting planners by performing routine tasks in everyday monitoring and control activities. The remainder of this section will elaborate on the scope of this thesis. Afterwards, Section 1.2 will discuss issues in monitoring and control in more detail. In Section 1.3, an overview is presented of the contribution of this thesis in solving these issues. This chapter ends with an overview of this thesis in Section 1.4.

Planning and control

The main business of most companies is to deliver products and services to their customers. In order to deliver products and services in an effective way, companies also need to manage their resources in an effective way. The activity of managing these resources (for the production and delivery of products and services) is typically referred to as operations management [166]. An important aspect of operations management is planning and control, as all activities require plans and all activities require controlling. Therefore, planning and control is needed to manage the ongoing activities in the company in such a way that customer demands can be satisfied.

Planning is an explicit description of what is intended to happen at some time in the future. A plan however does not guarantee that in reality it will happen accordingly. All kind of disturbances can occur, such as suppliers which are not delivering on time, physical resources which are failing, or staff which is absent due to illness. Furthermore, customers can change their minds about what they want and when they want it. Therefore, adjustments are needed, in order to cope with these disturbances. It may mean that plans need to be changed on short notice, or that some other kind of intervention is needed, such as finding a new supplier who can deliver quickly, repairing resources which are failing, or find staff who can replace the absentees.

Control makes the adjustments to the plan which are needed to still achieve the original goals of the plan, when possible, even if the assumptions on which the plan was based appeared to be incorrect or obsolete [166].

Planning and control activities

There are typically four overlapping activities distinguished in planning and control, namely: loading, sequencing, scheduling, and monitoring and control [166].

- The *loading* activity is concerned with allocating amounts of work to specific resources.
- The *sequencing* activity is concerned with determining in which order the work is going to be tackled.
- The *scheduling* activity is concerned with the question when exactly the work is going to be done.
- The *monitoring and control* activity is concerned with ensuring that the planned activities are indeed happening, and if needed, taking corrective measures.

Although these four activities are overlapping, the first three collectively constitute the planning function, while the last one represents the control function.

Monitoring and control

In the last decades, the vast majority of the practical and academic effort was focused on improving the planning function, both in theory and industrial practise. Improving monitoring and control has therefore received much less attention (see e.g. [25, 106, 107, 187]). As will become clear throughout this thesis, monitoring and control often largely relies on manual steps, such as interactions between planners and the operational staff, in order for the planners to be informed about the plan progress and the disturbances that occur. As a result of that, planners in many companies spend most of their time to monitor and control a plan, rather than to create a plan (see e.g.

[69, 107, 118, 143]). This justifies a renewed interest in monitoring and control.

1.2 Issues in monitoring and control

Issues in business can be defined as the difference between the current state and the goal state. In this thesis, issues in monitoring and control are analysed from the point of view of the planners and schedulers. As these issues will be described and investigated in greater detail in the chapters to follow, they will only be introduced on a quite generic level in this chapter. The issues in monitoring and control are divided in three categories, namely issues in information availability, problem detection, and decision making.

Information availability

The first type of issues refers to the fact that planners often do not have the information available which they need for properly and effectively dealing with disturbances during plan execution. This can be due to several reasons.

An important reason why information is not always available stems from the fact that most companies have a hierarchical structure. This has the advantage that the complexity on the various organisational levels is reduced, with each level being able to function partially independent. However, performance feedback to the planners is crucial for the proper functioning of a hierarchical organisation [121, 170]. Therefore, appropriate and timely feedback has to be provided to the central planners. Furthermore, the central planners need to be able to respond adequately and in time to this feedback. If any of these requirements are not met, it becomes impossible for planners to effectively monitor the plan's execution. This problem has been referred to as the vertical communication bottleneck in organisations [53]. In fact, monitoring and control often still largely relies on manual steps, such as making phone calls and other kind of interactions with the operational personnel, in order to gather all the needed information [108]. Therefore, information is often not directly available to the planners when disturbances occur.

Besides timely information, accurate and detailed information is needed for effective monitoring and control. For example, as it will be elaborated in Chapter 3, problems with resources always relate to specific equipment that is no longer available and may be in need of maintenance. Or, as another example, problems with material always relate to a specific piece, pallet, batch or other unit of processing. These are specific problems that occur in detailed, disaggregated form. However, aggregation is widespread in many computer-based planning systems (see e.g. [8, 156]). Accordingly, authors like MacCarthy and Wilson claim that computer-based support systems often fail to provide the required accurate information [108]. Therefore, acquiring the information needed for effective monitoring and control still largely relies on manual steps.

Problem detection

The second kind of issues refers to the fact that even when planners have the right information available, it can still be a difficult task for them to actually detect problems caused by disturbances. Especially in larger organisations, large amounts of data on plan execution progress are often available within their information systems. It can however be too much effort to manually monitor all this data, as is for example shown by a case study at a transportation company as described in Chapter 5 and 6. According to the planners in this case company, it is too much effort for them to monitor the progress of all individual trucks and pallets of the company, even though a computer-based support system is capturing progress data. Therefore, the planners at this company typically only become aware of delayed trucks or pallets, when this information is pushed to them by the driver of a truck through a phone call or text message. This is in line with observations in literature stating that computer-based support systems often lack the appropriate functionality to support planners and schedulers (see e.g. [22, 108, 117, 149, 169]). Therefore, detecting problems in plan execution is still mainly a manual activity, which can result in problems being detected too late. This in turn reduces the possibilities for solving the problems effectively.

Decision making

The third kind of issues refers to the fact that when problems are detected, it is still a difficult task to solve them effectively. Typically, the main target is to solve the problem in such a way that the adapted plan is close to the initial plan with adding minimal supplementary costs. Therefore, complete re-planning is typically not recommendable, as complete re-planning can also affect other parts of the plan where no disturbances occurred, resulting in a decreased plan stability and an increased plan nervousness [187]. However, due to the high amounts of data available and a huge search space for finding a suitable solution, monitoring and control is a highly complex and time-consuming problem solving task, requiring human knowledge, ingenuity, highly experienced personnel, as well as tailored and sophisticated IT support tools.

1.3 Research and design approach

The issues described in the previous section hamper further progress in monitoring and control. Therefore, the work described in this thesis is focused on giving a contribution in solving these issues. For that purpose, a design science approach is applied, in order to create new and innovative artefacts [70]. According to Hevner et al. [70], design is essentially a search process to discover an effective solution to a problem. Problem solving can be viewed as utilising available means to reach desired ends while satisfying laws existing in the environment [163]. In this context, means are a set of actions and resources available to construct a solution, ends represent goals and constraints on the solution, and laws are uncontrollable forces in the environment.

Research contribution

The result of this research and design process should be one or more purposeful IT artefacts, created to address the organisational issues as described in Section 1.2. According to Hevner et al., such an IT artefact can either be a construct (vocabulary and symbols), model (abstractions and representations), method (algorithms and practises), or instantiation (implemented and prototype systems). In this case, the IT artefacts will be models and instantiations for systems designed and implemented to address the issues as identified above, in order to improve the monitoring and control function of organisations. Two different levels of systems will be distinguished in this thesis:

- *System architecture*: A model of the system, describing how the system can be implemented and can be applied in an organisation.
- *System prototype:* An instantiation of the system, showing how the system is implemented and applied in an organisation.

These systems, both architectures as prototypes, will be the main contribution of the research as presented in this thesis. Out of the many available software architectures that may be considered appropriate to tackle the described issues, an architecture based on intelligent products is considered the most appropriate for developing such systems. This is due to the fact that intelligent products can represent individual physical objects and are capable of autonomously performing some of the repetitive activities required for their monitoring and control. Moreover, by presenting the available information of the physical objects in a comprehensive way to the planners, they can potentially support the planners with their monitoring and control activities. However, to our knowledge, this is hardly ever evaluated and confirmed in practical settings, especially regarding the activities in monitoring and control. Therefore, the key question which is tried to be answered in this thesis is:

- *How can intelligent products be applied to improve everyday monitoring and control activities of organisations?*

For this purpose, the theoretical foundations of intelligent products will be elaborated in Chapter 2.

Research scope

According to the definition of Beamon [13], production, storage, and transportation are the three main components of the supply chain process with respect to the conversion of raw materials into final products. As storage and inventory control are widely studied in literature (see e.g. [7]), the research as presented in this thesis mainly focuses on production and transportation. Hence, Chapter 3 and Chapter 5 will demonstrate how intelligent products can be applied in order to improve monitoring and control activities in production and transportation, respectively. In this way, the work as described in this thesis is adding value to the knowledge base of the more practical field of monitoring and control as well as to the knowledge base of the more theoretical field of intelligent products. Therefore, an important aspect of the research as described in this thesis is to bridge the gap between theory and practise with respect to intelligent products and monitoring and control.

Research evaluation

According to Hevner et al. [70], the usefulness of a design artefact must be rigorously demonstrated via well executed evaluation methods. Just as it is the case when designing purposeful systems, it is also key to effectively use the knowledge base for evaluating the proposed systems. Therefore, the TAC SCM framework [34] has for example been used for evaluation purposes, as it is a well-founded framework, and widely reported in the literature (see e.g. [35, 57]).

In this thesis, usefulness is demonstrated by applying a multi-method evaluation approach for measuring the efficiency, efficacy, and effectiveness [30]. In this context, efficiency refers to how well a system performs its intended behaviour with the minimum use of resources. Efficacy refers to which extent the behaviour of a system results in the output that was intended. Effectiveness is a measure on how purposeful the system is in a practical business environment. In order to determine how well the developed artefacts perform on these three measures, multiple evaluation methods have been applied:

- *Descriptive evaluation:* This evaluation method is applied to demonstrate the usefulness of a system architecture, by constructing detailed scenarios around the system to demonstrate its utility.

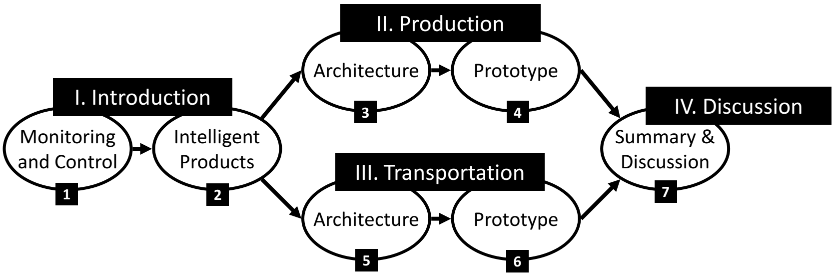


Figure 1.1: Thesis outline

- *Experimental evaluation:* This evaluation method is applied to demonstrate the usefulness of an implemented system in a experimental setting, by executing the system with artificial data (i.e. simulation).

- *Observational evaluation:* This evaluation method is applied to demonstrate the usefulness of an implemented system in a practical setting, by studying the system in depth in a business environment.

Chapter 4 and Chapter 6 will present in detail the performed evaluations of the developed systems, showing how intelligent products can improve monitoring and control activities of organisations in production and transportation.

1.4 Thesis outline

In this section, the structure of this thesis is explained in detail. A visual representation of the outline of this thesis can be found in Figure 1.1.

Chapter 2

This chapter will give an extensive overview of the field of intelligent products. Definitions as well as a novel classification will be introduced. Furthermore, the chapter elaborates on the technical enablers and potential applications. This chapter is an edited version of a journal paper published in Computers in Industry (see [122]).

Chapter 3

This chapter will explain how the concept of intelligent products can be applied in a production context for improving monitoring and control activities. For this, issues in production will be analysed in detail, and, based on this analysis, a novel system architecture will be presented. This chapter is an edited version of a journal paper published in International Journal of Production Research (see [125]).

Chapter 4

This chapter will show how the concept of intelligent products applied for improving monitoring and control activities in a production context is evaluated. For this purpose, the developed system prototype will be described in detail. Furthermore, the conducted experimental evaluation will be presented in detail, including the evaluation results. This chapter is an edited version of a book chapter published in Lecture Notes in Business Information Processing (see [124]).

Chapter 5

This chapter will explain how the concept of intelligent products can be applied in a transportation context for improving monitoring and control activities. For this, issues in road freight transportation will be analysed in detail, and, based on this analysis, a system architecture will be presented. This chapter is an edited version of a conference paper published in the proceedings of the 4th IEEE International Conference on Management and Service Science (see [123]).

Chapter 6

This chapter will show how the concept of intelligent products applied for improving monitoring and control activities in a transportation context is evaluated. For this purpose, the developed system prototype will be described in detail. Furthermore, the conducted experimental and observational evaluation will be presented in detail, including the evaluation results.

This chapter is an edited version of a submitted journal paper, which is not published yet.

Chapter 7

This chapter is bringing all the previous chapters together, by providing a discussion about all the achieved results. Furthermore, limitations and directions for future work will be discussed.

Chapter 2

Intelligent Products

This chapter presents an overview of the field of intelligent products. As intelligent products have many facets, this chapter is mainly focused on the concept behind intelligent products, the technical foundations, and the achievable practical goals of intelligent products. A novel classification of intelligent products is introduced, which distinguishes between three orthogonal dimensions. Furthermore, the technical foundations in the areas of automatic identification and embedded processing, distributed information storage and processing, and agent-based systems are discussed, as well as the achievable practical goals in the contexts of manufacturing, supply chains, asset management, and product life cycle management.[1]

[1] This chapter appeared earlier as: G.G. Meyer, K. Främling, and J. Holmström. Intelligent products: A survey. *Computers in Industry* 60(3):137-148, 2009, doi:10.1016/j.compind.2008.12.005.

2.1 Introduction

This chapter gives an overview of the recently emerged field of intelligent products, by analysing and proposing definitions of what they are and by performing a survey of how they have been or can be implemented and used in different application areas. In this context, intelligent products and concepts like smart products can be used interchangeably. However, intelligent products are not a synonym for concepts like ubiquitous and pervasive computing, ambient intelligence etc. that tend to focus on how human users interact with their environment. The Internet of Things [59] concept could be a better fit, but it tends to be focused rather on connectivity and information exchange than on the "intelligence" of the products. Intelligent products are not always invisible and unnoticeable, they are rather reactive actors that are capable of autonomously adapting to changes in their environment. Even though this is still largely a vision for the future, this chapter will provide a picture of the current status and how it can evolve towards this vision in different application areas.

Intelligent products have many facets. In this chapter, the concept, technical implementation, and achievable practical goals will be reviewed. Based on that review, a classification of intelligent products will be introduced, which distinguishes between three orthogonal (albeit not independent from each other) issues: what is the intelligence of the product, what is the location of intelligence, and whether the product consists of a single entity or if it is an aggregation or composition of several entities. The reason for introducing such a three-dimensional classification is that previously proposed classifications seemed to be under-developed either in the lower or the upper range of "intelligence" and did not necessarily take into account e.g. how the embedded processing capabilities affect the implementation of such intelligent products. Previous classifications also tend to focus only on limited parts of a product's lifecycle, e.g. manufacturing or maintenance only, rather than taking into account the entire lifecycle. Analysing different approaches to intelligent products using the proposed three-dimensional classification makes it easier to identify what their limitations are, and which are the main aspects that need further development.

Furthermore, the technical foundations of intelligent products will be discussed in detail in this chapter. These foundations can mainly be found in the areas of automatic identification and embedded processing, distributed information storage and processing, and agent-based systems. In order to keep the chapter reasonably limited, some other relevant domains such as technologies for fault detection and remote maintenance are largely omitted from this chapter. For these domains, there already exists dedicated journals and other dissemination channels. Also, challenges related to privacy, security, trust etc. are not discussed in detail here, but such aspects in the context of intelligent products are discussed in detail in e.g. [68, 100, 101, 174]. Some other challenges for implementing intelligent products, such as the cost and the availability of skilled personnel are pointed out in e.g. [5] and [94].

Regarding how, when and why to implement intelligent products, the achievable goals for the intelligent product concept will be presented as a starting point for developing practical business cases in individual companies. It is important to note that solutions developed for one purpose can, if appropriately designed, be employed for other purposes as well. Means-ends propositions [163] for intelligent products in specific contexts will be discussed, such as manufacturing, supply chain, and asset management, as well as across contexts, i.e. for product lifecycle management.

2.1.1 Background

In the early days, factories were often powered by one central steam engine. As mentioned in [15], the electric engine was meant to replace the steam engine. Just as there was one steam engine that would power an entire factory, the electric motor was also initially a single device installed at a central location in the factory, with belts running to the remote areas of the factory. The electric motor improved to the point where a single motor with belts could be replaced by motors built into each device. Now you could place the instruments wherever it made sense to put them, and the motor became an invisible part of the instrument.

According to Norman [134], computers and computer networks should be thought of as infrastructure. It should be quiet, invisible and unobtrusive, instead of being too visible and too demanding. He therefore envisages a change occurring from one centrally located infrastructure (the personal computer), to a set of rather small, widely distributed devices. These devices will not even be thought of as computers or telecommunication devices. Instead, these devices will be seen as a natural part of our daily activities and the tools that we use [15]. He argues that the proper way to achieve this is through the user-centred, humane technology of appliances, where the technology of the computer disappears behind the scenes into task-specific devices that maintain all the power without the difficulties [134]. Similar views about computing had earlier been proposed mainly under the name ubiquitous computing (see e.g. [192, 193]), that is also sometimes called pervasive computing or ambient intelligence depending on the context.

Gershenfeld shares this vision, as he calls invisibility the missing goal in computing [58]. According to him, we can bring technology so close to people that it can finally disappear. Furthermore, he emphasises that the barrier between digital information and our physical world should be removed. The real challenge in this is to figure out how to create systems with many components that can work together and adapt to changes in the physical world. This vision has sometimes been called the Internet of Things, which is also adopted e.g. in [21, 59, 77]. However, in many contexts such as supply chain management, the Internet of Things concept tends to be focused on product identification technologies, information storage and information exchange rather than on the "intelligence" of the products.

It seems like intelligent products were first discussed in an after sales and service context in 1988 by Ives and Vitale [81]. The first examples of intelligent products in the after sale context were computers running programs that tracked the configuration and performance, and could request for service and maintenance. The benefits in efficiency of service and reliability of operation could be substantial and was the basis for successful start-ups and new lines of business for established companies.

Only later did the idea of integrating intelligence and control into the product spread to manufacturing [116] and supply chain control [98]. In these application domains, new auto identification (Auto-ID) technologies, such as Radio Frequency Identification (RFID) have made the tracking and tracing of products throughout the entire supply chain possible. When product individuals in a logistic/production setting are not only given a traceable individuality, but also the associated content (e.g. delivery terms, contract terms, exceptions, etc.), and also decision power is delegated to them, we enter the realm of intelligent products. Such intelligent products will have the means to communicate between themselves and also with logistic service providers. Intelligent products link the Auto-ID technology to the agent paradigm and Artificial Intelligence. Agent technology has already been considered as an important approach for developing industrial distributed systems (e.g. intelligent manufacturing systems) [85, 84, 160].

Intelligent products can also play an essential role in product lifecycle management by their capability of collecting usage information and reacting on it proactively, e.g. estimating needs for maintenance or repair. By using sensor technologies like thermal, acoustic, visual, infrared, magnetic seismic or radar sensors, the conditions of products can be continuously monitored. The access to information on how products have been used could significantly improve the way that products are recycled when they arrive to their end-of-life. Sensor technologies can also contribute to improvements in manufacturing nodes and to the logistics of the entire supply chain, by giving real-time status information (e.g. identification, location and other conditions) of the products.

What is common to such tracking and tracing in the supply chain and to product lifecycle management is that information needs to be represented at the item level and communicated between different organisations. From an information system perspective, a shipment is indeed just a "product" with a relatively short lifecycle, where the actual products that were included in the shipment may have a much longer lifecycle. However, currently used information systems typically focus on managing batches and accounts using centralised databases, hence representing item-level information and communicating it between organisations can be a challenge for them, in case of mass-customisation of products. Therefore, there is increasing interest in the development of Auto-ID technologies and intelligent products which is being reflected in on-going work, current project proposals and future research areas.

2.1.2 Chapter outline

After this introduction, Section 2.2 will analyse different proposals for defining intelligent products. Furthermore, a classification method for such products that can be used as a tool for classifying the different implementation approaches will be presented. Section 2.3 gives an overview of the enabling technologies of intelligent products. Section 2.4 will analyse how intelligent products can be implemented and used in different application domains, followed by conclusions and future trends in Section 2.5.

2.2 What are intelligent products

This section will start with presenting the existing definitions of intelligent products found in the literature. All these definitions focus on certain aspects of intelligent products and on certain application areas or parts of the product lifecycle. Afterwards, based on the existing definitions, a classification of intelligent products will be proposed, which tries to cover all aspects of intelligent products while taking into account the whole product lifecycle.

2.2.1 Definitions of intelligent products

From the existing definitions of intelligent products, the complementary notions of McFarlane et al., Kärkkäinen et al. and Ventä will be discussed next.

McFarlane et al.

McFarlane et al. define an intelligent product as a physical and information-based representation of a product [116]. Figure 2.1 shows an example of such a product. In this figure, the jar of spaghetti sauce is the physical product, the information-based representation of the product is stored in the database, and the intelligence is provided by the decision making agent. The connection between the physical product and the information-based

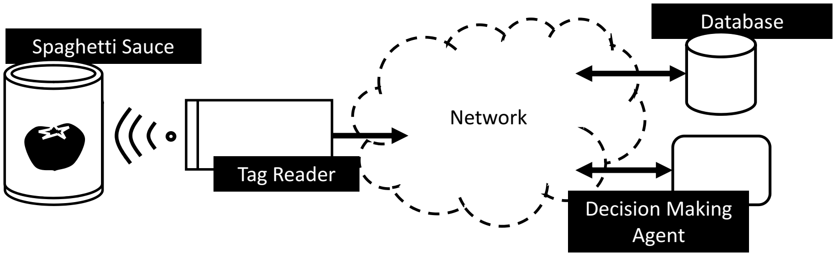


Figure 2.1: Intelligent jar of spaghetti sauce (derived from [195])

representation is made using a tag and a reader, as will be further discussed in Section 2.3.1. According to McFarlane et al., an intelligent product has the following properties:

1. Possesses a unique identification
2. Is capable of communicating effectively with its environment
3. Can retain or store data about itself
4. Deploys a language to display its features, production requirements, etc.
5. Is capable of participating in or making decisions relevant to its own destiny

Based on this definition, Wong et al. [195] have defined a two-level classification of intelligence. When the intelligent product only covers points 1 to 3, it is information oriented, and is called a product with level 1 product intelligence. A product with level 2 product intelligence covers all points, and is called decision oriented. Even though this intelligent product classification is quite generic concerning the level of intelligence of an intelligent product, it is based on a separation between the actual product and its information-based counterpart (as seen in Figure 2.1). Therefore, it is mainly intended for describing the use of RFID technology in for example manufacturing and supply chain purposes, without covering for instance products with embedded processing and communication capabilities.

Kärkkäinen et al.

The fundamental idea behind an intelligent product according to Kärkkäinen et al. [98] is the inside-out control of the supply chain deliverables and of products during their lifecycle. In other words, the product individuals in the supply chain themselves are in control of where they are going, and how they should be handled. To move to inside-out control of products, the products should possess the following properties:

1. Globally unique identification code

2. Links to information sources about the product across organisational borders, either included in the identification code itself or accessible by some look-up mechanism

3. Can communicate what needs to be done with them to information systems and users when needed (even pro-actively)

In this definition, the classification goes from no intelligence (unique identification only) towards decision-oriented products when covering the last property, in a similar way to the classification by McFarlane et al. Despite a slightly bigger consideration for embedded processing capabilities and the whole product lifecycle, this classification is still mainly focused on the use of RFID technology, similar to McFarlane et al's classification.

Ventä

Another definition of intelligent products is given by Ventä in [186]. Ventä refers by intelligence to products and systems that:

1. Continuously monitor their status and environment

2. React and adapt to environmental and operational conditions

3. Maintain optimal performance in variable circumstances, also in exception cases

4. Actively communicate with the user, environment or with other products and systems

This definition is clearly focused on decision-oriented products, thereby extending point five of the first definition and point three of the second definition. However, this definition is more focused on products with sufficient embedded computing power for communicating directly with other information systems. The main application area is the running and maintenance of products in use, with little or no consideration of manufacturing and supply chain management. This is a noteworthy difference with the first two definitions, as the first two mainly deal with products that only possess an identification such as a barcode or an RFID tag, thereby requiring external information storage and communication facilities.

2.2.2 Classification of intelligent products

All three definitions focus on certain aspects of intelligent products and the product lifecycle, and thereby cover only a part of the total field of intelligent products. Therefore, a more comprehensive classification of intelligent products that covers all the aspects of the field is needed. This classification can be used for analysing different information architectures according to what kind of intelligent products and what parts of the product lifecycle they are suited for. A classification based on three orthogonal dimensions will be presented in the remainder of this section.

Level of intelligence

The degree of intelligence of an intelligent product can vary from "dumb" products to pro-active entities. This is the main focus of the definitions and classifications of McFarlane et al. and Kärkkäinen et al. Based on these definitions, the level of Intelligence of intelligent products can be divided into three categories:

- *Information handling.* An intelligent product should at least be able to manage its own information, given by sensors, RFID-readers and other techniques. Without this capability, it can hardly be called intelligent. When the intelligent product is only capable of information handling, it is not in control of its own life, as full control of the product is external or outside the product.

- *Problem notification.* A more intelligent product is a product which can notify its owner, when there is a problem. Such a problem could for example be that it has fallen, the temperature is too high, etc. Still the product is not in control of its own life, but it's able to report when there are problems with its status.

- *Decision making.* The most intelligent product is the product which can completely manage its own life, and is able to make all decisions relevant to this by itself, without any external intervention. In this case, the product has full control over itself, and there is no external or outside control of the product. This has been called inside-out control of products in [98].

Location of intelligence

When each object has its own intelligence, it does not necessary mean that the intelligence is located at the object. Two extremes can be identified:

- *Intelligence through network.* The intelligence of the product is completely outside the physical product, at a different location. For example, there is a server where a dedicated agent for the product is running [52]. The definitions of McFarlane et al. and Kärkkäinen et al. are mainly focused on this approach. The product only contains a device that is used as an interface to the intelligence. In the research field for smart devices, such devices are often called *small SD* (Smart Device) [26, 27]. Platforms in which the intelligence of the product is executed entirely on other hosts are sometimes called *portal platforms* [145].

- *Intelligence at object.* All the intelligence, whether this is only information handling, or advanced decision making, takes place at the physical product itself. The definition of Ventä is mainly focused on this approach. The object has the needed computational power, storing capacities and network connectivity. In the research field for smart devices, such devices are often called *big SD* [26, 27]. Platforms in which the intelligence of the products is executed entirely on the devices are sometimes called *embedded platforms* [145].

There can also be intermediate solutions, these platforms are sometimes called *surrogate platforms* [145]. In Section 2.3, the techniques underlying these differences will be further elaborated.

Aggregation level of intelligence

A third dimension of intelligent products is one which is lacking in the definitions and classifications discussed in the first part of this section. However, the aggregation level of the intelligence is also considered as an important dimension, as many products are composed from parts, which can also be products in itself. For example, a car is an assembly of components that are manufactured by different organisations and that may by themselves be composed of other parts. In the case of modern cars or other products with sufficient information processing and communication capabilities, a lot of decision-making can be embedded into the product itself. However, some parts of the product may have only an identifier, while other parts may have their own embedded information processing capabilities. In order to make it possible to access information in a uniform way from all levels, at least the communication interface should be similar for all components of the product, as proposed for instance in [51]. For analysing this dimension, the following separation is made:

- *Intelligent item.* The object only manages information, notifications and/or decisions about itself. If it contains any components, they can not be distinguished as individual objects.

- *Intelligent container.* The intelligent container not only manages information, notifications and/or decisions about itself, it is also aware of the components that it is made of and may act as a proxy device for them. If the intelligent container is disassembled or parts are removed or replaced, the parts may be able to continue as intelligent items or containers by themselves. For instance, an engine may be removed from a vehicle, be re-furbished and then start a new life in another vehicle, possibly together with new or re-furbished components (alternator, clutch, etc.). Another example from the domain of supply

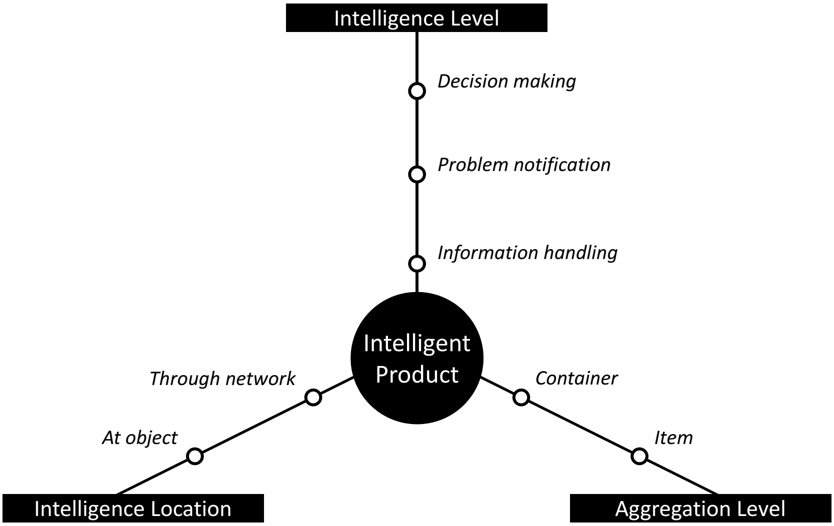


Figure 2.2: Classification model of intelligent products

chain management is an intelligent shelve, which can notify its owner when a specific product is out of stock.

Classification model

Together, these dimensions lead to a three-dimensional classification model for intelligent products, which covers all the main aspects of the field. This classification model is shown in Figure 2.2. In Section 2.4, the classification model will be used to classify the intelligent products in the discussed applications.

2.3 Technologies enabling intelligent products

This section analyses the technologies behind intelligent products from three main points of view. Section 2.3.1 starts with the identification, sensing and information processing technologies that can be embedded in the product itself, ranging from barcodes to embedded computers with sensors, network connectivity etc. Section 2.3.2 discusses how the intelligence can be "outsourced" from the product itself to other storage and processing devices such as back-end systems. Three different approaches for how this could be implemented are studied with the objective to illustrate their possibilities and challenges. Finally, in Section 2.3.3 different agent-based platforms are discussed that have been proposed for addressing the challenges of local versus distributed information storage and processing.

2.3.1 Automatic identification and embedded processing

Already in the early 1970's, the first optical scanning systems using barcodes were installed to provide production line part tracking, as well as to satisfy the needs of companies for inventory and order fulfilment visibility down the supply chain [5, 176]. The adoption of the UPC standard in 1973 caused a sudden increase of barcode scanning, leading to a widespread use of laser scanning to track items ranging from convenience store purchases to overnight delivery packages. However, the disadvantages of these systems are a slow information flow, since barcodes are a line-of-sight technology that requires manual scanning and allows only one item to be read at a time. Consequently, barcodes are only read at a few control points in the supply-chain. Thus arose the need for a new auto identification (Auto-ID) technology such as RFID, which overcomes these limitations.

RFID is a wireless data collection technology that relies on tags, consisting of silicon memory chips equipped with radio antennas, which can be attached to objects to transmit streams of data about them. RFID tags, unlike barcodes, do not require a reader to come in direct contact with an item, nor do they require a line of sight between reader and tag. RFID tags are also more suitable than barcodes for identifying unique individuals, instead of only identifying them on the product type level. Furthermore, multiple tags can be read simultaneously. RFID tags are more difficult to counterfeit than barcodes because their manufacturer-assigned serial number is hard-wired into the chip. The data on the chip can also be protected from reading and writing in various ways, including encryption in more expensive tags. RFID tags can be categorised based on different aspects [173]:

- *Memory: read only, read/write, or a combination.* The read/write capability of a tag can be used for reading and recording data on the chip as it moves through the system. Tags with read only memory normally only store a unique identifier code.

- *Active or passive.* Active tags are powered with an internal battery that gives them a longer reading range and the possibility to include sensors and actuators. Passive tags draw power from the readers, making them lighter, smaller, and cheaper to produce.

- *Frequency bands.* Low-frequency tags are used in applications where the range is generally less than 25 centimetres, while high-frequency tags are used in areas of less than a meter. Ultra-high frequency tags have a longer reading range, currently up to about eight meters in optimal conditions. However, these distances tend to increase constantly as new technologies are developed.

As mentioned before, Auto-ID technologies, such as barcode, RFID, smart card, and biometric systems, are commonly used to identify products or delivery units. In addition to automatic identification, Auto-ID technologies often also include localisation and sensor technologies. Localisation techniques are often combined with automatic identification, as the location information is useless without the identity of the located entity [177]. The location of a product can be approximated using various techniques [176, 177]: monitoring by wireless and cellular access points, alteration and angulation of radio frequency or ultrasonic signals (e.g. Global Positioning System), scene analysis (e.g. image recognition), laser trackers (e.g. Coordinate-Measuring Machines), as well as micro-sensors and Micro-ElectroMechanical Systems (MEMS), Inertial Navigation Systems (MEMS INS) and MEMS Optical Identification and Communication Systems (MOICS). A detailed discussion of these techniques is outside the scope of this chapter. Another frequently applied technique is to update the location status of the product at the moment its barcode or RFID-tag is scanned, when the physical location of the scanner is known [77].

Typically, barcodes and passive RFID chips only have the capacity of storing information. Especially when automatic identification technologies are combined with sensor technologies, such as thermal, acoustic, visual, infrared, magnetic seismic or radar sensors, processing of this information locally at the product can be beneficial. For this purpose, Gellersen et al. [56] look at how to integrate sensors in mobile devices, in such a way that the context of the device can improve user interaction and support new types of applications. In this way, for instance mobile phones and PDA's can be used to support products when augmented with embedded computing.

Furthermore, there is an increase in interest on applying MEMS for creating smart devices (e.g. [54, 176]). Because of the small size of these sensors and chips, these technologies are well applicable on products. In the Smart-Its project[2], experiments are already conducted on different scenarios for attaching small-scale embedded devices (Smart-Its) to everyday artefacts, to augment them with sensing, perception, computation, and communication. In this project, "Smart-Its" is regarded as an enabling technology for building and testing ubiquitous computing scenarios, and therefore they will use them to study emerging functionality and collective context-awareness of information artefacts. Siegemund and Flörkemeier discuss several possible scenarios for Smart-Its in [162]. One possible scenario for the use of Smart Its is smart product monitoring. The smart product monitoring scenario is an example of a pervasive computing scenario where the interaction is initiated by a smart object. An example is presented where an egg carton represents an arbitrary object that is in store in e.g. a warehouse. The object is augmented in such a way that it detects whenever it is dropped or not stored within the appropriate temperature range. Whenever such an exception occurs, it triggers an alarm by informing the appropriate contact person via an SMS. Another scenario mentioned by Siegemund and Flörkemeier is the smart medicine cabinet, which was designed to support mobile and young patients with chronic diseases. It is supposed to improve the drug compliance of these patients by reminding them to take their medicine. The smart medicine cabinet also knows about its content so that the user can query it remotely to check which medication he/she has currently

[2] `http://www.smart-its.org/`

available. Other features include out-of-date detection and alarms for potential product recalls. Unfortunately, designers apparently did not consider Smart-Its very appealing [105].

Embedded processing is mainly related to the "Intelligence at object" approach. In situations where an "Intelligence through network" approach is needed, it becomes necessary to take into consideration how product information can be managed in a distributed way that may involve the product itself, end-users, manufacturers, other supply chain members etc. This is the subject of the next section.

2.3.2 Distributed information storage and processing

The vision of intelligent products is to seamlessly connect the products in the physical world with their representation in information systems e.g. through a product agent as proposed in [52]. Intelligent products would make it possible to avoid media breaks between the real word and the digital world. Thereby, data about the current and past context of objects from the physical world can be retrieved and updated when needed. As pointed out in Section 2.2, the basic building blocks for implementing "intelligence through network" is that products are identified by globally unique identifiers that either encode links to information sources directly or that can be used as look-up keys in some kind of network infrastructure. The three main approaches currently known are shortly analysed here. A deeper technical analysis and comparison can be found in [50].

EPCglobal

A tracking and tracing system for products throughout the supply chain was developed by the MIT Auto-ID Center [154], which later has been split into EPCglobal Inc.[3], and Auto-ID Labs[4]. In the EPCglobal approach (as shown in Figure 2.3a), every product is tagged with an Electronic Product Code (EPC). The EPC is a numbering scheme that can provide unique identification for physical objects, assemblies and systems. An Object Naming Service

[3] http://www.epcglobalinc.org/

[4] http://www.autoidlabs.org/

(ONS) tells computer systems where to locate information on the Internet about any object that carries an EPC. Because of security and performance issues, EPCglobal has started defining an alternative look-up infrastructure called the "discovery services". The application layer events (ALE) and EPC information service (EPCIS) published by EPCglobal provide standardised communication interfaces for communicating product-related information.

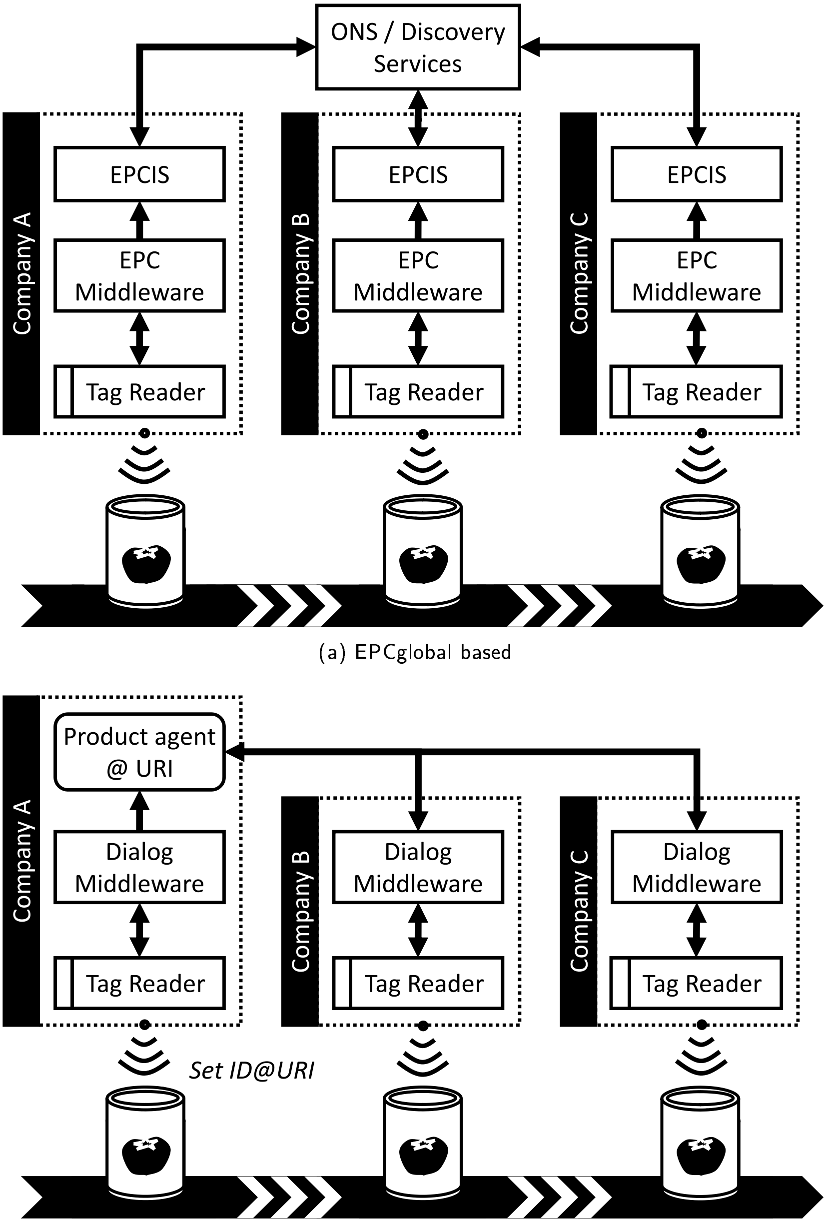
The main advantages of the EPCglobal approach are the strong industrial support and standards supported by organisations such as GS1. The main weak points are related to the fact that the proposed information architecture and standards remain focused on supply chain management applications using passive RFID tags. Supporting other Auto-ID technologies (especially high-end ones with embedded information processing and communication capabilities) may be challenging. The current lack of item-level look-up between product identifiers and related information sources is also a weakness.

ID@URI

At the Helsinki University of Technology, a product identification and information linking concept labelled ID@URI [77] was proposed. With ID@URI, each product carries the ID of the product, as well as the URI (Uniform Resource Identifier) where the agent of this product can be found. Thus, ID@URI links the physical objects directly with their product agent that is implemented as an Internet-enabled service. The URI is typically the URL where the product agent is located, which could for instance be the address of a manufacturer's server computer. Because the address of the product agent is directly embedded in the identifier, the existing domain name service (DNS) infrastructure is sufficient. The ID can also be chosen freely as long as it is unique in the context of the URI, therefore existing serial numbers or numbering standards (including EPC) can be used.

An information system called the Dialog platform[5] [52] that uses ID@URI was initially developed for tracking products through a supply chain. The Dialog platform contains two software components, as can be seen in Figure 2.3b. The first component is the product agent that is managing the product

[5] `http://dialog.hut.fi/`



(a) EPCglobal based

(b) ID@URI based

Figure 2.3: Tracking systems for products moving through a supply chain

information. The second component is used e.g. for updating the location of shipments passing at checkpoints or for querying or updating product information in general. The checkpoint can handle barcode, RFID-tags or any identification technology capable of storing at least an ID and a URI. Extensions for handling e.g. composite products and for propagating information updates have been presented in [48, 49]. Work on the ID@URI concept is continued in the TraSer project[6].

The initial goal of the Dialog platform was to develop intelligent products that could respond to the challenges found in international project deliveries [98]. There, the fundamental challenges come from the customised nature of project deliveries, the great number of individual deliveries to the project, the large number of suppliers, and the fact that deliveries to the project site are time-critical. In the proposed inside-out control of project deliveries, such an intelligent product could ask for itself when it is in need of assembling or transportation. Furthermore, it could have a more active role in after-sales, and should be able to manage its own lifecycle [98].

The main advantage of ID@URI is its simplicity and that it can be used without new standards or infrastructure. However, no communication interface standards have been proposed for the Dialog platform, which is therefore currently on a proof-of-concept level after successful industrial pilots [96, 97]. This is largely because the ID@URI concept and the Dialog platform can be implemented using existing or evolving standards, such as the messaging interfaces and data models developed in the PROMISE project[7].

WWAI

World Wide Article Information[8] is an application level protocol for distributed article information developed by the Trackway company[9]. WWAI uses a product identifier that combines existing GS1 identifiers for the organisation, product type and an item-level serial number. This product identifier is then used as a search key for retrieving available information sources that own information about the product. Both the retrieval of information sources

[6] http://www.traser-project.eu/
[7] http://www.promise.no/
[8] http://www.wwai.org/
[9] http://www.trackway.eu/

and the information exchange use principles of peer-to-peer networking. WWAI enables companies to share real-time product information, regardless of the Auto-ID method used, over the Internet. The WWAI protocol enables distribution of the information on the computers of the companies that have participated in the manufacturing, assembling or transporting of the product. Every participant has control of its own product information and decides whether the information is public of private. Distribution of information makes WWAI networks scalable and able to grow as the number of information provider nodes and products grow.

The main advantage of WWAI comes from its distributed nature of handling product information look-up and access, which makes it relatively fault-tolerant. WWAI also contains functionalities for managing composite products and other relations between products, as well as event propagation between organisations. The main challenge for WWAI is that it is currently not standardised and that it does not have a big installed base that would enable it to become the de-facto standard.

2.3.3 Agent-based platforms

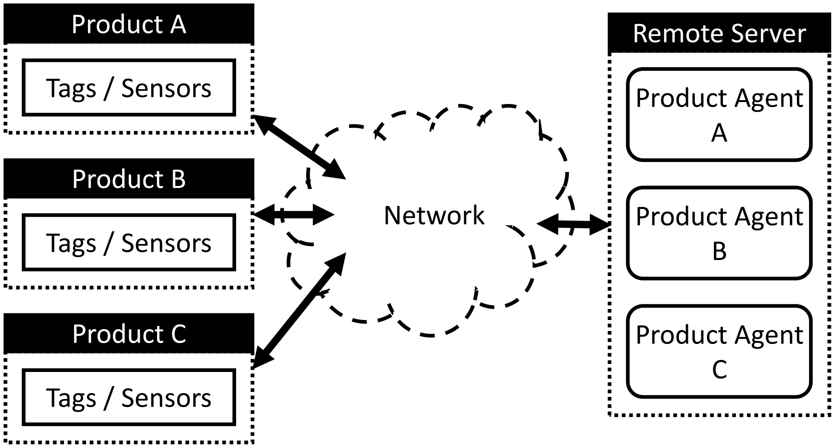
Agents are a useful paradigm to implement intelligent products, as the concept of an agent is close to the concept of an intelligent product. An intelligent agent is defined as "a computer system, situated in some environment, that is capable of flexible and autonomous action in order to meet its design objectives" [85]. A multi-agent system is a federation of software agents interacting in a shared environment, that cooperate and coordinate their actions given their own goals and plans. For this purpose, agents typically have four properties. The first property is autonomy. This means that agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state. The second property is social ability, where agents interact with other agents via some kind of agent-communication language. The third one is reactivity where agents perceive their environment and respond in a timely fashion to changes that occur. The fourth property is pro-activeness. Here agents do not simply act in response to their environment; they are able to exhibit a goal-directed behaviour by taking the initiative.

There are several reasons why the use of an agent-based platform for intelligent products is beneficial. Firstly, when there is a high number of products, the number of products needing explicit control from the user has to be reduced. This can be achieved by making the products autonomous. In this way, intelligent products with knowledge and reasoning capabilities can do most of the repetitive tasks in an automated way. Secondly, intelligent products should be able to detect and react to changes in the environment. Agents can pro-actively assist the product and try to achieve goals given the change of the environment. Agents can also help in discovering information about the environment by communicating with agents of other products. It is therefore clear that intelligent agents have characteristics which are desirable for intelligent products. Of course, an application for intelligent products can be created without the use of agents, but by using agents, one can take advantage of the methodologies and solutions provided by the multi-agent paradigm [27].

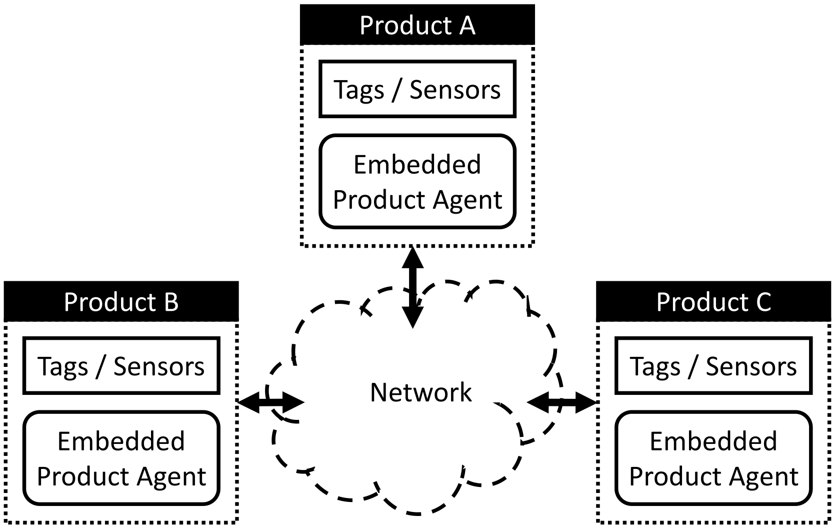
By using intelligent agents for implementing an application for intelligent products, each product can have its own intelligent agent. This does not necessary mean that the agent is located at the product. As discussed in Section 2.2, two extremes can be defined. These extremes are also shown in Figure 2.4a and 2.4b. Also some intermediate solutions exists, which are called surrogate platforms. Next, several platforms in those categories will be discussed. This discussion is partially based on the overview of [27].

Portal platforms

This kind of platforms mainly relate to the "intelligence through network" approach. Most standard agent platforms can be used as portal platforms, as in that case the agents are not embedded on the products, but run on "normal" desktop systems or servers. However, there are some specific platforms designed for this purpose, like the MobiAgent system. The MobiAgent [111] system architecture consists of three main components: mobile wireless devices (which the products should be equipped with in case of intelligent products), an agent gateway, and the network resources. The agent gateway is the location where the actual agents are executed. The



(a) Portal platform



(b) Embedded platform

Figure 2.4: Agent-based platforms

mobile devices can download an interface of an agent through which an agent can be configured. The agent will perform its task and will later report the results to the mobile device via the same mechanism.

Embedded platforms

This kind of platforms mainly relate to the "intelligence at object" approach. Several platforms have been developed to support agents embedded on mobile devices, in order to enable ubiquitous multi-agent systems. These platforms are mainly based on Java, in order to work seamlessly on any Java-enabled devices with sufficient resources, like mobile phones, PDA's, and in the future even smaller devices, which can be attached to the products. The Lightweight Extensible Agent Platform (LEAP) [14] is probably the most well known agent platform for small devices. Since version 3.0, LEAP is an add-on of the Java Agent DEvelopment Framework (JADE) platform[10]. The LEAP platform can be used as both a surrogate and as an embedded platform. Other examples of embedded platforms are the 3APL-M platform[11] [95], the MicroFIPA-OS platform[12], and the Grasshopper platform [12].

Surrogate platforms

An example of a surrogate platform is the KSACI platform [2]. This platform is an extension of the SACI (Simple Agent Communication Infrastructure) platform[13], in order to enable agents embedded in devices to exchange information and knowledge with other embedded agents or with agents located in desktop computers. Each (K)SACI agent has a mailbox to exchange messages with the other agents. The architecture contains one special agent, called the facilitator, offering white- and yellow-pages services of the system. The white-pages can be used by agents to locate other agents in the network, as the yellow-pages can be used to find agents which offer a specific service. This platform is a surrogate platform, as the facilitator agent is always

[10] http://jade.cselt.it/
[11] http://www.cs.uu.nl/3apl-m/
[12] http://fipa-os.sourceforge.net/
[13] http://www.lti.pcs.usp.br/saci/

running on a server. Furthermore, agents embedded on devices cannot pass messages directly to other agents, but instead they have to communicate with an intermediate HTTP server running a SACI proxy, which will deliver the messages to the appropriate receiver. The solution makes the embedded agents lighter, which makes them easier to embed on small devices.

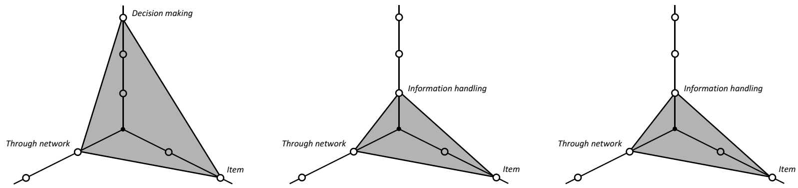
2.4 Goals of intelligent products

This section outlines a number of achievable practical goals for the application of intelligent products. A means-ends proposition [163] is a semi-formal description of a goal that can be achieved by applying a solution in different contexts. In formulating these propositions, the goals of an application of intelligent products are explicated, particular solution requirements are identified, and the circumstances where the goals can be achieved are discussed. Several authors in design science and related disciplines emphasise the need for such propositions when searching for new solutions and applications. Different terms used for the means-ends proposition include: base case [91], the technical norm [132], and the technological rule [1, 144].

The goals for intelligent products are context dependent and are reviewed for manufacturing, supply chains, asset management and product lifecycle management.

2.4.1 Manufacturing

Currently, the manufacturing industry is moving more and more from a supplier-driven to a customer-driven market. Due to the growing industrial capacity, customers are provided with a greater choice, and competition between suppliers is increased. As a result, companies must shorten product lifecycles, reduce time-to-market, increase product variety and instantly satisfy demand, while maintaining quality and reducing investment costs. This is a great challenge to the manufacturing process itself; it must be more flexible and robust as well as demonstrate enhanced scalability [23]. Therefore, the ends for introducing the intelligent product concept in manufacturing are to improve production planning and control, to enable customised products



(a) West (b) QSC Audio Products (c) SMED

Figure 2.5: Classification of intelligent products in manufacturing applications

and to make change-over between product variants more effective. The classification of the intelligent products in the applications discussed next can be found in Figure 2.5.

Production planning and control

A first goal for companies to introduce intelligent products in manufacturing is to improve their current operation in terms of production planning and control. Frequent changes of production plans caused by engineering changes as well as production disturbances, such as machinery breakdown or the late or uncertain arrival of component parts, can lead to instabilities in production and production scheduling, with a 'ripple effect' on other firm functional boundaries. In [102], Lee and Kim give an overview of how multi-agent systems are used for achieving local and global objectives in production planning and control. Further, they give an overview on multi-agent systems research applied in dynamic scheduling and shop floor job assignment, as well as how to solve process planning and scheduling integration problems.

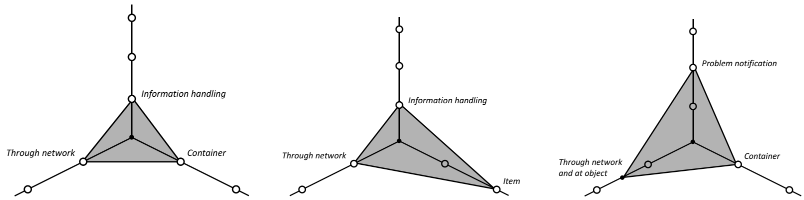
One of the first intelligent products application in manufacturing is the self-organising manufacturing control system of Bussmann, which was evaluated at Daimler-Chrysler [24]. In the control system (called *West*), developed for the Daimler-Chrysler concept of a modular and flexible manufacturing system, agents are assigned to both work pieces and to machines. The agent of a single workpiece negotiates with the agents of the machines about which one of the machines will process the workpiece next. The workpiece auctions off its current due operations and invites machines to bid. If a workpiece awards a specific machine, then an operation performed by this machine on the workpiece will be the next goal of the workpiece. A workpiece will continue to auction off operations and award machines until it reaches its desired state. Simulations have shown that the West mechanism is extremely robust against disturbances of machines, as well as failures of control units. According to Bussmann and Schild, its performance is nearly optimal [24], mainly due to the dynamic task allocation, with late commitment.

Customised products

A second goal for companies that have introduced intelligent products in manufacturing is a logical next step from the first goal. When intelligent products manage or assist in the production planning and control, they can be applied to control the manufacturing of customised products, i.e. producing efficiently products that vary from instance to instance. An example is QSC Audio Products [44], an early user, that was able to move from a build-to-stock operation to a build-to-order operation by introducing a solution based on RFID technology to track and control how work-in-process (WIP) moves through the facility. The application enables the company to manufacture customised products more efficiently because it can optimise the routing of work, and direct materials to where they are needed during assembly.

Change-overs

Another objective for intelligent product applications in manufacturing is to improve set-ups and change-over management. By developing intelligent product applications for containers of materials needed for different variants of standard products, it becomes possible to speed-up and reduce errors in set-ups and change-overs. [182] provides a nice illustration on how setup times can be reduced by tagging, tracking, and controlling materials and tools. In trying to apply the concept of single-minute-exchange-of-dies (SMED), that was originally developed in the sheet metal fabrication con-



(a) Wal-Mart (b) Skanska (c) ParcelCall

Figure 2.6: Classification of intelligent products in supply chain applications

text in the printed circuit board (PCB) assembly context, it was found that success required developing a simple intelligent product application. Material and tool tracking was needed to help operators locate and prepare the thousands of unique parts and feeders used in the circuit board assembly. Introducing SMED in a PCB fabrication context required a tracking and tracing solution that relied on the innovative use of wireless terminals, identification technology, and relational databases.

2.4.2 Supply chains

As for a few years ago, RFID technology has been successfully used in some portions of the supply chain [3, 19]. In this same supply chain context, the ends served by intelligent product applications are: more efficient goods issue and receipt, re-routing of deliveries in-transit, and improved security (e.g. anti-theft). The classification of the intelligent products in the applications discussed next can be found in Figure 2.6.

Sending goods

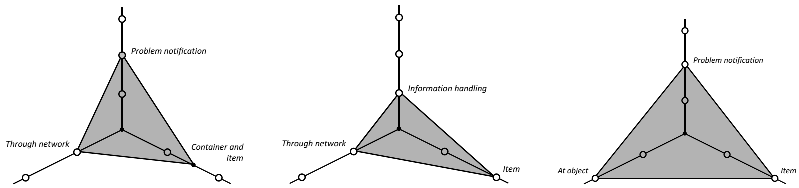
An end for the application of intelligent products in the supply chain is to improve the efficiency of sending and receiving goods. A track and trace application of British retailer Marks & Spencer's [88] reduces the lead time for distributing the frozen food from the distribution centres to the stores. The implemented solution tracks frozen food on RFID tagged and recycled transport assets. A similar, and more widely known example is Wal-Mart. Wal-Mart has mandated its suppliers to apply RFID tagging onto pallets and boxes so that Wal-Mart can speed up receiving of goods and reduce the incidence of stock-outs in the shop [6]. A majority of Wal-Mart's suppliers have answered to the mandate by adopting a "slap-and-ship" practise to product tagging [33]. In "slap-and-ship", the suppliers apply the RFID tagging to the units just before shipping or even by a third party before the delivery to Wal-Mart. By introducing the intelligent product concept, for example by linking handling directions to the container, products that are out of stock in the shop can be prioritised both when dispatched and when goods are received in the store.

Re-routing of deliveries

Another goal that is also based on the intelligent product concept is the re-routing of products and shipments in transit. This proposition is important for example in the delivery of components for complex systems where delivery to the customer site is time critical [98]. Each component delivery can be associated to an application that specifies what needs to be done with it, and this information can be used to re-route or change handling instructions to different supply chain members while the delivery is in transit. An example is the pilot by Skanska [133], a construction engineering and construction company that in a pilot started to control major pre-cast reinforced concrete components that were tagged with RFID. The component is linked to a tracking system and depending on the progress of different building sites interchangeable components can be re-routed to where they are needed the most.

Security

A third basic purpose of introducing the intelligent products concept in supply chains is to improve security. By maintaining the identity of the product or shipment, it is possible to pinpoint where thefts occur and/or to verify the authenticity of the item and reduce the risk of forgery. An example of developing an application of intelligent products that improves the security of the supply chain is from the European IST project ParcelCall [40]. In the ParcelCall solution the intelligence is linked to the transport



(a) U-Library (b) ToolWatch (c) Smart-It

Figure 2.7: Classification of intelligent products in asset management applications

unit. Each transport unit has a mobile logistic server that keeps track of the goods within that unit. In advance of the loading process, the transport unit receives over a communications network a list of contents from a goods tracking server. While the items are loaded, the server associated with the transport unit checks whether the item belongs to the list of items to be loaded or not. If an item is loaded that is not in the list of contents, the transport unit sends a notification to the goods tracking server. When the loading procedure is finished, the transport unit server also notifies the goods tracking server that the loading procedure has been completed.

2.4.3 Asset management

Asset management is the context where it is currently most straightforward to develop practically relevant means-ends propositions at least regarding RFID technology. Expensive assets such as tools and equipment often need to be used by many parties, and their continued use require the services of different service providers. By introducing intelligence to the assets, it becomes easier to share assets and also to service them. The ends for introducing intelligent product concepts are to improve the efficiency of asset usage and also to make service and maintenance of the assets more effective. The classification of the intelligent products in the applications discussed next can be found in Figure 2.7.

Efficiency

U-Library [126] illustrates how the introduction of intelligence makes it easier to share an asset. In the u-library (ubiquitous library), each book is equipped with an RFID tag, and linked to an intelligent agent managing it. Furthermore, every shelf, browsing table, etc. is equipped with RFID readers and writers, and also linked to an intelligent agent managing it. By tracking the books using the RFID tags, it becomes possible to monitor how books and other library materials are used and how customers are moving books inside of the library. More copies of items that are continuously used can be procured, while copies of items that are not needed can be sold-off or moved to another location. Therefore, by applying intelligent products in this way, the utilisation can in theory be improved at the same time as the investment in assets is reduced. Another example of applying intelligent products in asset management is from industry. Bowen Engineering used a tool tracking solution called ToolWatch[14] that combines both identification and tracking. This resulted in an improved utilisation of assets, as well as a big reduction in tool investments.

Service and maintenance

An example that well illustrates the benefit of the intelligent product concept to improve service and maintenance is from health care. A patient in a hospital or a care service needs different types of maintenance and service depending on her condition. Attaching a Smart-It device to a mobile medicine cabinet can greatly facilitate the health care of young patients with chronic diseases. Smart-It is a small-scale computing device that can be attached to different everyday objects to provide them with sensing, computing and communication capabilities [162]. The intelligent product application makes it possible for the care giver to track medicine use and drug compliance of the patients, and to remind the patients to take their medicine. The intelligent mobile medicine cabinet also keeps account of its content so that the patient's doctor or pharmacist can query it remotely to check which medication he/she has currently available, and whether it is in need of replenishment.

[14]http://www.toolwatch.com/

Other useful functions that can be easily included are out-of-date detection and support for product recalls.

2.4.4 Product lifecycle management

According to Kiritsis [94], the focus today in the business environment is on innovation: products that differentiate themselves from others while also being affordable, reliable and early to market. Total management of the product lifecycle is critical to innovatively meet customer needs throughout the entire lifecycle without driving up costs, sacrificing quality, or delaying product delivery. The ability of industry to provide such holistic products and supporting services is currently limited by the information gap in the product's lifecycle. The development of ubiquitous computing (in the form of Product Embedded Information Devices (PEID)) is expected to progress rapidly and to be largely used for advanced Product Lifecycle Management (PLM) and real-time data-monitoring throughout the product supply chain. The basic idea behind PEIDs is to store information about an individual product on the product itself, by applying technologies as discussed in Section 2.3.1.

Practical business cases of the lifecycle management proposition have been addressed in the PROMISE project[15]. An information architecture has been defined that makes it possible to collect information from any lifecycle phase and to use it in the same or any other phase of the product lifecycle. The information architecture defines communication interfaces based on Web Services technology for communication over the Internet and a UPnP technology for short-range communication especially with mobile PEIDs that have intermittent network connectivity. Any software that implements either one of these interfaces can be a PROMISE information provider. A system object model developed in PROMISE [28] proposes a universal way for storing and interpreting lifecycle-related data. The developed model would extend current ISO STEP and PLCS (Product LifeCycle Support) standards especially for managing information gathered during the use of products, including consumer products such as cars, refrigerators and other potentially

[15] http://www.promise.no/

"intelligent" products.

Improved product design, manufacturing and customisation

Applications of intelligent products that have been developed for a specific context can in certain situations be extended across many stages in the product lifecycle. For example, an application that was initially developed for controlling customisation in manufacturing can perhaps also be used for improved handling in the supply chain, and to support efficient maintenance in asset management. Car manufacturers Ford, BMW and Vauxhall already use RFID-tags to improve product quality, to store information about the car during its whole lifecycle, and to enable accurate customisation of customer orders [9, 18, 86, 203]. An additional purpose of this type of lifecycle application of the intelligent product concept is better coordination between product development, service operations and sales. For example, by using the same intelligent product platform, the manufacturer collects information to improve its product development, to improve the efficiency of its service operations, and to identify sales and marketing opportunities more accurately.

Maintenance

The proposed information architecture can be used to manage and control information on product individuals in the manufacturing and delivery process, as well as after the product has been sold [4]. The PEIDs handle information on the product individual level (and possibly also on part and sub-assembly level), instead of on the product type level, as typically is the case with current product data management (PDM) systems. The PEIDs can store data about the products locally (i.e. at the product itself) which enables the distribution of analysis and control tasks to the product itself. In addition to local analysis and alerts to the user/owner, the distributed information architecture supports alerts to the manufacturer or service provider when certain thresholds are violated or abnormal conditions are detected. In this way, failure of a product can be better prevented, and the product can in many times be replaced before breaking down.

End-of-life management

Information about usage conditions can also be used when the product is at its end-of-life for determining how to handle the product and its parts. When combining usage information with design and manufacturing information, it is possible to determine the presence of valuable material or hazardous substances and create a list of parts that have to be removed or special treatments that are required. In some industries, there are databases in which the currently estimated market value of spare parts is available. When combining the usage information with a value estimate, it becomes possible to calculate a residual value of each part and make an even more fine-grained decision of what is the most appropriate action to take for each part. Such possibilities could enable new recycling and refurbishing business opportunities as in the automotive industry [92] or for heavy machinery as identified by Caterpillar [38].

2.5 Conclusions and future trends

In this chapter, the concept, technical implementation, and achievable practical ends of intelligent products have been reviewed. As discussed in the introduction of the chapter, the intelligent product concept is not very well-defined because it combines many disciplines and could be used in many ways. The need for a new classification of intelligent products that was identified in Section 2.2 illustrates that we are dealing with a concept that is still evolving. The classification distinguishes between three orthogonal aspects: what is the level of intelligence of the product, where is the intelligence (or processing power) located, and whether the product is managed as a single entity or as an aggregation. The reason for introducing such a three-dimensional classification is that the earlier uni-dimensional classifications seemed to be under-developed either in the lower or the upper range of "intelligence" and did not necessarily take into account e.g. how the embedded processing capabilities affect the implementation of such intelligent products. Analysing different approaches of intelligent products using the proposed three-dimensional classification makes it easier to identify the main limitations and aspects for improvement of a certain approach. However, the classification model proposed in this chapter may still need to evolve as in the future more processing power, communication capabilities, sensors and actuators will be embedded into products.

The main technical foundations in the areas of automatic identification and embedded processing, distributed information storage and processing, and agent-based systems have been discussed. Regarding how, when and why to implement intelligent products, means-ends propositions for the intelligent product concept have been presented as a starting point for developing practical business cases in individual companies. This showed that the intelligent product can be employed to specific contexts such as manufacturing, supply chain, and asset management, as well as across contexts, i.e. for product lifecycle management. In these contexts, globalisation, virtual enterprises etc. will make it increasingly difficult to manage all information in centralised ways. Associating information, processing power and communication capabilities with products themselves and their surrounding environment can be an efficient way to relieve humans and corporate information systems from the management of routine operations. Therefore, we believe that the main contributions of intelligent products to manufacturing and supply chains are threefold. First of all, intelligent products enable their owners and users to know at any time the location and condition of their physical assets. Secondly, intelligent products can sense their location and condition and therefore can raise the red flag for "out-of-condition" situations. Thirdly, intelligent products allow to postpone decisions to the last moment, in such a way that adequate reaction to disturbances is possible.

Furthermore, we believe that intelligent products will have a visible impact on humans and society in the future. The decreasing price of embedded systems signifies that an increasing number of consumer products will become "intelligent". Through this evolution, we think new application domains will become attractive in addition to those mentioned in Section 2.4. Even though it is difficult to estimate how people appreciate new services enabled by intelligent products, we believe that they will be increasingly important e.g. for reducing energy consumption and for care of the elderly and disabled. The energy consumption of buildings, vehicles and machines, could be significantly reduced by better fault detection and control methods that would adapt to the state of the products and their environment. This increase in "intelligence" will also enable a better integration between infrastructure such as buildings, home electronics, mobile phones etc.

Monitoring the health of elderly people living in their homes will be facilitated by such technology, which might be the only way for many countries to take care of their ageing population in a decent way and at a reasonable cost. It will also be interesting to see whether robotics will become important in the landscape of intelligent products. For the moment, it seems like humans would not be ready or interested in interacting with or being taken care of by human-like robots; however, people do accept autonomous grass-cutters, vacuum cleaners and other everyday devices that make their lifes easier.

In order to make the above-mentioned scenarios possible, inter-operability and standardisation plays an important role. There is still a long way to go before all different kind of machines and systems will be able to communicate and understand each other. Ontology- and semantic web-related research are expected to produce new tools for solving these inter-operability issues as no clear best solution exists yet. We also expect multi-agent systems and research to play an important role in the future.

2.6 Addendum

The content of this chapter as presented till this point has been submitted to the journal Computers in Industry in 2008, and was accepted and published in 2009. The goal of this section is to provide an update of the work conducted in the field of intelligent products since then. Therefore, a search has been performed for all relevant papers and projects since 2009 which are discussing the application of intelligent products. For each main application domain of intelligent products, the results of this search are presented next.

2.6.1 Manufacturing

Several authors are investigating how intelligent products can be applied for production control. For example, Tu et al. [183] propose an agent-based distributed production control framework with the purpose to help firms adapt to a dynamic and agile manufacturing environment for making complex and highly customised products. Within this framework, intelligent product technology is applied to offer intelligent collaborative support for just-in-time and just-in-sequence production strategies. For this purpose, product agents are for example applied to represent workpieces in the factory. Similarly, Borangiu et al. [16] present a new open control paradigm for discrete, repetitive shop floor production, designed as a solution for agile manufacturing re-engineering. In this paradigm, intelligent product technology is applied by means of so-called Active Holon Entities, which represents the products being fabricated, who travel through the system to find free manufacturing resources capable to offer the requested manufacturing operations. A solution to dynamic routing within a Flexible Manufacturing System (FMS) is presented by Sallez et al. [152]. In their approach, the intelligent products are capable of making routing decisions as well as providing information about the fluidity in the transportation system. Meyer et al. [125] investigate the possibility of using intelligent products for decentralised production monitoring and control, in order to increase the robustness of the overall plan execution. In this approach, intelligent products technology is applied to enable individual products to analyse their progress, and when problems occur, to propose solutions on how to reduce the severity of the problem.

More focused on expressing semantics of data, Vrba et al. [190] investigate the possibility to apply ontologies for advanced handling, exchanging and reasoning about knowledge in production systems based on multi-agent technology. Within a proof-of-concept scenario, intelligent product technology is applied to implement the agent-based control, in which product agents plan the execution of the required production steps. Focused on manufacturing resources, another application of intelligent products in manufacturing is presented by Park and Tran [140]. They present the novel concept of Intelligent Manufacturing Systems with Biological Principles, in which genetic and intelligent technologies are applied for embedding knowledge in machines. Within this approach, intelligent products technology is applied for creating intelligent components by equipping machine components with tags and sensors, which results in machines which can "feel" their machine components. Overall, various authors are nowadays investigating how intelligent products can be applied for increasing flexibility and robustness of the production process, typically by enabling the products which are being fabricated to take an active role in their production process.

2.6.2 Supply chains

Within the context of supply chains, many European projects funded by the European Union are focused on improving logistics by applying the intelligent products concept. Often referred to as "Intelligent Cargo", both the e-FREIGHT[16] and EURIDICE[17] project focus on linking individual cargo items with the electronic flow of information, making them context and location aware, and allowing them to interact with its surrounding environment and users in the field. Other European projects, like INTEGRITY[18], SMART-CM[19], and ADVANCE[20], focus on developing systems for capturing huge quantities of data on transported goods for different purposes, such as security, customs administration, and planning. Another example of an European project is SMARTFREIGHT[21], which focuses on making urban freight transport more efficient, more environmental friendly, and safer.

Comparable to the Intelligent Cargo concept, Hribernik et al. [76] present a standards-based approach to connect the information and material flows in autonomous cooperating logistic processes, in order to illustrate how an Internet of Things for Transport Logistics can be created. Within this approach, the information flow is represented by a multi-agent system, and the material flow consists of the actual physical logistics objects. Woo et al. [196] propose an active architecture that tracks the locations and

[16] http://www.efreightproject.eu/
[17] http://www.euridice-project.eu/
[18] http://www.integrity-supplychain.eu/
[19] http://www.smart-cm.eu/
[20] http://www.advance-logistics.eu/
[21] http://www.smartfreight.info/

attributes of logistics objects in sensor enabled networks, which is even able to track products when they are enclosed in a box, a pallet, or container. In this architecture, the locations and attributes of products can be monitored in a timely manner, and exception handling can be triggered when the constraints associated with the product are violated.

Siror et al. [165] investigate the use of intelligent technologies to address the challenge of security, speed and efficiency of customs administration in trade facilitation. They propose an enhanced automated method of electronically verifying cargo contents using RFID and intelligent products technology, which is able to generate alerts when the automatic verification of certain cargo is not successful. With respect to inventory management, Holmström et al. [72] describe how the item dwell-time measurement can be used in the context of capital investments. They find that when individual items cannot be used interchangeably at project sites, conventional inventory measures do not provide sufficient timely and accurate information about emerging problems in project inventories. Therefore, Intelligent products are applied to empirically demonstrate the value of item dwell-time alerts in the context of project delivery.

Overall, applying intelligent products within the context of supply chains has become an active area of research, in which many authors as well as European projects are investigating how different aspects of logistics and distribution can be improved.

2.6.3 Product lifecycle management

Several authors are investigating how the intelligent products concept can be applied for management of the whole product lifecycle. For example, Seitz et al. [158] present concepts for generating and accessing product memories, which provide a digital diary of the complete product lifecycle. They describe an architecture for autonomous product memory, in which the product memory itself determines which data becomes part of the memory. A similar approach is presented by Yang et al. [201], in which Intelligent Data Units are embedded into products to automatically acquire lifecycle data. Such an Intelligent Data Unit is a hardware device that consists of sensors, a controller, memory and a data communication interface. Sallez et al. [151] demonstrate how the concept of active or intelligent products can be extended to the whole product lifecycle, based on the so-called augmentation concept, which allows them to intentionally activate their environment through an augmented system which is embedded during production.

Focusing on the Beginning-of-Life phase of products, Hribernik et al. [75] show concepts and technologies about how intelligent products can be implemented through integration of RFID tags into metal parts of products during the casting process. This technology provides unique identification of metal parts immediately upon their creation, enabling linking of the physical metal parts with their digital counterparts in the network. According to Ilgin and Gupta [80], sensors implanted into products during their production can provide valuable information on the number, condition, and version of components in the End-of-Life phase of products, prior to dis-assembly. For this purpose, they investigate the impact of sensor embedded products on various performance measures of dis-assembly lines. Together, these approaches can be combined to enable individual products to autonomously collect, store, and use data about their complete lifecycle.

2.6.4 Summary

In recent years, the field of intelligent products has become an active area of research. Nowadays, many authors are investigating numerous applications of intelligent products in various contexts. In the context of manufacturing, intelligent products are often applied to enable the products which are being fabricated to take an active role in the production process. With respect to supply chains, many authors as well as European projects are applying intelligent products to improve different aspects of logistics and distribution. In the context of product lifecycle management, different approaches have been presented on how products can individually collect and store data about their complete lifecycle, which can be useful for many different purposes during the product lifecycle. However, although the field of intelligent products is an active and promising area of research, most of the proposed applications are still in a preliminary phase. Therefore, a lot more research effort is still required to investigate how exactly intelligent products can be applied within various contexts, as well as to validate and evaluate these applications in a rigorous way. In order to contribute to that, the remainder of this thesis does not only present system architectures showing how intelligent products can be applied for monitoring and control, it also presents prototype implementations of these systems for application within a production and transportation context. Moreover, these prototype systems have been used for extensive experimental and observational evaluation, which will be described in detail as well.

Part II

Monitoring and Control in Production

Chapter 3

System Architecture for Production

Advances in production planning and control in recent decades have focused on increasing the sophistication of the planning function. For good reasons, these advances have led to the centralisation of the planning function in production. However, centralised planning and control has drawbacks concerning monitoring and control, due to the many small disturbances that occur. Monitoring and control are by their nature decentralised, beginning on the shop floor, and, therefore, the desire for greater sophistication in monitoring and control leads to renewed interest in decentralised and localised approaches. This chapter demonstrates a system architecture for decentralised production monitoring and control based on the concept of intelligent products. Intelligent products are aware of their local context and can negotiate with local manufacturing resources if needed. As such, local solutions to problems can be proposed directly when problems occurs. With the advancement of the Internet of Things, such a scenario is likely to become feasible in the near future.[1]

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[1]This chapter appeared earlier as: G.G. Meyer, J.C. Wortmann, and N.B. Szirbik. Production monitoring and control with intelligent products. *International Journal of Production Research* 49(5):1303-1317, 2011, doi:10.1080/00207543.2010.518742.

3.1 Introduction

This chapter presents a new architecture for a monitoring and control system in the context of Production Planning and Control (PPC). PPC is concerned with reconciling the demand and the supply of products and materials in terms of volume, timing and quality. The activities required to achieve this are typically clustered into four broad functions: (1) loading, (2) sequencing, (3) scheduling and (4) monitoring and control [166]. The first three collectively constitute the production planning function; the fourth the production control function. Advances in PPC over recent decades have mainly focused on increasing the sophistication of the production planning function. This has steadily resulted in centralised PPC activities.

There are good reasons for centralising the loading, sequencing and scheduling activities. From a materials perspective, centralised coordination of the supply chain reduces the bullwhip effect [89, 114], by using appropriate rules for safety stocks and lot sizes. In addition, centralised coordination can solve the problems of matching sets of parts and balancing the supply streams of all components in an assembly's bill-of-material [136]. From a capacity perspective, optimising one resource will usually have an impact on other resources. Given this situation, some form of coordination is not only useful but virtually unavoidable.

Monitoring and control cover the activities performed in order to react to disturbances. These activities may lead to deviations from the original plan [166]. The vast majority of academic effort into PPC has been spent on the more sophisticated planning concepts, while monitoring and control has received much less attention [187]. However, planners in real life devote most of their efforts to monitoring and controlling, rather than carrying out planning activities [69, 118, 143]. This justifies a renewed interest in monitoring and control.

Centralised planning and control can have drawbacks concerning monitoring and control (see e.g. [171]). Drawbacks appear due to the many small disturbances that occur. A well-known example is when a component is damaged just before it is needed in manufacturing. This is especially problematic in case of production of highly customised products, where buffer stocks are typically small or even non-existent, due to expensive components or order-dependent customisation. The damaged component must be repaired, or a similar component has to be sourced from elsewhere, in order to continue with the original plan. Often, these minor disturbances are not even made known to the central planners, and are simply solved at a more local level by the shop floor supervisor. Other examples of disturbances are production errors, machine failures, quality problems and shipment errors. As will be discussed in detail in Section 3.3, centralised planning and control systems typically have problems in handling with such disturbances, due to the applied aggregation and the hierarchical nature of these systems. The advancement of the Internet of Things however enables new system designs which might address these problems.

Based on these arguments, a new design approach for a monitoring and control system is presented in this chapter. The main goal of this approach is to enable new ways in which disturbances can be dealt with, in order to increase the robustness of the overall plan execution. To investigate the potential of the proposed system design, computer simulations have been performed, which are described in detail in the next chapter. In the various simulation runs, several existing hierarchical and centralised planning and control systems will be compared to the approach presented here. The usual measures of performance in PPC studies are based on financial results (see e.g. [34]). However, profit as the main measure of performance does not give sufficient weight to the impact of disturbances. Our fundamental observation is that studies focusing on production planning performance tend to ignore small disturbances, although these, in reality, dominate the planner's activities in practise. Therefore, robustness is proposed here as an important additional measure of performance of a monitoring and control system.

This chapter is structured as follows. Section 3.2 will elaborate on the background and related work. Next, Section 3.3 will define the problem statement, based on an analysis of the problem area. Afterwards, the new architecture for a monitoring and control system will be presented in Section 3.4. The chapter ends with conclusions.

3.2 Background and related work

3.2.1 Centralisation versus decentralisation of PPC

The roots of production planning and control reside in decentralised approaches. In the years following the Second World War, authors such as Magee [110] approached production planning and inventory control as two separate problem areas. In academia, authors such as Conway et al. [37] studied job shops using queueing theory. In these earlier times, the focus was on simple rules to support decentralised decision-making.

Centralised production planning and control became the dominant paradigm when computers entered the scene, especially because computers could maintain interrelated time-phased plans for the flow of goods (leading to inventory control based on "time-phased order point"). Based on early experiences with the time-phased order point concept, authors such as Orlicky [136] advocated Material Requirements Planning (MRP I) as the panacea for problems related to production planning and control.

However, MRP I turned out to be based on many assumptions, such as batch manufacturing, production to stock and a stable master schedule, which limited its applicability. Therefore, MRP I evolved into MRP II, which is a hierarchical framework for PPC rather than just a material planning algorithm. However, the focus with MRP II remained on providing decision support to the master planner and the material planner, rather than offering innovation in monitoring and control. Although the claims for MRP II have been challenged by authors writing about Just-in-Time production [64, 161], Optimised Production Technology [61] and customer-driven manufacturing (see e.g. [199]), most current approaches continue to reflect the centralised and hierarchical nature of MRP II with little focus on monitoring and control. In these approaches, monitoring and control are typically implemented through decentralised Manufacturing Execution Systems (MES) [113]. These MES deliver work-order progress transactions to the PPC systems. However, the advancement of MES does not change the centralised and hierarchical nature of the PPC systems. The technological change in information systems, from client-server technology to Advanced Planning Systems (APS), has also not changed the focus on decision support in central planning systems [198]. Lean manufacturing does, however, take a slightly different position (see e.g. [159]). The main scheduling principle in lean assembly is Hejunka scheduling, in which material flows are balanced. Although this principle is a concept within central planning, the Kanban system can be interpreted as a system of decentralised monitoring and control. In this respect, lean manufacturing is an exception to the rule that central planning concepts tend to neglect monitoring and control.

3.2.2 Distributed monitoring and control

Monitoring and control of manufacturing equipment and automated control of manufacturing steps have made great progress in recent decades. In general, the term intelligent resources is used to indicate manufacturing resources in modern factories that are being able to execute and control manufacturing activities, as well as being capable of monitoring and controlling their own status [160]. Process quality parameters are monitored, such as tolerances in mechanical machinery, or pressures and temperatures in chemical equipment.

Many authors consider agent encapsulation as the most natural way to make resources intelligent (see e.g. [24, 150, 185]). In this context, an agent is defined as a software system that communicates and cooperates with other software systems to solve a complex problem that is beyond the capability of the individual software systems. Intelligent resources can react to manufacturing problems and investigate alternative machines and routes for products on the shop floor in the event of disturbances. Another approach is holonic manufacturing, in which a holon is defined as an autonomous and cooperative building block of a manufacturing system for transforming, transporting, storing and/or validating information and physical objects [74, 103].

Although individual resources are becoming more intelligent and autonomous, integrating various intelligent resources has remained cumbersome due to their dedicated and propriety nature. In order to achieve interoperability among the various autonomous intelligent resources, an open, flexible and agile environment with "plug-and-play" connectivity is seen as essential [83]. As such, there is an increased interest in developing architectures

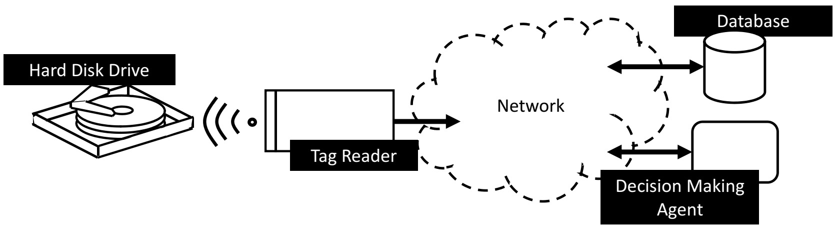


Figure 3.1: Intelligent Hard Disk Drive (derived from [195])

that enable a more generic integration between intelligent resources. An example is the SOCRADES project, in which a device-level Service-Oriented Architecture for factory automation is being developed [179]. Furthermore, there is increasing interest nowadays in applying intelligent products and the Internet of Things in manufacturing and supply chain management, as described in Chapter 2. McFarlane et al. [116] define an intelligent product as a physical and information-based representation of a product. This is the basic principle behind the Internet of Things: all everyday devices will be enabled to connect to a data network [59]. Figure 3.1 provides an example of a hard disk drive as an everyday device connected to a data network. A decision making agent is attached to provide the intelligence.

It is likely that in the future not only resources but all items and devices on the shop floor will become intelligent due to advancements in intelligent products and the Internet of Things. The interoperability between all these connected devices will be provided using the same data protocols that are currently used for the Internet [45, 58]. Therefore, the challenge is to determine how one can create manufacturing systems involving many intelligent items and resources that can work together and adapt to changes both on the shop floor level as well as on a factory-wide basis. This work anticipates on these future developments.

3.3 Problem analysis

3.3.1 Analysis

The term monitoring and control needs elaboration in the context of a discussion about aggregation. Aggregation is widespread in PPC (see e.g. [8, 156]). The first observation is that most centralised systems aggregate over time. These systems perform loading, sequencing and scheduling tasks in aggregated time periods of months, weeks, days or even shifts. As such, these systems are unable to identify sequencing problems within these periods. Secondly, centralised planning systems aggregate by location. Materials issued to the shop floor are booked as work-in-progress, but no information is available on where on the shop floor these materials are to be found. In many instances this is not problematic, but if materials become lost it suddenly becomes a huge issue. Thirdly, centralised PPC systems aggregate similar resources. Most factories have a number of machines which are similar but not exactly the same: machines differ in speed, quality range, changeover patterns, maintenance requirements, supervisory requirements and many other features. Finally, centralised PPC systems aggregate over materials. Small differences in material batches are ignored in material planning systems. These details are unmanageable in central planning systems. Nevertheless, these examples of aggregation are best practises in planning, and there is no obvious reason to change them.

Monitoring and control problems however seldom present themselves in aggregated terms. Manufacturing and distribution problems usually occur in real time, not far away in a future period. Materials mislaid in a warehouse or on the shop floor are missing now. Quality problems leading to the production of scrap are always related to a specific machine, tool or operator. Resource problems relate to specific equipment that is no longer available and maybe in need of maintenance. Material problems are related to a specific piece, pallet, batch or other unit of processing. These are specific problems that occur in detailed, disaggregated form. Therefore, it takes humans to estimate their impact on the aggregated plans.

Another issue stems from the fact that planners using a centralised PPC system typically adopt a hierarchical approach. This has the advantage that the complexity on the various organisational levels is reduced, with each level able to function partially independent. However, performance feedback is important in hierarchical systems for proper functioning [121]. Therefore, appropriate and timely feedback has to be provided by the lower levels to the higher levels. Furthermore, the higher levels need to be able to respond adequately and in time to this feedback. If any of these requirements are not met, it becomes impossible for planners to effectively monitor the plan's execution. This problem has been referred to as the vertical communication bottleneck in organisations [53]. Therefore, due to these issues, monitoring and control in the PPC context still largely relies on manual steps.

3.3.2 Problem statement

The fact that humans are needed to interpret problems in materials or equipment that have factory-wide consequences hampers further progress with PPC. Human expertise is generally not available around the clock, and humans have limited information processing capabilities. People cannot always know the exact manufacturing conditions and constraints in remote manufacturing facilities. When manufacturing problems are detected, they first have to be communicated and interpreted, then the PPC systems are notified and, finally, planners will react. Consequently, reaction to manufacturing problems by PPC systems and central planners is usually slow [194]. This analysis brings us to the initial problem statement:

➟ *Is it possible to design an automated monitoring and control system which works at the level of detail where problems typically occur and which can interpret these problems directly, then inform and propose solutions to the appropriate person (typically the shop floor supervisor) and, if necessary, provide feedback to PPC systems?*

3.3.3 Performance measures

The performance of PPC systems is generally studied in logistic and economic terms. Logistic performance measures include service levels of stock points, average lead times and due-date reliability. Economic aspects cover inventory levels, resource utilisation, overtime costs, profit margins etc. It is not easy to relate the performance of monitoring and control activities to such indicators. Therefore, the designed artefact described here will also be evaluated in terms of its impact on the robustness of the larger PPC system. The argument is that the more problems that can be handled locally without even being observed in the wider PPC context, the better the system performs. To achieve this, a monitoring and control system should prevent small disturbances having large consequences.

3.4 System architecture

This section describes the proposed architecture of a production monitoring and control system. First, the requirements are presented. Next, the main design properties of the proposed monitoring and control system will be described in greater detail.

3.4.1 Requirements for monitoring and control systems

As discussed earlier, centralised planning and control systems have problems in dealing with disturbances because they work with aggregated data. However, as disturbances seldom present themselves in aggregated terms, an effective monitoring and control system needs to work with data on the same level of detail as where the disturbances normally occur. This leads to the formulation of the first requirement:

- ➟ *Requirement 1*: The system should work with data on the same level of detail as where disturbances occur.

Furthermore, it was stated that feedback from the machine level to factory-level PPC systems has remained problematic. Therefore, a monitoring and control system should be able to provide useful feedback about disturbances to the appropriate person in order to enable efficient handling of the disturbances and, when required, communicate this feedback to the factory-level PPC systems. This leads to the formulation of the second requirement:

- ➟ *Requirement 2*: The system should be able to provide feedback about disturbances to the appropriate person directly when they occur and, if needed, communicate this feedback to the factory-level PPC systems.

By using detailed, real-time disaggregated data, the search space available for a suitable solution to a disturbance increases significantly compared to the current situation. However, the large amount of information in this space can make it difficult to manually find a suitable solution. Therefore, if a person is to adequately respond to the provided feedback in a timely fashion, the support of a system which can search this space effectively is required. This leads to the final requirement:

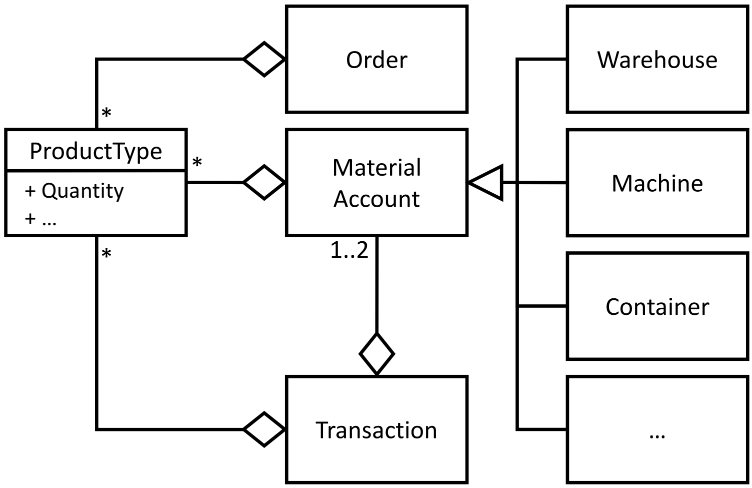
➟ *Requirement 3*: The system should be able to propose solutions to the appropriate person immediately when a disturbance occurs.

Below, it is explained how these requirements are incorporated in the system design, by applying the concept of intelligent products.

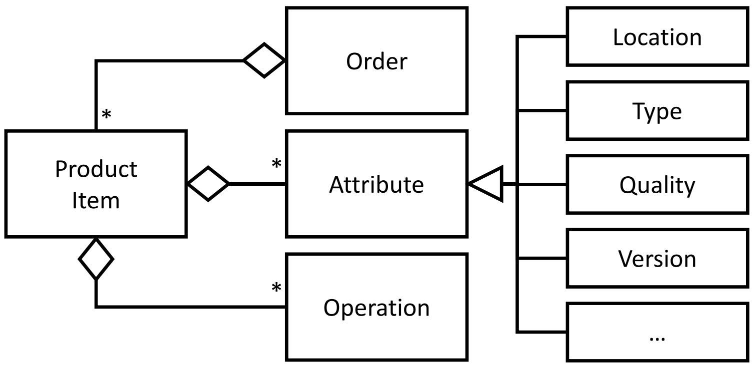
3.4.2 Structural design

Centralised PPC systems are generally inventory-based systems, built around material accounts and transactions between such accounts. Each account represents the quantity of a particular material in a specific location [146]. Such a location can belong to any warehouse or shop floor facility, or it can be a packing unit (e.g. a container or pallet) which can store material. A simplified UML class diagram of an inventory-based system is shown in Figure 3.2a. As shown in the figure, an inventory-based system keeps track of the number of units of each product type stored in every location by means of a material account. Further, through transactions, the number of products of a certain type at a specific location can change. The inventory-based system design shows that no information is stored about individual products [197]. This functionality of linking data to individual physical products is referred to as tracing, defined as the ability to preserve the identity of a particular physical product, as well as its complete history [184].

However, in order to meet *Requirement 1*, the monitoring and control system has to be able to store detailed information on the level at which disturbances occur. Therefore, tracing functionality has to be incorporated in the system design. Accordingly, a product-centric (rather than an inventory-based) system design is adopted. A typical UML class diagram of



(a) Inventory-based system



(b) Product-centric system

Figure 3.2: System designs

a product-centric system is shown in Figure 3.2b. As shown in the figure, the physical product item becomes a new entity in the system, replacing the product type entity which was associated with locations and transactions. In this new design, attributes such as location, type, quality and version can be stored for every individual physical product. Further, for each product, the physical operations through which it has been transformed into its current state can be stored. The location of each item can be more specific since there is no longer a need to aggregate over fixed locations. This approach enables monitoring and control on the level of individual products at which disturbances typically happen. It is important to note that this design assumes that the system has up-to-date information about all products, and that the system is able to detect irregularities in this information.

3.4.3 Product agent behaviour

In order to collect up-to-date information on all products, to be able to detect problems and provide feedback to the appropriate person, and to be able to propose solutions to these problems, some form of intelligence is needed. As discussed in Section 3.2, agents are considered the natural response to the need to implement the intelligence part of intelligent resources. Similarly, agents also seem best suited to implementing the intelligence part of intelligent products due to their knowledge and reasoning capabilities which can enable them to carry out most repetitive tasks. Therefore, in the system design proposed here, every product will have its own agent for performing these tasks. The behaviour of these product agents will be introduced below, according to the three levels of intelligence as distinguished in Chapter 2.

Level 1: Information handling

Firstly, product agents need up-to-date information. In order to execute its tasks properly, the most important information required by an agent consists of two parts: the current status of the product, and the planned or desired status of the product. Determining the desired status of the product is relatively easy, the agent can analyse information in currently applied PPC systems, such as order due dates and planned transactions and operations which will affect the product. However, determining the current status of the product can be more problematic. One approach is to re-examine the information already present in the current systems: this will reveal which transactions and operations have already been performed, and which still need to be performed. However, it is unlikely that this information will be sufficient since there may be delays between when a transaction is performed and when this is recorded in the system and, more importantly, the information will most probably be on a higher aggregation level. Therefore, in order to obtain up-to-date status information on individual products, auto-ID technologies, such as barcodes and RFID, will have to be introduced to uniquely identify individual products. Further, the location of a product can be approximated using various techniques [177]: monitoring by wireless and cellular access points, alterations to and triangulation of radio or ultrasonic signals, scene analysis, laser trackers, as well as micro-sensors and micro-electromechanical systems etc. Another frequently applied technique is to update the location status of a product each time its barcode or RFID tag is scanned provided the physical location of the scanner is known [77]. To gain more detailed status information about a product, identification and localisation technologies can be combined with sensor technologies, such as those based on thermal, acoustic, visual, infrared, magnetic seismic or radar systems [177]. All these techniques bring the Internet of Things to the shop floor.

Level 2: Problem notification

Provided the product agent has knowledge of the plan as well as the current status in terms of plan execution, it is enabled to detect disturbances as needed for meeting *Requirement 2*. To achieve this, the agent employs a mechanism, such as a utility function, to determine whether progress matches the schedule and whether other status properties are still within an acceptable range. Such utility functions can be based on factors such as the amount of time remaining to the order due date, whether there is a proper plan to finish the product on time, whether the plan execution is on schedule, plus factors such as whether the product is within the desired temperature range. If an agent's utility score drops below a certain threshold, the agent will enter a problem state, and can immediately provide feedback about the problem to the appropriate person who then knows which precise products on the shop floor are currently having problems. Moreover, if needed, feedback about the problems can also be communicated to the factory-level PPC systems.

Level 3: Decision making

Besides providing feedback on problems, it is beneficial if the agents propose solutions or suggest how to reduce the severity of the problem. As a result of the continuous information gathering, all agents are aware of the current situation. This enables the agents to negotiate in real-time about alternative plans to overcome the disturbance. However, it will not be feasible to let each product agent negotiate with all other product agents, especially when the number of products is high. Therefore, an auctioning approach based on the Contract Net Protocol [167] is proposed, one in which factory resources, such as machines, can offer their capacity, and product agents can bid for this capacity. The overall result of the negotiations between resources and product agents will be presented to the appropriate person who can then decide whether or not to schedule the tentative actions. If the person does not agree with parts of the schedule, changes can be proposed in such a way that the agents can learn new preferences from them. In this way, *Requirement 3* can be met. This approach is similar to the Escape and Intervention monitoring and control mechanism proposed by Roest and Szirbik [147].

The proposed system architecture was evaluated by means of simulation experiments, through the development of a prototype implementation. A thorough elaboration on these experiments and the results can be found in Chapter 4.

3.5 Conclusions

In this chapter, the following has been concluded:

- Improving monitoring and control activities has received much less academic attention than improving planning activities.
- During production, many different kind of disturbances can occur, leading to deviations from the original plan.
- Centralised production planning and control systems have drawbacks concerning monitoring and control, with respect to the many small disturbances that occur during plan execution.
- Intelligent products appear to be a new and promising approach for dealing with these disturbances, as when disturbances happen, the intelligent products can directly investigate all available information, inform the planners if needed, and propose solutions to reduce the severity of the problems caused by the disturbance.
- A novel architecture for a production monitoring and control system based on the concept of intelligent products is presented.

Chapter 4

System Prototype for Production

As discussed in the previous chapter, centralised production planning and control has drawbacks concerning monitoring and control, with respect to the many small disturbances that occur. Therefore, a novel architecture for production monitoring and control system based on the concept of intelligent products was presented. However, the feasibility of this approach has not been investigated. This chapter demonstrates this feasibility through experimental evaluation. For reasons of comparison, the TAC SCM simulation environment is used. The implementation of a TAC SCM manufacturer is presented, in which the intelligent products are aware of their local context and can negotiate with local manufacturing resources. Therefore, they can suggest local solutions to manufacturing problems virtually at the same time at which the problem occurs. This approach is compared with highly ranked TAC SCM manufacturer implementations. Besides financial results, robustness is used as an additional measurement of performance. The results of the simulations are encouraging.[1]

[1]This chapter appeared earlier as: G.G. Meyer and J.C. Wortmann. Robust planning and control using intelligent products. *Agent-Mediated Electronic Commerce*, pp. 163- 177. Springer-Verlag, Lecture Notes in Business Information Processing 59, 2010, doi:10.1007/978-3-642-15117-0_12.

4.1 Introduction

Advances in production and supply chain planning and control over the past decades have steadily resulted in centralisation of the planning function. There are good reasons for this centralisation, both from a material perspective and from a capacity perspective. From materials perspective, coordination over the supply chain reduces the bullwhip effect [89, 114]. When combined with proper rules for safety stocks and lot sizes, this effect may almost be eliminated. Moreover, the problem of matched sets of parts in assembly requires coordination of supply streams for all components in the bill-of-material [137], which seems again to justify centralised planning. From capacity perspective, optimisation of one resource will usually impact other resources, such that some kind of coordination is not only useful but nearly unavoidable.

However, centralised planning and control also has its drawbacks, as for example is shown by [170]. These drawbacks appear in practise, and are caused by the many small disturbances that occur in manufacturing and transportation. A typical example of such a small disturbance is when a component is damaged, although it was planned to be used in manufacturing. In this case, a similar component needs to be sourced from somewhere else in order to continue with the original plan. Often, these kind of disturbances are not even made known to the central planners, as they are often solved on a more local level by for example a shop floor supervisor. Other kind of disturbances can include production errors and misshipments. These disturbances are one of the many causes why central plans in factories are seldom realised. Therefore, in the previous chapter, the architecture of a more robust monitoring and control system was proposed, based on the concept of intelligent products, which goal is to handle these disturbances in a more effective way.

In this chapter, the performance of the proposed system will be compared with other approaches, using the Trading Agent Competition Supply Chain Management (TAC SCM) simulated supply chain [34]. However, the usual measurement of performance in TAC SCM are the financial results, in terms of costs made and penalties paid balanced against profits made in sales. In contrast, it is argued here that such a measurement of performance does not reflect the impact of disturbances enough. More fundamentally, simulation studies tend to ignore the disturbances, although they dominate the planner's activities in practise. Therefore, robustness is proposed here as an additional measurement of performance of planning and control systems.

This chapter is structured as follows. In the following section, the concept of intelligent products is elaborated. Next, the applied methodology is discussed in more detail in Section 4.3. Section 4.4 elaborates on the prototype implementation of the proposed monitoring and control system. Afterwards, the performance results of the proposed system compared to other systems are presented in Section 4.5. Conclusions are provided in the last section.

4.2 Background

Nowadays, there is an increasing interest in the field of intelligent products, and how intelligent products can be applied in different fields, such as in manufacturing and supply chain management (see Chapter 2). McFarlane et al. define an intelligent product as a physical and information-based representation of a product [116]. Figure 2.1 on page 21 shows an example of such a product. In this figure, the jar of spaghetti sauce is the physical product, the information-based representation of the product is stored in the database, and the intelligence is provided by the decision making agent. The connection between the physical product and the information-based representation is made using a tag and a reader, as will be further discussed later on. The fundamental idea behind an intelligent product according to Kärkkäinen et al. is the inside-out control of the supply chain deliverables during their lifecycle [98]. In other words, the product individuals in the supply chain themselves are in control of where they are going, and how they should be handled.

Recent technologies, such as automatic identification (Auto-ID), embedded processing, distributed information storage and processing, and agent based systems have been the main enablers for intelligent products. Auto-ID technologies, such as barcode and RFID, are commonly used to uniquely identify individual products or delivery units. Especially RFID tags are suitable for tagging individual products, as multiple RFID tags can easily be read simultaneously, without requiring a line-of-sight, such as is the case with barcodes. In addition to automatic identification, Auto-ID technologies often also include localisation and sensor technologies. Localisation techniques, such as GPS, are often combined with automatic identification, as the location information is useless without the identity of the located entity [177]. Another frequently applied technique is updating the location status of the product at the moment its barcode or RFID-tag is scanned, when the physical location of the scanner is known [77].

The vision of intelligent products is to seamlessly connect the products in the physical world with their representation in information systems, e.g. through a product agent as proposed by [52]. Intelligent products would make it possible to avoid media breaks between the real word and the digital world. Thereby, data about the current and past state of products from the physical world can be retrieved and updated when needed. The basic building block for implementing a distributed information storage and processing system for products is that products are identified by globally unique identifiers that either encode links to information sources directly or that can be used as look-up keys in some kind of network infrastructure. The three main currently known approaches for distributed information storage and processing are EPCglobal[2] [154], ID@URI[3] [77], and WWAI[4]. A technical analysis and comparison of these approaches can be found in [50].

The agents paradigm is considered useful to implement the intelligence part of intelligent products. There are several reasons why the use of an agent-based platform for intelligent products is beneficial. Firstly, when there is a high number of products, the number of products in need of explicit control from the user has to be reduced. This can be achieved by making the products autonomous. In this way, intelligent products with knowledge and reasoning capabilities can do most of the repetitive tasks in an automated way. Secondly, intelligent products should be able to detect and react to changes in the environment. Agents can pro-actively assist the product and

[2] http://www.epcglobalinc.org/
[3] http://dialog.hut.fi/
[4] http://www.wwai.org/

try to achieve their goals in a changing environment. Agents can also help in discovering information about the environment by communicating with the agents of other products. It is therefore clear that intelligent agents have the characteristics which are desirable for intelligent products. Of course, an application for intelligent products can be created without the use of agents, but by using agents, one can take advantage of the methodologies and solutions provided by the multi-agent paradigm [27].

4.3 Methodology

To compare the performance of the proposed system design, as described in the previous chapter, with existing designs, the TAC SCM simulated supply chain is used [34], due to several reasons. Firstly, it was designed to capture many of the challenges involved in supporting dynamic supply chain practises, including challenges related to production monitoring and control. Further, it is a well-founded framework, and widely reported in literature (see e.g. [35, 57]). Finally, the framework can be easily extended and modified for specific needs.

Within a TAC SCM simulation, a maximum of six manufacturers of personal computers compete with each other for customer orders and for the procurement of a variety of components. For every otherwise identical computer manufacturer, a different production planning and control system can be deployed. In this way, the performance of different production planning and control systems can be compared. The TAC SCM scenario from the perspective of a single manufacturer can be seen in Figure 4.1. As shown in the figure, a manufacturer has four major tasks to perform, namely negotiate with suppliers for components, bid for customer orders, manage the production schedule and manage the shipping schedule. Further, each manufacturer has an identical assembly cell capable of assembling any type of computer, and a warehouse that stores both components and assembled computers.

In the current TAC SCM simulations and competitions, the performance indication of a manufacturer is solely based on the financial result, in terms of costs made for material, storage and penalties paid balanced against

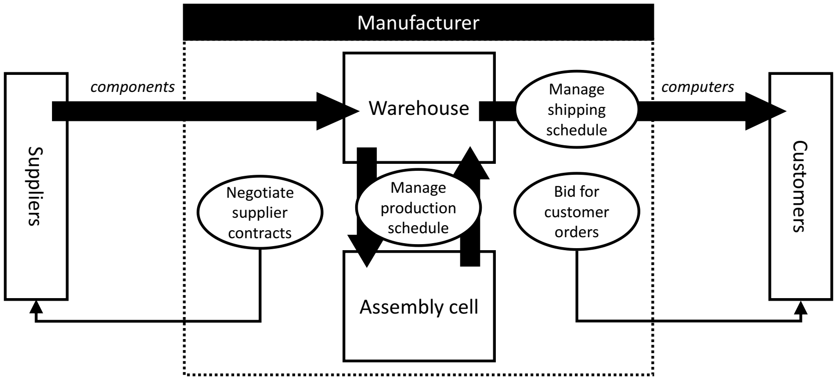


Figure 4.1: The TAC SCM scenario

profits made in sales. In principle, the manufacturer with the highest bank account at the end of a simulation run wins that run. This measurement of performance gives a good indication of which manufacturer is the most efficient one, in terms of costs and benefits. However, it does not provide a good indication about the robustness of the manufacturer, in case when the manufacturer has to deal with disturbances. For showing the robustness of a manufacturer, a measurement is needed which only indicates the capability of a manufacturer to handle unexpected disturbances in a flexible way. The financial results of the manufacturers give an indication of the overall performance, but robustness is only a minor part of that. Therefore, an additional measurement is used here. This measurement is the percentage of customer orders that are delivered to the final customer in time, i.e. if the delivery is before or on the due date of the specific order. This is considered to be a good measurement for the robustness of a manufacturer, as it gives an indication about the capabilities of a manufacturer to still deliver products to a customer in time, even when disturbances are happening.

Although there are some variations among the scenarios that manufacturers have to deal with, the standard TAC SCM scenario purposefully excludes disturbances. For the purpose of testing the performance of a manufacturer in terms of monitoring and control, a disturbance has been added to the simulated scenario. In the slightly modified version of the TAC SCM scenario, every component which is delivered by a supplier to a manufacturer has an *n* percent probability of being rejected. When this occurs, the component will not be added to the manufacturer's inventory. This amounts to a material shortage disturbance, the most common disturbance in practise [104]. In reality, such disturbances can have a variety of reasons, such as components being damaged, broken, delayed or wrongly shipped. With this additional disturbance added to the simulated scenario, experiments have been conducted with three different values for n, namely:

- $n = 0$. In this case, none of the delivered components will be unusable. Therefore, this scenario is the same as the original TAC SCM scenario.
- $n = 5$. In this case, every component has a chance of 5% of being unusable.
- $n = 10$. In this case, every component has a chance of 10% of being unusable.

In order to achieve reasonable confidence in the results, the experiments were repeated 25 times for every value of *n*. Besides the proposed manufacturer implementation, the same competing manufacturer implementations were used in every experiment, namely: TacTex-07 [138, 139], PhantAgent-07 [175], DeepMaize-07 [93] and Mertacor-08 [29, 181]. These 'opponents' were chosen for their high rankings in recent TAC SCM competitions, as well as their availability on the agent repository of the TAC website[5]. The next section of this chapter describes how the proposed monitoring control system of Chapter 3 is implemented as a TAC SCM manufacturer. Following this, the simulation results are presented.

4.4 Prototype implementation

This section describes the system prototype, and how it is implemented as a TAC SCM manufacturer. The implemented manufacturer was named GRUNN within the conducted simulations. The GRUNN manufacturer can be downloaded from the agent repository on the TAC website, as well as

[5] `http://www.sics.se/tac`

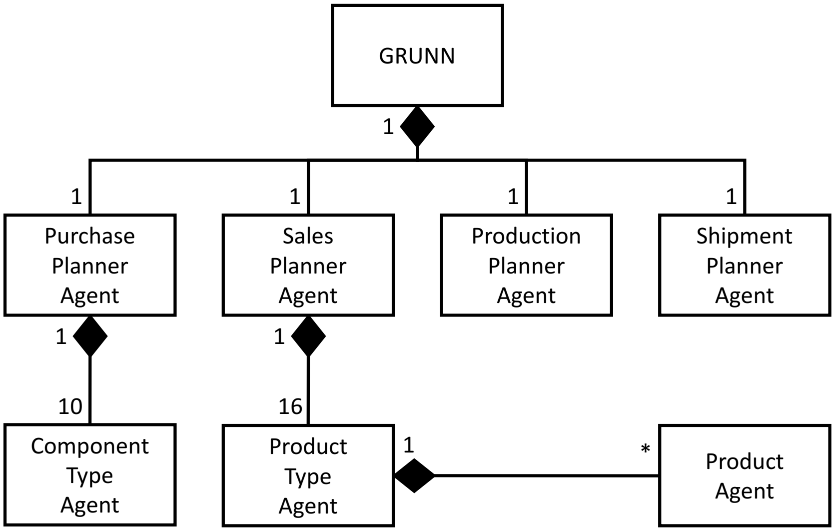


Figure 4.2: Class diagram of the GRUNN manufacturer

from the GRUNN project website[6]. In this section, the description of the prototype is split into two parts, namely a part discussing the system structure, and a part discussing the system behaviour.

4.4.1 Structure

The basic idea of the implemented manufacturer system for TAC SCM simulations is illustrated in Figure 4.2, which shows a UML class diagram, in which the various internal agents of the GRUNN manufacturing are depicted. As shown in the figure, there are four different planner agents in the system, each to perform one of the four basic TAC SCM tasks as described earlier. In addition, the product agent has to perform tasks for monitoring and control of a single product, as described in Section 3.4.3, and is responsible for the successful production and delivery of this single product.

In case of the TAC SCM simulation, one order in the simulation is considered as one product in the presented system design. This however does not have any consequences in implementing the structural design presen-

[6] `http://code.google.com/p/tacscm-grunn/`

ted in Section 3.4.2. Further, as the TAC SCM simulation does not allow for negotiation with human planners, the product agents will not use the decision-making mechanism described in Section 3.4.3 for proposing solutions, rather this mechanism will be used to create the overall production plan. As such, the responsibility of a product agent for completing an order covers the procurement of the components required for the assembly from the warehouse, the allocation of the required production capacity and arranging the shipment of the finished products to the customer.

The purpose of each agent type present in the system, including the planner and product agents, will be shortly described next.

- The *purchase planner agent* is responsible for acquiring components, which are required for the production of the to be delivered products. However, most of the tasks of this agent are transferred to other agents, as the purchase planner agent creates a separate agent for each component type. Such a separate component type agent is responsible for all the tasks related to one particular component type.

- The *sales planner agent* is responsible for acquiring orders. However, most of the tasks of this agent are transferred to other agents, as the sales planner agent creates a separate agent for each product type. Such a separate product type agent is responsible for all the tasks related to one particular product type.

- The *production planner agent* is responsible for assigning production capacity to products which are in need of assembly.

- The *shipment planner agent* is responsible for shipping assembled products to the waiting customers.

- A *component type agent* is responsible for acquiring components of one certain type. For this, every component type agent needs to negotiate with the suppliers of this component type. Furthermore, a component type agent is responsible for the distributing of this one type of components among unfinished products.

- A *product type agent* is responsible for acquiring orders of one certain

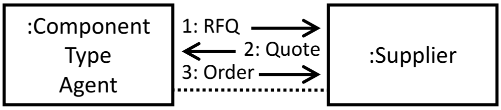


Figure 4.3: Behaviour of a component type agent

product type. For this, every product type agent needs to negotiate with potential customers.

- A *product agent* is responsible for the complete processing of one final product. In the case of TAC SCM, every customer order is considered to be a product, as every customer order can be seen as an individual and unique product which needs to be delivered by the manufacturer to the customer. Therefore, every customer order will have one product agent assigned to it, which makes the customer order an intelligent product. The responsibility of the product agent includes the procurement of components required for the assembly, the procurement of the required production capacity, as well as arranging the shipment of the finished products to the customer.

4.4.2 Behaviour

This subsection will describe the behaviour of the three most important agent types within the manufacturer implementation: the component type agent, the product type agent, and the product agent.

Component type agent

Every component type agent needs to acquire sufficient components of one certain type. For this, the behaviour of Figure 4.3 is applied by every component type agent. The figure shows a UML communication diagram, in which the communication of a component type agent with a supplier can be seen. This act of communication consists of three steps, which will be discussed next.

First, the component type agent will send Request For Quotes (RFQs) to every supplier, which can deliver the component type this agent is respons-

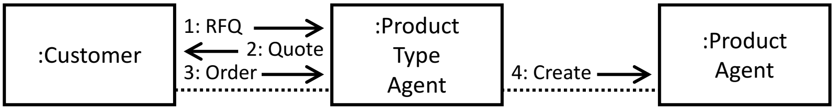


Figure 4.4: Behaviour of a product type agent

ible for. The amount of components as well as the delivery date asked for in an RFQ are based on sales estimations, the quantity that is still in inventory, and the quantity that is ordered but still needs to be delivered. This sales estimation is based on (historical) information which the component type agent receives from the different product type agents. Secondly, suppliers will send quotes back to the component type agent, telling the agent how much they can deliver, on what date, and for what price. Finally, the component type agent will compare the different quotes, and respond by sending orders back to the suppliers who had the best quotes for this component type. Which quote is considered to be the best quote is primarily based on the price per component, but when prices are almost the same it is also based on the quantity and the delivery date.

Product type agent

Every product type agent needs to acquire orders for products of one certain type. For this, the behaviour of Figure 4.4 is applied by every product type agent. The figure shows a UML communication diagram, in which the communication of a product type agent with a customer and a product agent can be seen. This act of communication consists of four steps, which will be discussed next.

First, the product type agent will receive RFQs of customers, in case customers are requesting quotes for products of the type this agent is responsible for. Each RFQ will contain information about the amount of products, as well as a due date. Secondly, the product type agent will respond with a quote, when the agent considers it feasible to deliver the product before the due date of the customer with a positive financial result. To achieve this, the agent will calculate a price per product based on an estimation of the current market price and adjusted according to the current factory load.

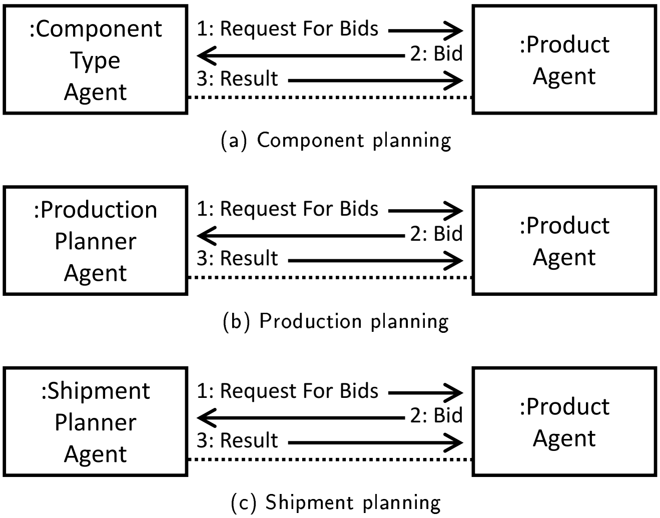


Figure 4.5: Behaviour of a product agent

This price is compared with the costs of the required components, resulting in a decision whether the quote will be send to the customer or not. Thirdly, when a customer considers the quote of the product type agent the best compared to the other manufacturers, the customer will send back an order. Finally, for every customer order the product type agent receives, a product agent is created, which will be responsible for the complete processing of this one order.

Product agent

As mentioned before, a product agent is responsible for the complete handling and processing of one particular order. For this, the behaviour of Figure 4.5 is applied by every product agent. The figure shows UML communication diagrams, in which the communication of a product agent with a component type agent, a production planner agent, and a shipment planner agent can be seen. These communication acts are part of the different planning tasks in which the product agent is playing a role. These different planning tasks in which the product agent is involved will be discussed in more detail next.

➟ The *component planning* is the first planning task in which the product agent is involved. Product agents should be able to assist the component type agent in distributing available components among the different products who require components for production. This functionality requires the intelligent product to already exist before the actual product is produced, i.e. the intelligent product is already in existence from the moment that there is the intention to make the product. This distribution of components among products should be based on priority, therefore, products with earlier due dates should get priority above products with later due dates. In order to achieve a distribution of components based on priorities, an auction based negotiation system is used, which consists of several steps. First, every component type agent will send a Request For Bids to all product agents, when it has components to distribute. Secondly, every product agent who is in need of this component type will send a bid to this component type agent, containing the amount of components of this type it needs, as well as the offered price per component. In this approach, the price per component the product agent is offering will increase when the amount of days left till the due date of the specific order is decreasing. Finally, the component type agent will inform all agents who have send a bid whether they have won the components or not. The product agents with the highest bids will always win the auction, as long as the component type agent has enough components in stock.

- The *production planning* is the second planning task in which the product agent is involved. Product agents should be able to assist the production planner agent in distributing the available production capacity among the different products who require production. As with the component planning, the distribution of production capacity among products should be based on priority, therefore, products with earlier due dates should get priority above products with later due dates. In order to achieve a distribution of production capacity based on priorities, an auction based negotiation system is used, which consists of several steps. First, the production planner agent will send a Request For Bids to all product agents, when it has production capacity to distribute. Secondly, every product agent who is in need of production will send a bid to the production planner agent, containing the amount of production capacity it needs, as well as the offered price per production unit. In this approach, the price per production unit the product agent is offering will increase when the amount of days left till the due date of the specific order is decreasing. Finally, the product planner agent will inform all agents who have send a bid whether they have won the production capacity or not. The product agents with the highest bids will always win the auction, as long as the production planner agent has enough production capacity available.

- The *shipment planning* is the third planning task in which the product agent is involved. Product agents should be able to assist the shipment planner agent in planning the shipments of finished products to the customers. Differently than the component planning and production planning, no prioritising is needed, as there is no limitation on the shipment capacity in case of the TAC SCM scenario. However, for design consistency, the applied approach assumes a limited shipment capacity, which therefore requires prioritisation. In order to achieve a distribution of shipment capacity based on priorities, an auction based negotiation system is used, which consists of several steps. First, the shipment planner agent will send a Request For Bids to all product agents. Secondly, every product agent who is in need of shipment will send a bid to the shipment planner agent, containing the amount of shipment capacity it needs, as well as the offered price per shipment unit. Finally, the shipment planner agent will inform all agents who have send a bid whether they have won the shipment capacity or not. However, in case of the TAC SCM scenario, there is no limitation on the shipment capacity available. Therefore, product agents with bids will always win the auction and will always get shipped.

The developed system will not result in the best possible plan because a centralised system is always able to find a more-optimal solution within a mathematical domain. Distributed systems are typically greedy and therefore suboptimal. However, as will be illustrated by the results in the next

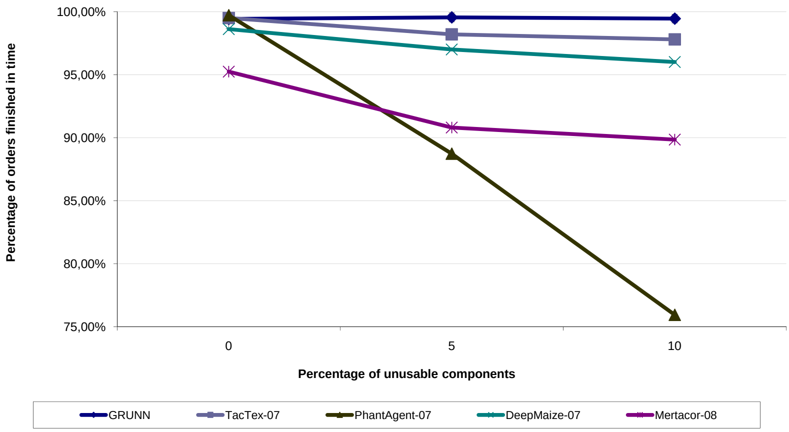


Figure 4.6: Performance of manufacturers in terms of orders finished in time

section, the system presented here can result in a very robust manufacturer.

4.5 Simulation results

This section presents the results from the simulation experiments, as described above. As described in the methodology section, three different experimental setups have been used, namely with zero, five, and ten percent of the delivered components being unusable, and therefore not delivered to the inventory of the manufacturer. The results presented in this section are based on the averages of the conducted simulations. For the GRUNN manufacturer, the standard deviations are also shown in every graph by means of error bars. The dummy manufacturer is omitted in the results presented in this section, as this manufacturer did not provide any relevant results. However, all detailed results including standard deviations for all manufacturers can be found in Appendix A on page 177.

The newly developed monitoring and control system did perform well when considering the robustness performance measure. This robustness measure is defined as the percentage of orders that are delivered to the final customer on time, i.e. the delivery of a specific order is on or before the due date. Figure 4.6 shows the results from the conducted simulations in terms

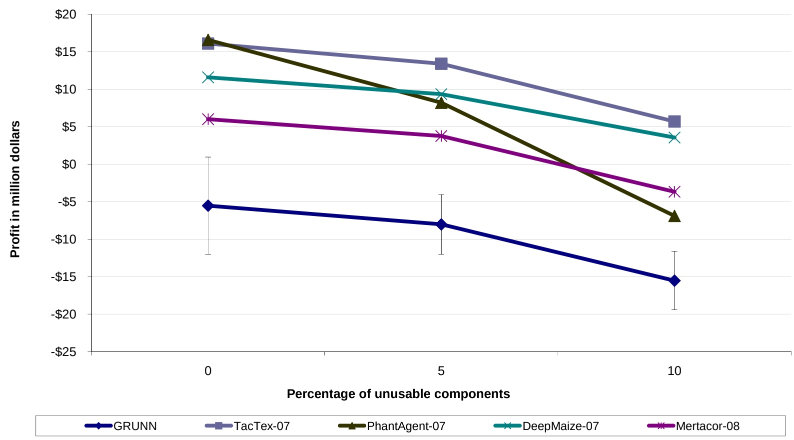


Figure 4.7: Performance of manufacturers in terms of profit

of orders finished on time. The graph shows that the percentage of orders finished in time is decreasing for all manufacturers when the percentage of unusable components is increasing. Only GRUNN is an exception to this. Even in the case where ten percent of all components are unusable, GRUNN still manages to finish nearly all orders in time. This observation confirms that an approach based on intelligent products can be very effective in handling disturbances in the simulated scenario.

Figure 4.7 shows the results of the conducted experiments in terms of profit. Two important observations can be made from the graph. Firstly, the graph clearly shows that for all three different experimental setups GRUNN does not perform as well as the other manufacturers in terms of profit. This observation is in line with our expectations. Secondly, for all manufacturers, the profit is decreasing when the amount of unusable components is increasing. This observation is also in line with our expectations, as manufacturers need to buy more components to finish the same amount of orders, when the amount of unusable components is increasing.

One obvious approach to overcoming the problem of unusable components is to increase the component inventory "safety stock" margin. Figure 4.8 shows the average storage costs per accepted order for each applied manufacturer system, and this gives a good indication of the inventory levels of

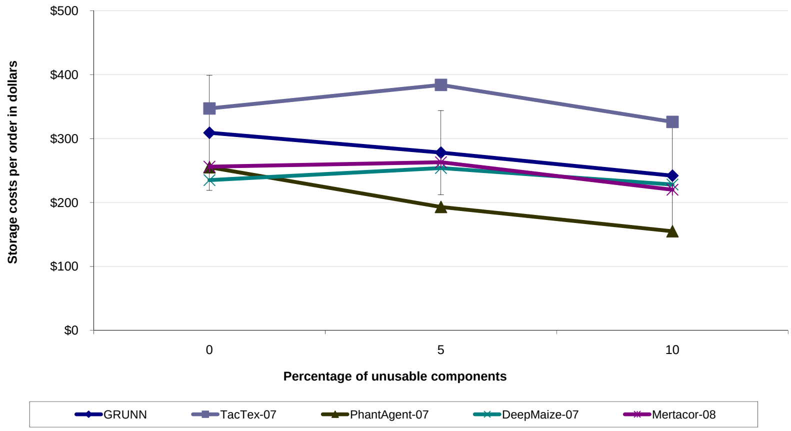


Figure 4.8: Storage costs of manufacturers per accepted order

each manufacturer. The figure clearly shows that using the GRUNN approach does not lead to a significantly larger inventory, and therefore that it is not dealing with the problem of unusable components by increasing safety stock levels.

4.6 Conclusions

In this chapter, the following has been concluded:

- The TAC SCM simulated supply chain is very suitable for demonstrating the performance of production planning and control systems.
- A robustness measure and an additional disturbance have been added to the TAC SCM scenario, in order to test the performance of manufacturers in terms of monitoring and control.
- A prototype implementation of the production monitoring and control system based on the concept of intelligent products is presented.
- Experimental evaluation with the TAC SCM simulated scenario has shown that intelligent products perform very well in terms of robustness, but poor in terms of profit.

➟ The intelligent products approach showed to be very promising for monitoring and control purposes, when robustness is considered as an important factor.

Part III

Monitoring and Control in Transportation

Chapter 5

System Architecture for Transportation

The typical business in road freight transportation is to transport goods from a certain source to a certain destination by the use of trucks. During the actual transportation of goods, small disturbances such as delays or wrongly loaded goods can prevent the original plan from being executed as intended. Some of the main problems caused by these disturbances, and how they are currently dealt with, are investigated in a medium-sized road freight transportation company. Typically, traditional planning and control systems have difficulties handling these kinds of problems effectively. This chapter presents a new system architecture for monitoring and control of road freight transportation, to tackle the outlined problems. Enabled by recent technical developments, the new system architecture is based on the concept of intelligent products. The system is designed to detect local disturbances in real-time, and to directly propose solutions to problems caused by these disturbances.[1]

[1]This chapter appeared earlier as: G.G. Meyer, G.B. Roest, and N.B. Szirbik. Intelligent products for monitoring and control of road-based logistics. *Proceedings of the 2010 IEEE International Conference on Management and Service Science*, August 2010, Wuhan, China, doi:10.1109/ICMSS.2010.5577852.

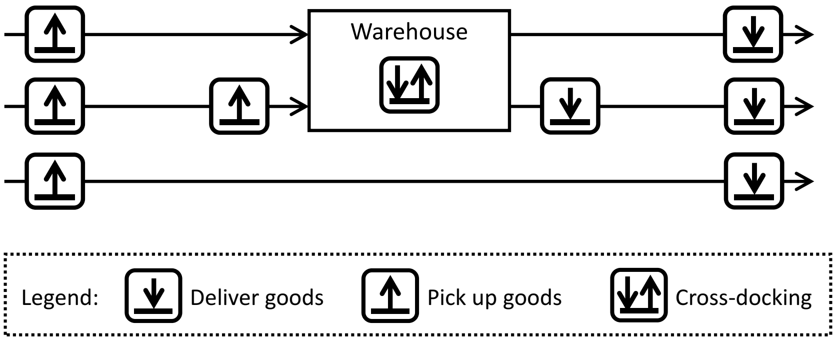


Figure 5.1: Overview of transport processes in a road freight transportation company

5.1 Introduction

The typical business of road freight transportation companies is to transport goods from a certain source to a certain destination by the use of trucks. This can be done in several ways, as is shown in Figure 5.1. The way this is typically done in practise is that trucks pick up nearby goods from several sources, and deliver them to a central warehouse. Other trucks deliver these goods from the warehouse to their final destination. The process of unloading goods from trucks at the company warehouse, grouping them, and loading them onto other trucks is referred to as cross-docking. In some cases, a truck directly delivers goods from a source to the destination, without an intermediate stop at a warehouse. This typically happens when the amount of goods which have to be transported from a single source to a single destination fills the entire capacity of the truck. However, when transportation requests only require a small part of the capacity of the truck, goods of several transportation requests have to be combined in order to improve transport efficiency.

In order to proper schedule truck capacity for the transportation demands, planning and control of the transport processes is required. To achieve this, four overlapping activities are typically performed within planning and control: loading, sequencing, scheduling, and monitoring and control [166]. The first three constitute collectively the planning function, the last function represents control. The advances in planning and control over the past decades have mainly focused on the sophistication of the planning function. This steadily resulted in centralisation of the planning and control activities such as vehicle routing and fleet management [60, 78, 135]. This seems to be justifiable especially for the planning activities, due to their mathematical nature. However, the monitoring and control activity as performed by planners has received much less attention, although planners in real life spend most of their effort to monitor and control, instead of performing planning activities [69, 118, 143, 168].

The drawbacks of centralised monitoring and control appear in practise, and are caused by the many small disturbances that occur during transportation, and the way they are dealt with. A typical example of such a small disturbance is when a truck is delayed by a traffic jam, at the pick-up, and/or delivery of goods at customer locations. Because of these events, the execution of the plan can be troublesome, especially if several other trucks are waiting for goods which are currently carried by the delayed truck. In this case, proper and timely rescheduling is needed in order to minimise the effect of the delay. Often, these kinds of disturbances are not made known to the central planners in time, although they might be registered by a vehicle tracking system, as the truck drivers try to solve first these problems themselves on a local level. Other kinds of disturbances can include: goods loaded in the wrong truck, last-minute order cancellations, etc. These disturbances are part of the many causes why central plans in transportation are rarely realised as intended.

Here, it is argued that proper monitoring and control in the context of road freight transportation requires detailed feedback on disturbances, in terms of the transported goods, the resources, and the conditions. In order to allow timely response to disturbances, agents representing the goods and resources should act immediately, investigate the options for re-planning, and inform the human planners. Therefore, a new system architecture for monitoring and control of road freight transportation is presented in this chapter.

The remainder of this chapter is structured as follows. In Section 5.2, several problems in monitoring and control of road freight transportation are further analysed. Afterwards, the system architecture is presented in Section 5.3, and evaluated in Section 5.4. The chapter ends with conclusions.

5.2 Problem analysis

The problems as described in this section are inspired by a case study in a Dutch medium-sized road-based transportation company, but these problems are more generic and are likely to also apply to similar companies (see e.g. [22, 109]). The main business of the company studied is to transport frozen and cold goods from The Netherlands and Belgium to destinations in Central Europe. During the execution of a plan in such a company, several problems occur which cannot be managed effectively by the planners in their current approach towards monitoring and control. Several of these problems are discussed next. The system requirements and architecture as presented in Section 5.3 explicitly addresses these problems. The problems as discussed in this section are additionally clarified with several scenarios from the case company. These scenarios will also be used to evaluate the utility of the system architecture in Section 5.4.

Problem 1: A truck is delayed, but the planners are not aware of this.

This problem is quite common in the transportation company, due to how the progress is monitored. According to the planners in the company studied, it is too much effort for them to monitor the progress of all the trucks manually, even though an information system is monitoring this progress. This is also caused by the fact that they are already very busy with many other activities. A planner only becomes aware of a delayed truck, when this information is pushed to him by the driver of the truck, through a phone call or text message. In order to reduce the amount of telephone calls and text messages, the company has a policy that truck drivers should only call the planners if they have at least one hour of delay. This however implies that the planners become aware of the problem relatively late, which can make it more difficult to find a solution for the consequences of the delay.

➟ *Scenario 1*: A truck is 15 minutes behind schedule, due to a traffic jam. However, the truck is heading for the company warehouse, where 3 other trucks are waiting for cross-docking. This small delay can have bigger consequences for the global plan. Waiting another 45 minutes with reporting this delay to the planners will decrease the possibilities for rescheduling.

Typically, planners using a centralised planning and control system work in a hierarchical way. This has the advantage that the complexity on the different levels in the organisation's structure is reduced, when each level can function at least partly independent from the other levels. However, performance feedback is important in hierarchical systems, in order to have a properly functioning system [121]. Two assumptions are required to make such a system work properly. Firstly, proper feedback needs to be given in time by the lower levels to higher levels. Secondly, the higher levels need to be able to adequately respond in time to this feedback. If any of these requirements are violated, it is nearly impossible for planners to monitor the progress of the plan execution in an effective way. This seems to be the cause of problem 1. Feedback often reaches the planners too late, which is one of the reasons that prevent the planners to give an adequate response in time.

Problem 2: An individual pallet is loaded into the wrong truck, but the planners are not aware of this.

This is another typical problem in the transportation company, due to how the progress is monitored and controlled. The progress in the plan execution is monitored on the structural level of trucks, albeit in a delayed way. However, if by accident one box or pallet is loaded into the wrong truck by the crew of the company warehouse, this is only noticed at the moment when the driver wants to unload at a certain destination. Only at this moment the driver will inform the planners, which is too late for the planners to resolve the matter properly.

➟ *Scenario 2*: An order of 30 pallets is split up where by accident 29 pallets are loaded into one truck and one single pallet is wrongly loaded into another truck. In this case, information about the location of individual pallets would be needed to detect that one pallet is wrongly loaded. An early notification would again enable a quicker response which would allow the problem to be resolved more effectively.

Currently, centralised planning and control systems often have difficulties dealing with problems related to individual boxes or pallets. The main reason for this is that these systems typically work with aggregated data. Firstly, central planning systems aggregate over location. Goods which have to be transported are for example booked as being inside a warehouse or truck, but no precise account is available where inside exactly these goods can be found. In many cases this is no problem, but if goods are lost, it suddenly becomes a huge issue. Secondly, central planning systems aggregate over the goods which are to be transported. For example, all the different boxes and pallets of one order and the small differences between them are not explicitly present in planning systems. Furthermore, the progress during plan execution is often only monitored on a truck level, which also results in an aggregating over the progress of individual pallets. However, problems in monitoring and control often occur in a detailed, disaggregated form.

Problem 3: A truck will arrive too late at the company warehouse, but several other trucks are waiting for the goods inside the delayed truck.

The third problem is a more complicated problem for the transportation company. The plans as created by the planners often require that many transported goods have to be cross-docked at the warehouse. As long as everything goes according to schedule, this will not cause any problems. However, when one truck with goods for the warehouse is delayed, this can cause delays for all the other trucks which are waiting for goods inside that truck. To minimise this 'avalanche'-effect, proper and timely rescheduling is needed. However, this can be a difficult task for human planners, as it is difficult to analyse all possibilities for rescheduling in a very limited amount of time.

➟ *Scenario 3*: The truck that was 15 minutes behind schedule is now 20 minutes behind schedule. However, the driver of the truck reports that

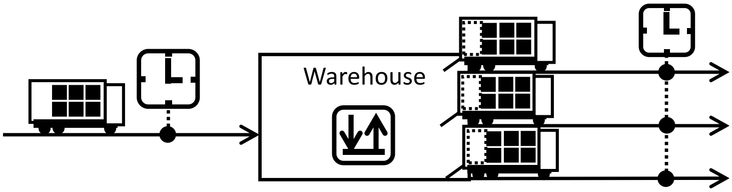


Figure 5.2: Truck delayed, 3 trucks waiting

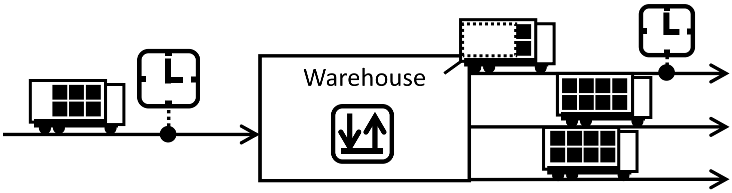


Figure 5.3: Truck delayed, 2 trucks rescheduled, 1 waiting

> the total delay will be at least one hour. This situation is depicted in Figure 5.2. For human planners, it is very hard to find and analyse all possible alternatives. However, a proper monitor and control system could come up with alternatives and propose them to the human planners. Such an alternative could for example be that the 3 trucks, which were waiting for cross-docking, redistribute their goods in order to let 2 trucks leave the warehouse and have only one truck waiting for the delayed truck. This alternative is depicted in Figure 5.3. In this way, the majority of the goods will be delivered in time. The total driving distance per truck will be increased, but the total costs can be lower compared to the situation where all 3 trucks keep waiting for the delayed truck.

Without proper and fast feedback on problems, and without detailed, disaggregated data, it is currently a difficult task for human planners to find the best solution to a disturbance in plan execution. However, even if those two properties are present, it can still be hard for planners to find a good solution to this problem. Currently, such a problem is solved manually based on the aggregated data available. However, such a solution is not likely to be optimal. Using aggregated data however leads to a reduced solution space, which makes it possible for a human to at least find a solution. When detailed, disaggregated data is used, new and better possibilities for solutions can become available, but the solution space may become too big and complex for human planners to find them. In that case, a proper monitor and control system should assist the human planners, by searching through a bigger solution space to find a more elaborated and (near-) optimal solution.

5.3 System architecture

This section will describe the generic architecture of the proposed monitoring and control system. This architecture is similar to the architecture presented in Chapter 3, albeit focused on a transportation context. First, the requirements are presented. Next, certain new technologies are discussed which can be applied to incorporate these requirements. Afterwards, the structure and behaviour of the proposed planning and control system architecture are described in detail.

5.3.1 System requirements

As discussed in Section 5.2, centralised planning and control systems have problems dealing with disturbances. One important reason is that feedback often reaches the planners too late, which prevents the planners to respond adequately and in a timely fashion to disturbances. This leads to the formulation of the first requirement:

➟ *Requirement 1*: The system should be able to give feedback about disturbances to planners directly when they occur.

Another reason why centralised planning and control systems have difficulties dealing with disturbances is because centralised planning and control systems work with aggregated data. However, as disturbances seldom present themselves in aggregated terms, an effective monitoring and control system should work with data on the same level of detail as disturbances occur. This leads to the second requirement:

➟ *Requirement 2*: The system should work with data on the same level of detail as disturbances occur.

With the use of detailed, real-time, and disaggregated data, the search space for a suitable solution to a disturbance increases significantly, compared to the current situation. The big amount of information in this space can make it difficult to find a suitable solution manually. Therefore, the support of a system which can search this space effectively is required. Hence, the third requirement is as follows:

➟ *Requirement 3*: The system should be able to propose solutions to problems directly when they occur.

5.3.2 New technologies

Nowadays, there is an increasing interest in the field of intelligent products, and how intelligent products can be applied in different fields, such as in manufacturing, logistics and supply chain management (see Chapter 2). McFarlane et al. [116] define an intelligent product as a physical and information-based representation of a product. A pallet or box can for example be the physical product, the information-based representation of the product can be stored in the database, and a decision making agent can provide the intelligence. The fundamental idea behind such an intelligent product according to Kärkkäinen et al. [98] is the inside-out control of the supply chain deliverables during their lifecycle. In other words, the product individuals in the supply chain themselves are in control of where they are going, and how they should be handled.

The vision of intelligent products is to seamlessly connect the products in the physical world with their representation in information systems, e.g. through a product agent as proposed by Främling et al. [52]. Because of continuous synchronisation, data about the current and past state of products in the physical world can be retrieved and updated in the digital world when needed.

As is the case with intelligent resources, agent technology is considered as a good match to implement the intelligence part of intelligent products, because of several reasons. First of all, when the number of products is high, the number of products in need of explicit control from the user has to be reduced. This can be achieved by making the products autonomous. In this way, intelligent products with knowledge and reasoning capabilities can do most of the repetitive tasks in an automated way. Secondly, intelligent products should be able to detect and react to changes in the environment. Agents can pro-actively assist the product and try to achieve their goals in a changing environment. Finally, agents can help in discovering information about the environment by communicating with agents of other products. Therefore, intelligent products seem to be an appealing approach for solving problems within monitoring and control in the context of road freight transportation.

5.3.3 System structure and behaviour

As a starting point for the new system architecture, the current structure of the transportation company is used. A simplified version of this structure is presented in Figure 5.4. The transportation company at the top of the figure is composed of a set of planners, a number of drivers and trucks, and has an association with a global plan. The global plan is composed of trips, which in turn consists of drivers and their trucks that carry the goods of the orders. This structure reveals the location of the problem concerning the aggregation over individual products by only focusing on the order. As shown in Figure 5.5, the aggregation problem is addressed by decomposing the order into products. In this way, *Requirement 2* can be met, as problems with goods typically happen on the level of pallets or boxes (which are now represented as products in the system) and not on the level of orders. This enables the system to monitor the location of every individual product.

Products, drivers, and trucks are considered atomic elements or objects in the architecture, since disturbances that occurs during the plan execution typically originate from these elements only. However, in order to be able to incorporate *Requirement 1* and *Requirement 3*, the products, drivers, and trucks are designed to be autonomous and intelligent entities. Therefore, in the new architecture, they have an intelligent agent attached to them. The purpose as well as the behaviour of the intelligent agents will be explained next.

The behaviour of the intelligent agents will be introduced here according

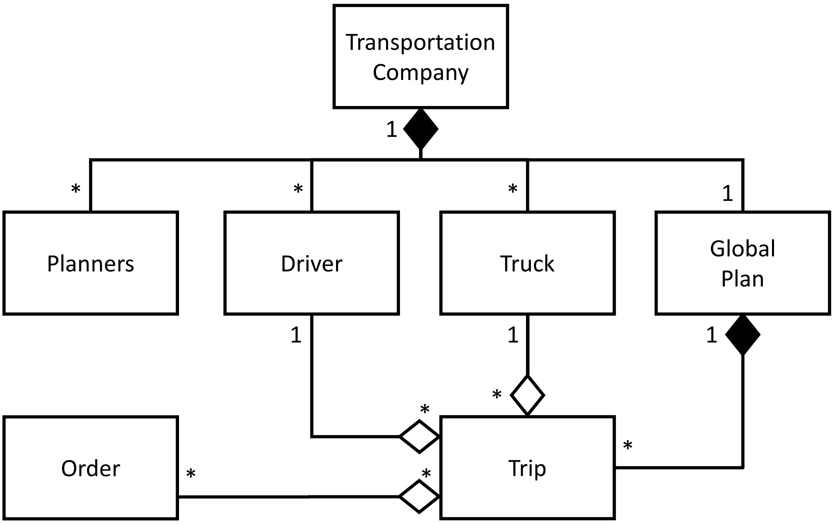


Figure 5.4: Existing company class diagram

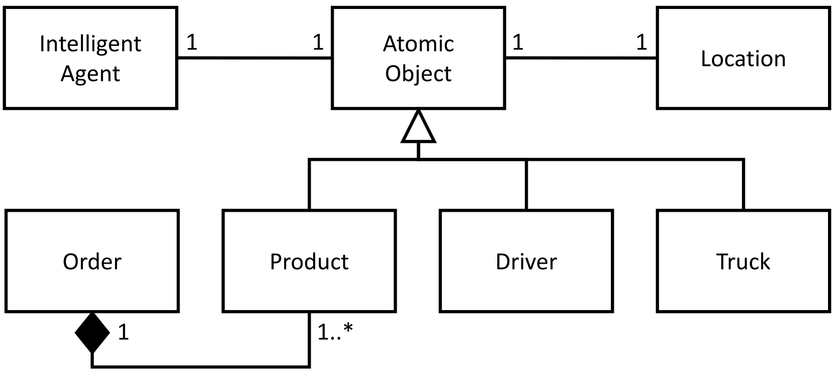


Figure 5.5: Addition of Product and Intelligent Agent classes in new system design

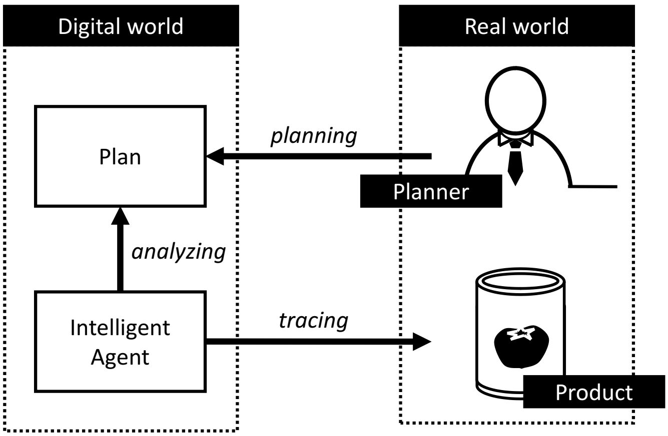


Figure 5.6: Information gathering of the intelligent agent

to the three levels of intelligence as described in Chapter 2. These three levels are discussed separately below, with the focus on the intelligent agents representing products.

Level 1: Information handling

Every agent, regardless of the fact whether it represents a product, driver, or truck, is aware of its part in the global plan. It is able to analyse the trips as planned by the central planners in which the object it is representing is involved. In this way, the agent is continuously aware of changes in this plan, because the agent knows where the product, truck, or driver it is representing is expected to go. However, to enable plan monitoring, the agent needs to keep track of the current status as well as the history of the object it is representing. This functionality is often referred to as tracing [184]. This requires continuous synchronisation between the real world and the digital world, which can be achieved with the technology described in Section 5.3.2. This flow of information gathering for an intelligent agent representing a product is modelled in Figure 5.6.

Level 2: Problem notification

When the agent has knowledge about the plan as well as the current status regarding plan execution, it is able to detect disturbances. The agent employs a mechanism such as a utility function to determine whether the progress is still within schedule. In case of a product, such a utility function can be based on factors like: the distance of the product to the destination, the amount of time until the delivery is due, whether there is a proper plan to get the product to the destination, and whether the plan execution is on schedule. When the utility score of an agent drops below a certain threshold, that agent enters a problem state. The agent will then decide if it is necessary to notify a human planner.

Level 3: Decision making

Besides the notification of their problem state to human planners, the agents can also search for solutions themselves. As a result of the continuous synchronisation, all agents are aware of the actual situation in the real world. This enables the agents to negotiate in real-time about alternative plans to properly cope with a disturbance. The agents follow the general behaviour of maximising their utility continuously. This is achieved by negotiation among trucks and products, in which trucks try to optimise their route and capacity, and products try to find a truck which best matches their delivery demands. In this system design, this is solved with an auctioning mechanism, where products place bids for truck capacity. The bid of an agent representing a product is always equal to the expected utility gain for that product. Trucks will select products based on their own utility gain, which is the value of the offered bid reduced by additional costs for the truck, such as an increased travelling distance. Figure 5.7 depicts an illustrative situation which can occur after a disturbance, where the truck at the warehouse has capacity for only one additional product. Two products at the warehouse bid for this capacity and the truck analyses the additional costs. In this particular case, taking product A will yield a total utility gain of 7 whereas taking product B only yields 5.

The total result of the negotiation between truck- and product-agents

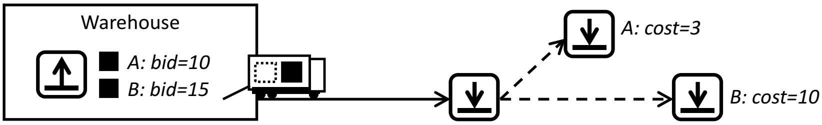


Figure 5.7: Product selection based on utility gain

will be presented to the human planners. They will decide whether the tentative actions will be scheduled or not. If the planners do not agree with parts of the schedule, they can propose changes in a way that enables the agents to learn from it. This approach is similar to the monitoring and control mechanism of escape and intervention as proposed by Roest and Szirbik [147].

5.4 Evaluation

Before developing a prototype system for experimental and observational evaluation, it is good practise to first evaluate the proposed architecture. For this purpose, an appropriate assessment method has to be selected. Due to the orientation of the case analysis towards scenario-based problem definition and requirement specification, only methods that are scenario-based have been considered from the Taxonomy of Software Architectural Evaluation [148]. Out of the so-called "early" evaluation methods, the SALUTA (Scenario-based Architecture Level UsabiliTy Analysis) method [47] has been selected, due to its orientation towards usability. This method can be applied for three different goals: to predict the usability level, to detect usability issues (i.e. risk assessment), and to select a software architecture by assessing multiple candidates. In this case, the main goal was to predict the usability level.

The SALUTA method requires two types of information as input. The first type of information needed is the required usability by the system users, which is captured through interviews. The second type of information needed is the provided usability by the proposed system architecture, which is captured by analysing the proposed software architecture. By comparing these two types of information, an assessment can be made whether

Table 5.1: Required usability

no.	Scenario	Satisfaction	Learnability	Efficiency	Reliability
1	Detect that a truck is behind schedule	2	1	3	4
2	Detect that a pallet is loaded into the wrong truck	2	1	3	4
3	Re-plan in case when a truck is too late for cross-docking	2	3	4	1

the proposed system architecture provides the usability level as required by the system users.

Required usability by the users

First, the required usability by the system users has been captured. In the used evaluation framework, usability is described by four predefined usability attributes: *Satisfaction*, *Learnability*, *Efficiency*, and *Reliability*. For a number of scenarios, a value between 1 and 4 has to be assigned to each usability attribute, indicating how important the intended system users consider each of the usability attributes in that specific scenario. In this case, the intended users for the proposed architecture are the planners at the case company described earlier in this chapter. In order to determine the importance of the usability attributes, open interviews with these planners have been conducted. In these interviews, they explained their usability preferences of the system for each of the three scenarios as described before in Section 5.2. The results of these interviews have been translated into score values for the usability attributes, and are shown in Table 5.1. The table shows that the planners are considering *Efficiency* and *Reliability* as the most required usability attributes.

Provided usability by the system

Second, the provided usability by the system under development has been captured. In the used evaluation framework, this is achieved by first de-

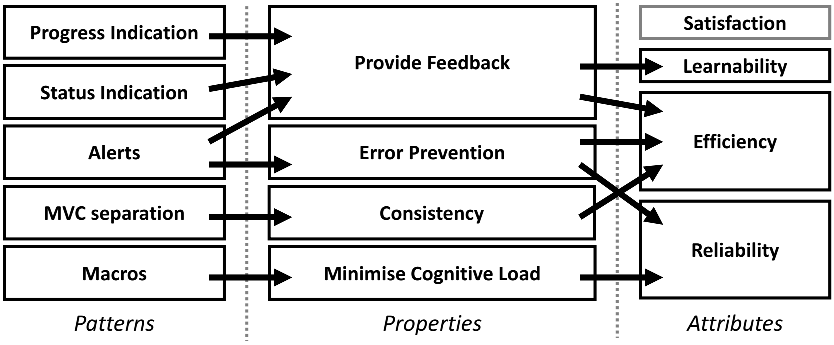


Figure 5.8: Provided usability

termining the main usability *patterns* of the proposed system architecture. The framework provides a list of possible usability *patterns*, as well as an indirect mapping from these usability patterns to the usability *attributes* (the same as mentioned above) via usability *properties* [46]. The usability patterns have been captured by a software engineer not involved in this project through analysis of the architecture as described in Section 5.3. The main usability patterns captured are shown in the left-hand side of Figure 5.8. Next to that, the figure also shows to which usability attributes the captured usability patterns are mapping. The figure shows that *Efficiency* and *Reliability* are the most prominent usability attributes provided by the proposed system architecture, as due to the mapping they receive the most incoming arrows.

Assessment result

By comparing the required usability in Table 5.1 and the provided usability in Figure 5.8, it appears that in both cases, the *Efficiency* and *Reliability* attributes are the most prominent, which shows that the required usability level matches the provided usability level. This is a positive result of the usability assessment, indicating that the proposed system architecture provides the usability level as required by the system users. Furthermore, to verify this result, the proposed system architecture has been evaluated through experimental and observational evaluation. For this purpose, a prototype implementation of the system has been developed. A thorough elaboration on these evaluation activities including the results can be found in Chapter 6.

5.5 Conclusions

In this chapter, the following has been concluded:

- During transportation, many different kind of disturbances can occur, leading to deviations from the original plan.
- Planners in road freight transportation have difficulties dealing with disturbances, due to being informed too late and not having the required information available.
- Intelligent products appear to be new and promising approach for improving monitoring and control in transportation, as intelligent products are aware of their local state, objectives, and dependencies.
- A novel system architecture for monitoring and control of road freight transportation is presented, based on the concept of intelligent products. The intelligent products can monitor individual products locally and in real-time, by applying detailed data, as opposed to aggregated data. Furthermore, these intelligent products can notify planners about disturbances at the same time as they occur, and can collaboratively propose solutions to them.
- The evaluation of the proposed architecture has shown that the system will provide the usability level as required by the system users.

Chapter 6

System Prototype for Transportation

Many transportation companies are making considerable investments in tracking technologies, such as GPS and RFID. These companies face challenges in utilising the information provided by these tracking technologies for operational monitoring and control. Moreover, literature shows inconclusive and sometimes even contradictory research findings on the utilisation of tracking technologies. This chapter identifies the challenges which are faced by a transportation company when utilising tracking technologies. A design science research methodology is adopted, as it allows for an explicit focus on solving these challenges. As a result, a set of design principles is proposed, which prescribe how intelligent products can be applied for supporting operational monitoring and control activities of transportation companies. Experimental and observational evaluation results show that the proposed design principles contribute in better utilising tracking technologies for operational monitoring and control.

6.1 Introduction

In recent years, transportation companies have made considerably investments in information technology [157], including investments in tracking technologies such as GPS and RFID. It is often claimed that the information provided by tracking technologies improves operational control[1] and thereby operational performance [188]. However, many transportation companies struggle to effectively exploit the information provided by tracking technologies for operational control. Although the information is there, the appropriate methods to transform this information into the information required for operational control is lacking [39]. Therefore, the main objective of this chapter is to investigate how tracking technologies can be better utilised for operational control of transportation companies.

This chapter identifies the challenges faced when utilising tracking technologies for operational control, and proposes solutions to overcome these challenges. Considerable research effort in operations management focuses on explaining or predicting phenomena associated with the utilisation of information technology in organisations (see e.g. [17, 67, 87]). In addition, design science research [70, 142] allows shaping such phenomena by the design of novel artefacts [164], and can thereby complement theory-oriented research in operations management [1, 71]. Therefore, design science research is considered an appropriate paradigm for studying information technology in operations management.

By applying the design science paradigm, this chapter contributes in overcoming the identified challenges by proposing a set of design principles for information system design. This set of design principles enables the application of intelligent products [116, 122] for better utilising the information provided by tracking technologies. Intelligent products can represent physical objects such as pallets, and are capable of autonomously performing some of the repetitive tasks required for operational control. The set of design principles is validated by means of experimental and observational evaluation.

After the overview of related work in Section 6.2 and the discussion of

[1]Please note that the terms *operational control* and *operational monitoring and control* are used interchangeably.

the methodology applied in this study in Section 6.3, Section 6.4 analyses the challenges faced by a transportation company in utilising tracking technologies for operational control. Contributing in solving these challenges, Section 6.5 proposes the set of design principles. Section 6.6 describes how these principles have been evaluated. Conclusions are provided in the last section.

6.2 Related work

In order to reflect upon the findings of recently published research on the utilisation of tracking technologies, a literature search was performed. This search included papers published after 2004 in the most relevant journals in operations management, according to the journal evaluation of Theoharakis et al. [180]. All the papers which discuss the utilisation of tracking technologies were selected. From this selection, *RFID* and *GPS* were identified as the *means* being studied. Subsequently, the papers in the selection were classified based on the identified *ends* for utilisation of tracking technologies, being *improved visibility* and *improved operational performance*. Finally, the papers were classified according to the research *approaches* as distinguished by Meredith [120], being *experiments or statistical methods* and *case or field studies*. Table 6.1 presents the classification of the selected papers.

As can be seen from the table, much research effort is focused on the utilisation of tracking technologies for improved visibility, for which both classes of research approaches have been frequently applied. The research findings on utilising RFID-based tracking technologies indicate an improved visibility in specific domains, such as supply chain management [11, 42, 172], tools and items management [31, 130, 204], quality management [99, 200], waste management [20], inventory management [90, 191], assembly guidance [202], and customer services [66]. The research findings on utilising GPS-based tracking technologies indicate improved visibility with respect to vehicle locations, which enable the estimation of queue lengths at intersections [36], and the monitoring of trucks used for container terminal operations [131]. Except for Ngai et al. [131] and Wang et al. [191], the research findings in these studies do not show whether this improved visibility

Authors	Means		Ends		Approaches	
	RFID	GPS	Improved visibility	Improved operational performance	Experiments or statistical methods	Case or field studies
Barratt and Oke (2007) [11]	*		*			*
Brintrup et al. (2010) [20]	*		*			*
Cheng et al. (2010) [31]	*		*		*	
Comert and Cetin (2009) [36]		*	*		*	
Dehning et al. (2007) [41]	*			*	*	
Delen et al. (2007) [42]	*		*		*	
Gaukler and Hausman (2008) [55]	*			*	*	
Guo and Zipkin (2009) [62]	*			*	*	
Heese (2007) [65]	*			*	*	
Heim et al. (2009) [66]	*		*			*
Hong et al. (2010) [73]	*			*	*	
Kang and Gershwin (2005) [90]	*		*		*	
Kumar and Schmitz (2011) [99]	*		*			*
Ngai et al. (2007) [130]	*		*			*
Ngai et al. (2011) [131]	*	*	*	*	*	*
Sari (2010) [153]	*			*	*	
Schmid and Doerner (2010) [155]		*		*	*	
Soroor et al. (2009) [172]	*		*		*	
Visich et al (2009) [188]	*			*	*	
Wang et al. (2010) [191]	*		*	*		*
Xu (2011) [200]	*		*		*	*
Zhang et al. (2011) [202]	*		*			*
Zhou (2009) [204]	*		*		*	

Table 6.1: Literature review taxonomy

also leads to improved operational performance.

A substantial research effort is focused on the utilisation of tracking technologies for improved operational performance. Most of the research findings indicate that utilising tracking technologies can improve the performance of operations in specific domains, such as warehouse management [191], supply chain management [41, 65, 73, 188], and fleet management [131, 155]. None of these studies have applied a research approach based on case or field studies, with the exception of Wang et al. [191] who focus on the utilisation of RFID-based tracking technologies for warehouse management. Other research findings indicate that operational performance will not always improve. Firms do not necessarily improve their internal operations when adopting tracking technologies [41], supply chain costs reductions are not significant [153], and applying tracking technologies can in some cases degrade the operational performance [62].

In conclusion, it is widely demonstrated that the utilisation of tracking technologies results in improved visibility. However, the results from these studies do not indicate whether that visibility will also lead to improved operational performance. Other studies which show improved operational performance seldom adopt case or field studies, leaving the results on the utilisation of tracking technologies in an organisational context inconclusive. Some contradictory research findings even indicate that operational performance will not improve. Therefore, a gap in existing theory becomes apparent, due to the inconclusive and sometimes contradictory research findings. Hence, it is key to demonstrate how tracking technologies can be utilised in order to achieve improved operational performance in an organisational context.

6.3 Methodology

The objectives of this research are to identify challenges in utilising tracking technologies and to contribute in solving these challenges by proposing a set of design principles for information system design. Considerable research efforts in operations management focus on explaining or predicting phenomena associated with the application of information technology. To study such phenomena, these efforts typically apply a methodology based on quantitative survey research (see e.g. [67]), qualitative case research (see e.g. [17]), or a combination of both (see e.g. [87]).

As an alternative to case and survey based research, design science research [70, 142] does not only explain and predict the phenomenon of interest, but allows shaping it by design of novel artefacts [164]. In doing so, design research can complement theory-oriented research in operations management [1, 71]. Due to its explicit focus to improve practise, design science is considered a particularly valuable paradigm for operations management research on the utilisation of information technology. Therefore, the study as described in this chapter is conducted within the tradition of design science research in information systems.

This methodology section describes three design science research activities that were performed in this study: problem identification, artefact development, and evaluation. The activities were derived from the design science guidelines provided by Hevner et al. [70] and procedures provided by Peffers et al. [142], which both originated in information systems research. The activities were adapted to respect the qualitative research tradition in operations management.

6.3.1 Problem identification

An in-depth single case study method was adopted to identify the research problem. The justification for that method is based on methodological guidelines [43, 120, 178] which strongly recommend exploratory case study research when the objective is to address gaps in existing theory. The problem identification started with a clean-slate in terms of validated theories, resulting in an inductive approach [178]. An interpretive research stance [141] was adopted, focused on explaining the operational control activities and describing the expressed thoughts of the actors related to the utilisation of available tracking technologies.

A typical medium-sized road freight transportation company in The Netherlands was selected as the case company. This case company has state-of-the-art tracking technologies in place, and allowed continuous and unrestricted access to all their data, documents, and operations for a period of six months. Therefore, this case company provided a unique research opportunity [43]. The planning department of the case company served as the source for empirical information. During the problem identification, data collection and data analysis were frequently alternated to allow cross validation of research outcomes and pursuance of interesting new paths of research.

Data collection

At the start of the case study, open question interviews with the management of the case company identified the main actors, the control activities in which they participate, and the nature of these activities. This enabled a clear definition of the unit of analysis [10] and its boundaries.

Observations, documents and databases, verification of observations, and interviews with the management of the case company were used as sources of data. Collected data has been triangulated by means of comparing researchers' interpretations of the observations made, comparing the formal and actual data flows, and interacting with the management.

Observations At the planning department of the case company, three-day operational cycles are planned twice a week. Three of such operational cycles were used to observe the control activities performed. To enhance understanding of the operations which require control, researchers also observed the process of planning these operations. In total, 75 hours of observing activities at the case company were documented.

The observations were aimed at understanding the operational control activities, as well as what triggered the actors to perform these activities. Afterwards, observations were briefly discussed with the actors involved. They were briefly interrupted and asked what activities were performed, which information was used, how that information was collected, what was eventually decided and how the control decision was communicated. Moreover, control activities were discussed during many informal events. Observations were documented in field notes, including a structured overview of triggers for control and actual control activities, relevant quotes of actors involved, and interpretations of the observing researchers.

Documents and databases The formal data flows between information systems in place at the case company were assessed by examining raw data, database schemata, and documentation including management memos and user manuals for the information systems. The main objective was to understand which data was captured by the available tracking technologies. Moreover, the meaning of that data and the relation between different types of data were studied.

Discussion of observations During the three operational cycles that were part of the case study, observations were frequently discussed with the head of planning. Moreover, the formal information flows studied were discussed with both the head of planning and the IT manager. The main objective was to expand and verify the researchers' understanding of the control activities and their triggers. Based on the discussions, the field notes were refined and relevant quotes of the head of planning and IT manager were added.

Semi structured interviews Semi-structured interviews with the management were conducted in order to further expand and verify the understanding of the operational control at the case company. Over the time span of the case study, five interviews were conducted: one at the start of the case study, one after each operational cycle observed, and one to finalise the case study. The CEO, the head of planning, and the researchers involved were present at the interviews, which each lasted between 2 and 4 hours.

Data analysis

Consistent with the data analysis procedures prescribed in McCutcheon and Meredith [115], the analysis in this study was conducted in two phases. Firstly, all the data in the field notes was distilled into a more concise and understandable form. The field notes were organised in two classes: *information available for operational control*, and *operational control at the case company*. Analysis of these two classes resulted in further categorisation for each class. The information available for operational control was categorised by information from computer-based information systems and information from conventional methods, such as phone calls and visual checks. The operational control at the case company was categorised by triggers for control, and control activities.

Secondly, logical analysis of the categorised data resulted in detailed descriptions of the information available at the case company and the structure and meaning of the information that is actually used for operational control. In line with the design science guidelines of Peffers et al. [142], the primary objective was to define the specific research problem and to justify the value of a potential solution. The research problem is formulated in terms of the challenges faced by the case company when utilising tracking technologies for operational control. These challenges were logically induced from the distilled field notes. Quotes of actors involved in the operational control activities were analysed to better understand potential causes for not utilising the available information. Perceptions and interpretations of researchers were discussed with the head of planning and during interviews with the management of the case company.

6.3.2 Artefact development

Design science proponents strongly recommend artefact development to take place within a scientifically rigorous environment (see e.g. [70, 142]). In response to the plea for rigour, Iivari [79] argues that transparency about the motivation and origin of the artefact development will increase to ability to value the rigorousness of the development. Iivari [79] suggests four sources of inspiration for the artefact development process that should be presented to make the origin more transparent: *practical problems and opportunities*, *existing artefacts*, *analogies and metaphors*, and *theories*.

Accordingly, the artefact developed is described in Section 6.5. Inspiration for the development process was foremost drawn from the opportunities and problems revealed during the problem identification at the case company. Existing information technology in the context of operational control was studied to ensure novelty and usefulness of the developed artefact.

During the development process, there was a strong emphasis on existing theories and methods, resulting in the selection and application of related application domain knowledge on intelligent products [116, 122].

6.3.3 Evaluation

A prototype system instantiating the design principles was developed and implemented at the case company. In line with methodological guidelines for design science research in information systems (see e.g. [70, 142]), the evaluation was performed at the same case company where the challenges were identified. A multi-method research approach [127] was adopted for the demonstration and evaluation of the developed artefact, comprising both experimental and observational evaluation methods. Experimental evaluation was conducted to demonstrate that the prototype is an appropriate instantiation of the design principles. Observational evaluation was conducted to examine the usefulness of the prototype at the case company. Finally, the evaluation results were used to reflect upon the validity of the developed artefact.

A collaborative research method [112] was adopted for the observational evaluation of the prototype at the case company. During this evaluation, events and observations were documented in field notes. The field notes include structured information about the output of the prototype, interpretations and thoughts of the collaborating researcher, as well as quotes of the IT manager, the planners, and the head of planning. The observational evaluation was performed in two phases. In the first phase, the collaborating researcher used the prototype during execution of operations. This phase lasted for one operational cycle of three days. In the second phase, two semi-structured interviews with the management of the case company were conducted, in which the evaluation results were verified and the implications for the case company were addressed.

6.4 Problem identification

This section provides the results of the case study that was performed to identify challenges faced when utilising tracking technologies for operational control. Although many aspects of the planning and control process were observed at the case company, this section is strongly focused on describing the process of operational control.

6.4.1 The case company

The case company ships temperature controlled, pallet-based products throughout Europe. Customer orders typically comprise a small number of pallets. In order to minimise the driving distance and maximise the effective use of truck capacity, the vast majority of pallets are grouped and cross-docked at a central warehouse. To transport the pallets, the case company owns 80 trucks and uses the capacity of another 20 trucks that are chartered from outside the organisation.

On-going transport operations frequently deviate from the plan due to unexpected events such as last-minute customer orders, truck break-downs, additional waiting times at pick-up or delivery locations, and traffic congestions. During the execution of the transport operations, a team of nine full-time planners performs operational control activities in order to respond to such unexpected events.

6.4.2 Information available for operational control

Three state-of-the-art information systems are in place at the case company with the purpose to capture, analyse and store information about the transport operations. An Enterprise Resource Planning (ERP) system is used to register and manage information on customer orders, including due dates, pick-up and delivery locations, and size of the orders. A vehicle tracking system, being the GPS-based tracking technology in place at the case company, provides detailed and real-time information on truck locations as well as information on the progress of operations in terms of pallet pick-up and delivery actions. Information provided by the ERP and the tracking system is automatically transferred to an Advanced Planning System (APS). The APS has a functionality to detect whether the actual progress of operations is according to plan. Moreover, the APS can automatically notify the planners in case of a delay in the execution of the planned operations.

Besides information from computer-based systems, it is observed that planners at the case company gather information about on-going transport operations through conventional methods, such as phone calls with customers and on-route truck drivers. Moreover, visual checks are performed to determine whether pallets have accidentally been left at the warehouse, and to determine whether trucks have arrived at or departed from the warehouse.

6.4.3 Operational control at the case company

Observations at the case company were focused on understanding the process of operational control, including the triggers for control and the actual control activities performed. It was observed that the planners get informed about unexpected events in three different ways:

- A notification by a truck driver through a phone call or text message, informing the planners for instance about a traffic congestion.
- A phone call from a customer, informing the planners for instance about a last-minute order or about a pallet that has not arrived on time.
- A manual browse through the information provided by tracking technologies, detecting for instance additional waiting time at pick-up or delivery locations.

After being triggered, planners typically perform five subsequent control activities:

1. Confirm the existence of an unexpected event.
2. Evaluate the impact of that event on the ability to continue the execution of operations as planned.
3. Investigate potential control decisions.

4. Decide which control decision will be taken.
5. Inform the relevant stakeholders about this.

It was observed that during each of the five control activities, the situation at hand is typically discussed internally among planners. Moreover, planners often manually analyse the information provided by tracking technologies. In case customers are potentially affected by a control decision, they are contacted to negotiate the possibilities for alternative pick-up or delivery times.

6.4.4 Using tracking technologies for operational control

Observations at the case company revealed a limited utilisation of the information provided by tracking technologies for performing operational control. To begin with, it was observed that the APS functionality to automatically notify planners about delays through pop-up messages was disabled.

- ➟ *IT manager*: "Subsequent to the APS implementation, the notification functionality was enabled for some time. At that time, the planners complained about the sheer number of notifications. Moreover, they argued that the vast majority of these notifications did not reflect the real situation of on-going transport operations. As we did not manage to overcome this issue, we decided to disable the notification functionality."

Examinations on the APS and available user manuals as well as interviews with the IT manager, the planners, and the CEO were performed to better understand why the notification functionality was disabled. It became clear that in order to provide notifications, the APS compares the information provided by tracking technologies with transport plans. During creation of these plan, the APS automatically generates plan details based on many transport constraints that are set in the APS.

- ➟ *Planner*: "The constraints are different for every customer, driver, and pallet. In case of a truck delay, it is actually often not a problem to arrive a little late at the next pick up or delivery location. However, some customers impose more strict arrival times than others."

- *Head of planning*: "The set of transport constraints is very large and constantly changing. It takes too much effort to continuously keep all the constraints up-to-date in the APS, and we already know most of these constraints by heart."

Observations confirmed that the set of transport constraints is present as tacit knowledge and are typically not made explicit in the APS. However, detailed understanding on the transport constraints is required for making informed control decisions.

The tracking technologies in place at the case company provide information about the on-going transport operations in much more detail and in higher volumes than the information provided by conventional tracking methods. When performing control activities, planners manually analyse the information provided by tracking technologies to assess the situation at hand. It is observed that the analysis of the information related to the delay of a single truck takes a considerable amount of their time.

- *Planner*: "In the case of a truck delay, I first seek to determine which parts of the operations are affected by that delay. Next, I aim to solve each of the potential problems with pick-up or delivery actions that cropped up due to the delay."

Due to the cross docking operations at the central warehouse, there are many complex relations between pick-up and delivery actions. Therefore, a delay of one truck may also affect pick-up and delivery actions of other trucks. A study on the availability of information on such relations showed that this information is available in the databases at the case company. However, it is observed that planners typically only focus on the impact of the unexpected event on the truck and its unfinished pick-up and delivery actions, due to the limited time available for making a control decision.

- *Head of planning*: "For control purposes, we use information about the truck with a delay, the pallets it is transporting, as well as the planned sequence of pick-up and delivery actions."

Further comparison between observations of control activities and a study of the case company's databases confirmed that much of the information stored in or created by the APS is not utilised by the planners.

6.4.5 Identified challenges

The tracking technologies in place at the case company provide detailed and real-time information about on-going transport operations. It was observed that planners at the case company hardly utilise this information for operational control, as manually browsing through all information for detecting unexpected events is unfeasible, due to the high amount of information provided by the tracking technologies. Hence, automatic analysis of the available information is required to detect unexpected events. However, the APS at the case company requires a high amount of transport constraints to correctly detect unexpected events. The planners consider setting all necessary constraints in the APS too time consuming. As a result, automatically analysing information provided by tracking technologies does not result in correct detection of unexpected events. Moreover, it was observed that the planners detecting unexpected events often only analyse a small subset of the related information for making a control decision, due to the limited time available.

In conclusion, the case study findings show that tracking technologies are hardly utilised for operational control, despite the fact that these technologies provide detailed information about on-going transport operations. Accordingly, three main challenges have been identified:

- *Challenge 1*: Manually browsing and analysing the high amount of information provided by tracking technologies is unfeasible.
- *Challenge 2*: Automatically analysing information provided by tracking technologies does not result in correct detection of unexpected events.
- *Challenge 3*: Analysing all information provided by tracking technologies related to an unexpected event for making an informed control decision is too time consuming.

The identified challenges confirm the need to demonstrate how tracking technologies can be utilised in an organisational context, as argued in Section 6.2.

6.5 Design principles

The previous section identified three main challenges in utilising tracking technologies for operational control in a transportation company. To overcome these challenges, a set of design principles for information system design is introduced in this section. The main goal of these principles is to support the development of information systems utilising the information provided by tracking technologies.

Out of the many available software architectures that may be considered appropriate to tackle the identified challenges, an architecture based on intelligent products [116] is considered the most appropriate for developing such a system. This is due to the fact that the intelligent products can represent physical objects, such as pallets, and the intelligent products are capable of autonomously performing some of the repetitive activities required for operational control. In this context, an intelligent product is defined as a physical and information-based representation of an object which has a unique identification, is capable of communicating effectively with its environment, can retain or store data about its status, has a language to display its features, and is capable of participating in or making decisions relevant to its own destiny [116].

In order to apply the intelligent products architecture for utilising the information provided by tracking technologies, a set of design principles is presented next. These design principles are introduced according to the three levels of intelligence for intelligent products as distinguished in Chapter 2: information handling, problem notification, and decision making.

6.5.1 Information handling

According to *Challenge 1*, manually browsing and analysing the high amount of information provided by tracking technologies is unfeasible. To utilise all the information provided by tracking technologies for operational control, the system should be able to handle this information. For this purpose, three design principles for the behaviour of intelligent products on the level of information handling are introduced next.

Before the intelligent products can analyse information about physical objects, information about these objects has to be made available. The basic assumption of this chapter is that existing tracking technologies are able to capture high amounts of detailed information on individual objects. Every intelligent product should be able to collect all information which is related to the physical object it is representing. Therefore, the first design principle is as follows:

➟ *Design principle 1*: Intelligent products should collect the available information of the objects they represent.

When all information of the physical objects is collected, every intelligent product should be able to freely add, change and remove information related to the object it is representing. For example, an intelligent product can add additional information, based on analysis of existing information. Therefore, the second design principle is as follows:

➟ *Design principle 2*: Intelligent products should be able to alter the information of the objects they represent.

As a result of the previous design principles, the amount of information related to the objects represented by intelligent products can be overwhelming. Representing all this information to the system users will therefore not overcome *Challenge 1*. Hence, the intelligent product should be able to determine which subset of the information will be represented to the system users. Therefore, the third design principle is as follows:

➟ *Design principle 3*: Intelligent products should be able to determine which information will be represented to the system users.

6.5.2 Problem notification

According to *Challenge 2*, automatically analysing information provided by tracking technologies does not result in correct detection of unexpected events. Therefore, the intelligent products should be able to detect problems for which operational control by the planners may be required, and notify the planners about them. For this purpose, three design principles for the behaviour of intelligent products on the level of problem notification are introduced next.

The system users should be able to train intelligent products by providing them the perceived status of the physical objects they represent. A perceived status indicates whether the physical object has a problem according to the system user. When such a perceived status is provided to an intelligent product, this intelligent product should generate a training instance based on the status and all the available information of the object it is representing. Therefore, the fourth design principle is as follows:

➟ *Design principle 4*: Intelligent products should allow training by the system users on the status of the objects they represent.

Providing sufficient training instances for each individual intelligent product would be unfeasible. Hence, training instances should be shared among all intelligent products representing the same type of object. For example, training instances should be shared among all intelligent products representing pallet objects. An intelligent product should be able to determine and update its status according to the training instances provided by the system users. The use of a machine learning classifier (see e.g. [129]) is proposed for providing the most appropriate status. Therefore, the fifth design principle is as follows:

➟ *Design principle 5*: Intelligent products should update their status according to the training by the system users.

The system users should be informed about the status of intelligent products. Hence, the system users should automatically be notified when important changes in the status of intelligent products occur, for example by means of emails or text messages. In this way, the system users are directly triggered about physical objects requiring operational control. Therefore, the sixth design principle is as follows:

➟ *Design principle 6*: Intelligent products should automatically notify the system users when important changes in their status occur.

6.5.3 Decision making

According to *Challenge 3*, analysing all information provided by tracking technologies related to an unexpected event for making an informed control decision is too time consuming. Therefore, it is important that the intelligent products are able to analyse the available information in such a way that planners can make a control decision in a shorter period of time. For this purpose, two design principles for the behaviour of intelligent products on the level of decision making are introduced next.

When intelligent products have a problematic status, they should be able to discover potential control decisions which solve or reduce the problem. This can for example be achieved by communicating and negotiating with other intelligent products in its environment. Therefore, the seventh design principle is as follows:

➟ *Design principle 7*: Intelligent products should discover potential control decisions when they have a problematic status.

The system users should be informed about potential control decisions. Hence, the system users should automatically be notified when potential control decisions are discovered, similarly as to the automatic notification of problems. In this way, users can directly determine whether the discovered control decision is suitable for solving or reducing the problem. Therefore, the eighth design principle is as follows:

➟ *Design principle* 8: Intelligent products should automatically notify the system users when potential control decisions are discovered.

6.6 Evaluation

As discussed in the methodology section, the proposed design principles have been instantiated and evaluated at the case company. First, this section describes how a prototype was developed based on the design principles. Next, this section presents the results of the experimental evaluation to demonstrate that the prototype is an appropriate instantiation of the design principles. Afterwards, the results of the observational evaluation examining the usefulness of the prototype at the case company are presented. Based on these evaluation results, a reflection is provided upon the validity of the design principles.

6.6.1 Prototype development

Based on the design principles, a prototype information system called Smart Objects System (SOS) was developed for evaluation at the case company. A detailed description of the more generic parts of the developed SOS prototype can be found in Appendix B on page 179. In order to build this prototype, the physical objects which require operational control due to unexpected events should be present in the prototype as intelligent products. Therefore, historical data sets of the case company were used to discover these relevant objects and their available data, which are:

- *Truck* objects, including data on the driver, the trailer, the pallets on board as well as its current and past locations.

- *Pallet* objects, including data on the source and destination location, plus the pick-up and delivery due date.

Information handling

For every truck and pallet object, an intelligent product is added to the prototype in order to represent this object and to collect all related information from the case company's databases. Moreover, every intelligent product will analyse and alter its collected information. For example, an intelligent product representing a pallet object will add information about its estimated delivery time, based on analysis of collected information about its current location, whether it is loaded in a truck, and what the distance to the delivery location is. Furthermore, the intelligent products are designed to only represent information required by the planner for operational control. For example, every intelligent product representing a truck object will only represent the plan it is involved in, together with the actual progress of operations. Figure 6.1 shows an example of how a truck object is represented in the SOS prototype, including a representation of the plan it is involved in and the actual progress.

Problem notification

The intelligent products will determine whether the object it is representing has a problematic status. For this purpose, the WEKA library [63] is used to provide the machine learning classifier. Although different classification algorithms provided by WEKA can be used, decision tree classifiers are applied for this prototype. An extensive discussion on the details of the classification algorithms is left outside the scope of this chapter. Planners can train the intelligent products to detect unexpected events which are perceived problematic. The intelligent products will notify the planners directly by means of email messages when unexpected events occur. An email message will be sent to the planners when for example a truck is delayed. Figure 6.2 shows an example of such an e-mail notification of the SOS prototype.

Decision making

The prototype supports the activities for finding potential control decisions by means of the intelligent products which are able to handle information and to notify planners about problems. However, the design principles related to decision making are not yet implemented in the prototype. Therefore, the conducted evaluations as described next mainly focus on information handling and problem notification.

6.6.2 Experimental evaluation

Two different kinds of experiments have been conducted. Firstly, it was evaluated whether the prototype is able to handle the information provided by the tracking technologies in place at the case company. Secondly, it was evaluated whether the prototype is able to perform the activities required for problem notification. The results of the experiments are presented next.

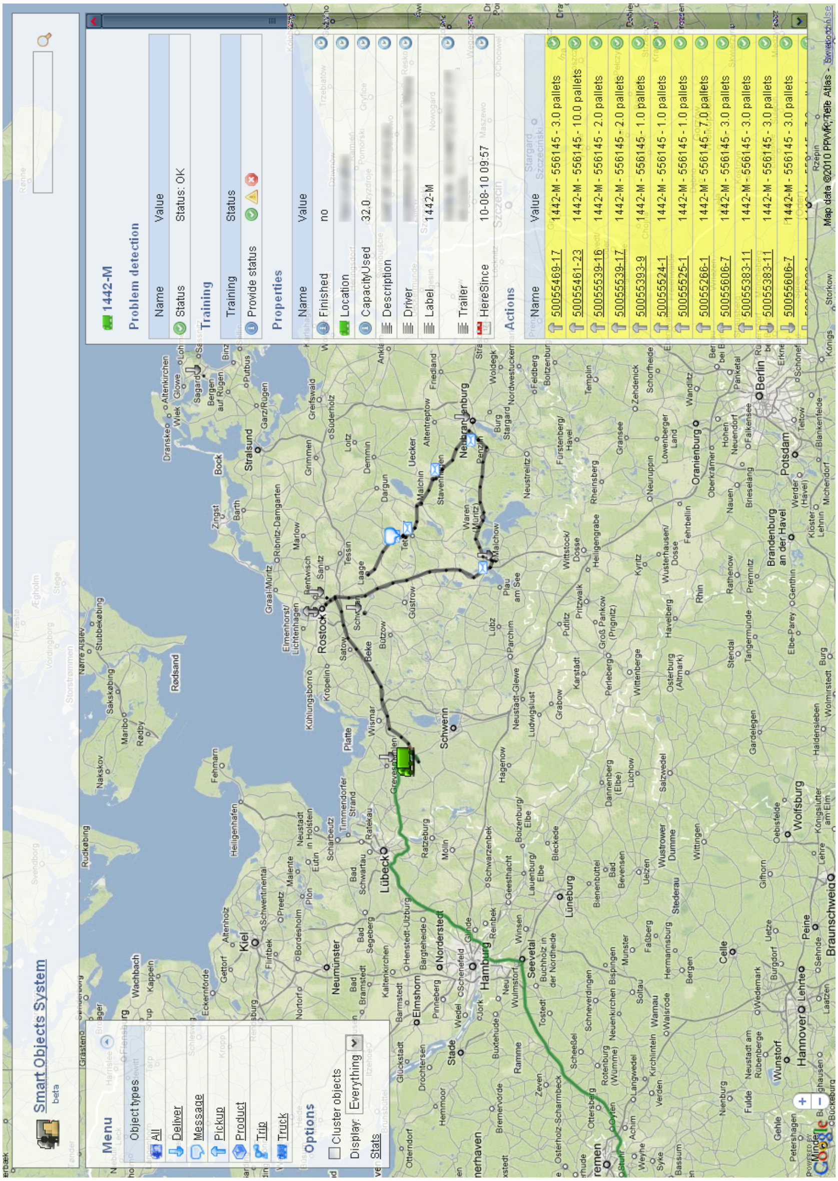


Figure 6.1: SOS representation of a truck object

New Issues

Code	Size	InTruck	Destination	Delay
50051503-25	7.0 pallets	1439-M		2.5 h
50051747-1	4.0 pallets	3133-M		0.2 h
50051802-2	5.0 pallets	1404-M		0.3 h

Existing Issues

Code	Size	InTruck	Destination	Delay
50051757-1	21.0 pallets	1413-M		0.6 h
50051802-4	2.0 pallets	1429-M		1.3 h
50051809-1	1.0 pallets	1440-M		2.2 h
50051834-10	3.0 pallets	1429-M		1.5 h
50051980-17	11.0 pallets	1416-M		3.3 h
50052103-1	33.0 pallets			6.5 h

Resolved Issues

Code	Size	InTruck	Destination	Delay
50051844-1	2.0 pallets	1431-M		0.0 h
50051891-1	5.0 pallets	1431-M		0.0 h
50051124-1	1.0 pallets			0.0 h
50051289-1	1.0 pallets			0.0 h
50051747-16	2.0 pallets			0.0 h
50051747-19	1.0 pallets			0.0 h
50051769-1	1.0 pallets			0.0 h

Figure 6.2: SOS e-mail notification

Information handling experiment

Information about approximately 10,000 truck and pallet objects has been captured from the databases of the case company and has been provided to the prototype. This amount of objects represents approximately three times the amount of objects which the prototype has to handle during the normal operational control process at the case company.

The experiment showed that every intelligent product was able to collect its related information from all the available information. Next to that, the experiment showed that all intelligent products were able to analyse and alter the information of the object they represent in real-time. Accordingly, the intelligent products were able to correctly add additional information, such as the estimated delivery time in case of intelligent products representing pallet objects. Finally, all intelligent products were able to correctly represent the required information to the system users, being the plan they are involved in, together with the actual progress of operations.

Problem notification experiment

In this experiment, the intelligent products were trained. Intelligent products representing pallets were trained based on their expected delay. In this context, the expected delay was defined as the estimated arrival time minus the planned arrival time. Only if the expected delay of the pallet was more than one hour, the intelligent product was trained to have a problematic status. Intelligent products representing trucks were trained based on the pallets they were transporting. Only if the truck was transporting a pallet with a problematic status, the intelligent product was trained to have a problematic status as well. Accordingly, fifty intelligent products representing pallets and fifty intelligent products representing trucks were trained.

The experiment showed that the intelligent products were able to determine their status correctly in real-time. Therefore, it was concluded that the intelligent products were sufficiently capable of learning whether their status is problematic. Moreover, all intelligent products were correctly notifying the system users when their status was changing to problematic.

6.6.3 Observational evaluation

The results of the two phases of observational evaluation are presented next.

Phase 1: Applying the prototype

In the first phase, a collaborating researcher used the prototype during execution of operations at the case company, and directly informed the head of planning about the notifications provided by the prototype. As illustrated by the following example, the prototype showed to be able to collect and analyse all available data required for detecting problems in time.

➟ *Example 1*: At 11 A.M., the prototype notified the collaborating researcher about an unexpected event. This notification was provided by an intelligent product representing a pallet with an expected delay of more than 1 hour. The pallet was planned to be delivered just before the closing time of a customer warehouse. According to the plan, the involved truck had to first deliver two other pallets before the problematic one. The prototype detected the problematic pallet delivery, notified the collaborating researcher, and provided the information that was required for understanding that specific problem. The head of planning mitigated the negative impact of the expected delay by directly changing the sequence of pallet deliveries for the involved truck. In case the problem would not have been detected in time, that sequence of deliveries would not have been changed. In that case, the specific pallet delivery would have to be postponed to the next day, which would also have affected other pallets on board.

Some problems that were detected by the prototype were not perceived as problematic by the head of the planning department, typically due to incorrect or incomplete information in the databases of the case company. Due to the representation of information provided by the prototype, the collaborating researcher could often directly determine whether a detected problem was based on incorrect or incomplete information, as is illustrated by the following example:

➟ *Example 2*: At 9 A.M., the collaborating researcher was notified about a problem detected by the prototype. A product had to be delivered before 6 P.M. on the previous day. Because all related information on the particular product is presented in a comprehensive way, the collaborating researcher directly observed that the product would actually be delivered before 6 P.M. on the present day. Therefore, the collaborating researcher concluded that the delay of 15 hours was due to a changed sequence of deliveries by a planner. However, as the planner did not change the delivery due date of the pallet in the existing information systems, the detection was based on incorrect information.

In total, the prototype notified the collaborating researcher 13 times about problems during the evaluation period at the case company. Out of the 13 notifications, in 4 cases informing the planners led to direct action by the planners to mitigate the severity of the problem, such as is the case in example 1. In 9 out of the 13 cases, the detection was based on incorrect information, such as is the case in example 2, and the notification led to planners changing the incorrect information. However, from a system perspective, the problem notification was correct in all cases, as the prototype is dependent on the provided information.

Phase 2: Discussions with the management

In phase two, discussions with the management have been conducted. Both the head of planning and the CEO articulated that an information system introduced for the support of their operational control activities, should, in the first place, be able to select and represent relevant information from the mass amount of information provided by tracking technologies.

➟ *Head of planning*: "Providing relevant information is the most important functionality for an information system supporting operational control. Based on such information, we can more easily make an informed control decision ourselves. The prototype appears to be useful for providing such information."

In contrast to the APS in place at the case company, the prototype is not designed to automate the operational control. On the contrary, the prototype is designed to support the planners, by providing relevant information needed for performing their control activities. Moreover, the notifications generated by the prototype were often triggering control activities.

➟ *Head of planning*: "Several notifications resulted in immediate phone calls to customers, negotiating the possibilities to change arrival times of pallets."

The management responded highly positive and was willing to take further steps in the implementation of the prototype, as they confirmed the positive influence of prototype on their operational control.

➟ *CEO*: "One major advantage of the prototype over our existing information systems is that, for detecting delays, the prototype requires a relatively limited information input from the planners. This would simplify the adoption of the prototype system."

6.6.4 Reflection upon design principles

Next, a reflection upon the design principles is provided by analysing to what extent the principles enable the development of an information system which overcomes the challenges identified at the case company.

According to *Challenge 1*, manually browsing and analysing the high amount of information provided by tracking technologies is unfeasible. In order to overcome this challenge, design principles 1, 2, and 3 postulate that intelligent products should be able to collect, alter, and represent information of the physical objects they represent. The experimental evaluation showed that the behaviour of the intelligent products in the prototype was according to these design principles. Moreover, the observational evaluation showed that the prototype allowed the case company to better utilise the information provided by tracking technologies, which enabled a better understanding about the impact of unexpected delays. Therefore, it can be concluded that the design principles 1, 2, and 3 enable the development of an information system which overcomes *Challenge 1* at the case company.

According to *Challenge 2*, automatically analysing information provided by tracking technologies does not result in correct detection of unexpected events. In order to overcome this challenge, design principles 4, 5, and 6 postulate that intelligent products should allow to be trained, update their status, and notify system users when their status is changing to problematic. The experimental evaluation showed that the behaviour of the intelligent products in the prototype was according to these design principles. Moreover, the observational evaluation showed that the prototype was able to notify the planners about several problems which were not yet observed by them, but nevertheless required immediate control decisions. Therefore, it can be concluded that the design principles 4, 5, and 6 enable the development of an information system which overcomes *Challenge 2* at the case company.

According to *Challenge 3*, analysing all information provided by tracking technologies related to an unexpected event for making an informed control decision is too time consuming. In order to overcome this challenge, design principles 7 and 8 postulate that intelligent products should discover potential control decisions and notify the system users. Although these design principles were not implemented in the prototype, the observational evaluation showed that the prototype assisted in solving the problems, by representing the information from tracking technologies in a comprehensive way. Hence, the developed prototype contributed in overcoming *Challenge 3* at the case company.

6.7 Conclusions

In this chapter, the following has been concluded:

- There are no comprehensive studies that demonstrate how tracking technologies can be utilised in order to achieve improved operational performance in an organisational context.
- An in-depth case study at a transportation company showed that available tracking technologies are hardly utilised for operational monitoring and control, for which three challenges have been identified.
- Eight design principles have been proposed, which prescribe how intelligent products can be applied for supporting operational monitoring and control activities of transportation companies

- Based on these design principles, a prototype system called SOS was developed for evaluation at the case company.

- Experimental and observational evaluation results showed that applying intelligent products as prescribed by the design principles contributes in better utilising tracking technologies for operational monitoring and control.

Part IV

Discussion

Chapter 7

Summary and Discussion

7.1 Research findings and contributions

The main purpose of this thesis was to investigate how intelligent products can be applied to improve everyday monitoring and control activities of organisations. For this purpose, several IT artefacts based on the concept of intelligent products have been developed and evaluated. The extensive survey on intelligent products presented in Chapter 2 distinguishes three levels of intelligence for intelligent products: information handling, problem notification, and decision making. Based on these levels of intelligence, Tables 7.1 and 7.2 present overviews of the research contributions presented in this thesis in terms of system development and system evaluation respectively, as well as in which chapter that specific topic was discussed.

Table 7.1: Contribution overview in terms of system development

Intelligent Products	Information Handling	Problem Notification	Decision Making
System architecture	Chapter 3 & 5	Chapter 3 & 5	Chapter 3 & 5
System prototype	Chapter 6	Chapter 6	Chapter 4

Table 7.2: Contribution overview in terms of system evaluation

Intelligent Products	Information Handling	Problem Notification	Decision Making
Descriptive evaluation	Chapter 5	Chapter 5	Chapter 5
Experimental evaluation	Chapter 6	Chapter 6	Chapter 4
Observational evaluation	Chapter 6	Chapter 6	

Intelligent products in production

In the context of production, Chapter 3 argued that centralised production planning and control systems have drawbacks concerning monitoring and control, when many small disturbances occur during plan execution. Therefore, a novel architecture for production monitoring and control system enabled by intelligent products was proposed in that chapter. In case disturbances occur, the intelligent products can directly investigate all available information, inform the planners if needed, and propose solutions to reduce the severity of the problems caused by the disturbance.

Chapter 4 presented a prototype implementation of this production monitoring and control system based on the intelligent products concept, which was evaluated with the TAC SCM simulation framework. The performed simulations showed that the proposed production monitoring and control system is very effective in handling disturbances in the simulated scenario. Therefore, intelligent products showed to be very promising for monitoring and control purposes, when robustness is considered as an important factor.

Intelligent products in transportation

In the context of transportation, Chapter 5 argued that planners in road freight transportation have difficulties dealing with disturbances, due to often being informed too late and not having the required information available. Therefore, a novel system architecture for monitoring and control of road freight transportation enabled by intelligent products was proposed in that chapter. Again, these intelligent products can monitor individual products locally and in real-time, notify planners about disturbances, and collaboratively propose solutions to them. The evaluation of the proposed architecture in Chapter 5 has shown that the system will provide the usability level as required by the system users.

Chapter 6 presented an in-depth case study performed at a road freight transportation company with advanced tracking technologies in place. Despite the fact that the available tracking technologies are able to capture high amounts of information on the state of ongoing operations, it was observed that this information is rarely utilised for monitoring and control of operations. This is mainly due to the fact that the planners face difficulties in analysing the high amount of available information. Therefore, the planners typically rely on manual checks of the state of operations, leaving the available information provided by tracking technologies unused. In order to enable better utilisation of the available tracking technologies, Chapter 6 presented a set of design principles, which prescribe how intelligent products can be applied for supporting operational monitoring and control activities of transportation companies. Based on these design principles, a prototype system called SOS was developed for evaluation at the case company. Both experimental and observational evaluation results showed that applying intelligent products as prescribed by these design principles contributes in better utilising tracking technologies for operational monitoring and control.

Effective monitoring and control with intelligent products

Overall, this thesis argues that monitoring and control is an highly important and underexposed academic field, in which many issues exist which hamper further progress. In order to contribute in solving these issues, this thesis presented how intelligent products can be applied for designing and implementing novel monitoring and control systems. For this purpose, two highly similar system architectures showed how intelligent products can be applied in both a production and a transportation context. Furthermore, various evaluations have confirmed that applying intelligent products in these ways indeed result in more effective and robust monitoring and control of operations.

7.2 Discussion and future work

7.2.1 Centralised versus distributed

Centralised planning

A centralised planning system supports human planners to define an optimistic planning. Such centralised systems are justifiable, especially when the focus is on classical performance indicators such as overall profit, utilisation of resources, or service levels. The simulation results of Chapter 4 also justify centralised planning, as all the manufacturers using conventional approaches saw higher average profits than the proposed approach based on intelligent products. This is not surprising: a central algorithm can always calculate the optimal solution in a closed and fully modelled world. In contrast, distributed planning systems are normally not only myopic but also greedy, and therefore suboptimal, which leads to a lower performance in terms of profit.

Distributed control

During the execution of a plan, disturbances can occur that require proper monitoring and control. In this perspective, a centralised system typically has three weaknesses. First of all, centralised systems tend to detect disturbances relatively slowly, due to the hierarchical distance to the actual disturbance. Secondly, centralised systems typically occurs with aggregated data, which leaves problems related to individual products undetected. Finally, due to being informed too late and not having the required information, it is virtually impossible to provide solutions to local disturbances in a timely and effective fashion.

In contrast to centralised systems, intelligent products showed to be a very promising distributed approach towards monitoring and control during plan execution. The simulation results presented in this Chapter 4 showed that the intelligent products approach is very robust in terms of handling disturbances. Similarly, the results of Chapter 6 showed that monitoring and control activities can be improved by applying intelligent products for better utilising available tracking technologies. This is due to the fact that individual products are monitored in real-time by intelligent products, which apply local data, as opposed to aggregated data. Furthermore, these intelligent products can notify planners about disturbances, and can collaboratively propose solutions to them. This enables planners to handle disturbances more effectively. Overall, this leads to a more robust global plan execution, by detecting and solving problems locally.

The best of both worlds

A central system is considered to be always better in terms of creating an optimal plan. However, an intelligent products approach seems to be more promising for effective monitoring and control in order to increase robustness of the plan execution. As such, the "ideal" planning and control system should combine the best of these two worlds. On this basis, future work should be focused on investigating how planning and control systems can be improved by combining a centralised planning approach with a distributed monitoring and control approach through the use of intelligent products.

7.2.2 Evaluation methods

Experimental versus observational

In this thesis, both experimental and observational evaluation methods have been applied. Although the experimental results of Chapter 4 are promising, the full potential of intelligent products can better be observed in reality. In general, even if a simulated environment reflects disturbances in a realistic way, the simulation still only contains modelled versions of these disturbances. Once a modelled environment including its disturbances is fully specified, a centralised approach to optimisation will always outperform a distributed approach since it is theoretically always possible to calculate an optimal solution within a specific model.

As such, the claimed advantages of resolving disturbances locally rather than centrally needs to be validated beyond a simulated environment. Although simulation is a valid method for investigating the feasibility of planning and control approaches, observational evaluation such as presented in Chapter 6 better demonstrates the benefits of intelligent products. This is due to the fact that in real-life, situations can always occur which are beyond the scope of specified models. Accordingly, many authors argue that research in Operations Management should have more emphasis on empirical case studies (see e.g. [10, 32, 120, 189]). Therefore, future work should mainly focus on how intelligent products can be applied in various real-life scenarios. This thesis adds an early contribution to evaluating intelligent products in real-life scenarios.

Observational evaluation with SOS

The developed SOS prototype, as described in Chapter 6 and in Appendix B, showed to be a suitable approach for applying intelligent products in a real-life scenario. However, three main limitations can be identified with respect to the observational evaluation of the SOS prototype as described in Chapter 6. Firstly, a collaborating role for the researcher was created due to the request of the management to disturb operations at the case company as little as possible. As only the collaborating researcher was using the prototype, certain feedback from the planners about the prototype might not have been better taken into account. Secondly, the evaluation conducted was mainly focused on applying intelligent products for information handling and problem notification. Additional focus on decision making could have led to more complete evaluation results. Hence, future work should focus on developing and evaluating more advanced decision making techniques, for instance as an extension of the current SOS prototype, which can support planners in making control decisions for effective tackling the consequences of disturbances. Finally, the SOS prototype is only evaluated at a single case company. Therefore, while the study performed provide insights in challenges and solutions with respect to applying intelligent products for better utilising tracking technologies, the generalisability of these insights is yet to be confirmed. However, due to the generic SOS prototype as described in Appendix B, other transportation companies facing similar challenges when utilising tracking technologies are likely to benefit from the system as well. Hence, future work should also focus on applying the system in other transportation companies, in order to increase the generalisability of the results. Moreover, exploratory research in other organisational domains could reveal similar challenges with utilising tracking technologies, for which a solution based on intelligent products may also apply.

7.2.3 The masses of information

Utilising information provided by tracking technologies

In Chapter 6, it was concluded that, despite the fact that tracking technologies are in place at the case company, the information provided by the tracking technologies is rarely utilised for monitoring and control of operations. One of the main reasons is that the information systems at the case company do not provide useful and required information automatically. On the contrary, the planners have to manually browse through the masses of available information if they want to use it for detecting unexpected events. As this is a very time consuming task, the planners mostly rely on manual checks of the state of operations, leaving most of the available information unused. In operations management literature focused on behavioural aspects of planning and scheduling, several authors observed similar issues with the availability of masses of information in decision making. For instance, Budihardjo [22] observed that computer-based support systems frequently fail to provide accurate and timely information for making planning decisions. Rushton et al. [149] discuss the significant human effort required to select useful information from different data sources.

Reducing information overload

Outside the context of operations management, the history of tracking technology implementation for the support of operational control shows an interesting trend. In the immediate wake of investing in the equivalents of tracking technologies (like sensor data collection), the human that was confronted with the information flow from such technologies suffered from an information overload effect. In response to that information overload, solutions were designed to transform the detailed information into information that is actually required for operational monitoring and control. In aviation, for instance, the cockpit design evolved from a very cluttered and attention burdening arrangement into the minimalist cockpits of today, where information provided by many sensors are aggregated and integrated into a single pilot-system interface that reduced workload and increased safety (see e.g. [82, 119, 128]). The current situation with tracking technologies in organisations calls for research to gain more understanding about the problems that arise from utilising the high amounts of information provided by such tracking technologies. Like in the historical case of cockpit design, systems that effectively aggregate and integrate the available information for operational control decisions in contexts such as production and transportation need to be designed. This thesis adds an early contribution to such system designs.

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Part V

Appendices

Appendix A

TAC SCM simulation results

The detailed TAC SCM simulation results are shown in Table A.1, A.2, and A.3 on the next page.

Table A.1: Percentage of orders finished in time

	$n = 0$		$n = 5$		$n = 10$	
Manufacturer	μ	σ	μ	σ	μ	σ
GRUNN	99.43	0.77	99.55	0.36	99.45	0.34
TacTex-07	99.50	0.51	98.20	1.35	97.80	1.50
PhantAgent-07	99.72	0.24	88.73	2.85	75.94	5.71
DeepMaize-07	98.62	1.09	97.00	2.06	96.01	3.79
Mertacor-08	95.25	3.98	90.81	7.86	89.85	8.04
Dummy	42.83	24.35	26.14	8.95	23.04	12.18

Table A.2: Profit in million dollars

	$n = 0$		$n = 5$		$n = 10$	
Manufacturer	μ	σ	μ	σ	μ	σ
GRUNN	-5.528	6.479	-8.028	3.969	-15.532	3.901
TacTex-07	16.093	7.859	13.405	3.723	5.691	5.244
PhantAgent-07	16.588	7.099	8.198	4.846	-6.904	4.220
DeepMaize-07	11.579	5.971	9.336	3.359	3.550	4.714
Mertacor-08	6.010	6.070	3.764	4.745	-3.675	5.272
Dummy	-10.210	15.066	-23.110	26.488	-21.562	17.139

Table A.3: Storage costs per accepted order in dollars

	$n = 0$		$n = 5$		$n = 10$	
Manufacturer	μ	σ	μ	σ	μ	σ
GRUNN	309	90	278	66	242	87
TacTex-07	347	69	384	52	326	66
PhantAgent-07	255	58	193	25	155	28
DeepMaize-07	235	39	254	42	228	40
Mertacor-08	256	61	263	33	220	46
Dummy	250	95	247	85	208	88

Appendix B

Smart Objects System

This chapter describes the generic framework of the Smart Objects System (SOS), which has been applied in the research as described in Chapter 6. The first main purpose of this framework is to enable applications which need to hold a high number of real-life objects including their properties. Such objects can be virtually anything, for example planes, trains, trucks, pallets, products, buildings, trees, animals, weather, tweets, etc. Next to that, it should be easy for the system users to investigate and analyse all these objects. In order to achieve this, the framework provides functionality to create a web interface, which enables the system users to easily browse and search through all the objects, as well as to visualise them on a world map.

The second main purpose of this framework is to provide the individual real-life objects with intelligence by means of software agents. The provided intelligence can be applied for problem notification. An agent representing an object can for example determine whether the object's current status is problematic or not, which can be useful for monitoring and control purposes. Moreover, the provided intelligence can be applied for decision making. An agent representing an object can communicate and negotiate with other agents, for example to discover opportunities on how problematic situations can be resolved. Therefore, besides the web interface, the framework also provides functionality to create e-mail notifications, which can pro-actively

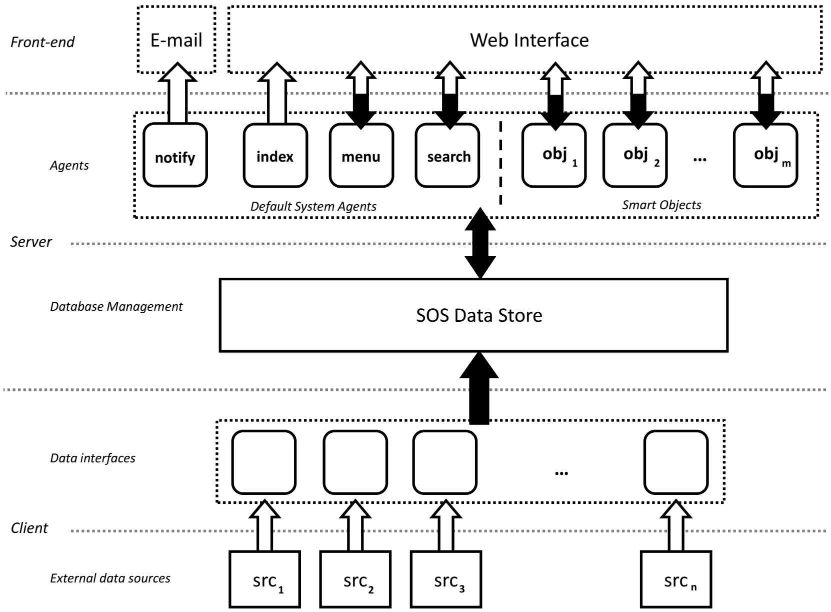

Figure B.1: System overview

inform the system users about objects with a problematic status as well as possible opportunities on how problematic situations can be resolved.

B.1 System overview

This section explains the overall system architecture of the SOS framework, which is shown in Figure B.1. Next, every layer as shown in the figure will be discussed in more detail. Examples of applications developed with this framework including their source code can be found on the SOS website[1].

B.1.1 Client

Every application build with the SOS framework needs data about real-life objects from one or more external data sources. For each of these external data sources, a data interface needs to be provided, which converts the

[1] http://code.google.com/p/smart-objects-system/

external data into objects with properties, in the way it is required by the SOS data store.

B.1.2 Server

The converted data provided from the external data sources are stored in the SOS data store. At this moment, every SOS application always has one data store, in which all objects with their properties are stored. For this purpose, a MySQL implementation of the SOS data store is provided.

For every object stored in the data store, the server is running an agent which adds intelligence to the object. In this way, an object with intelligence is created, a so called "Smart Object". Every agent can execute its own application specific behaviour, for example to determine whether its status is problematic or not. Besides the agents representing real-life objects, several default system agents are always present. The *index*, *menu*, and *search*-agent are responsible for generating the generic part of the web interface, and the *notify*-agent is responsible for generating e-mail notifications.

B.1.3 Front-end

The front-end of an SOS application consists of two parts, namely a web interface, and e-mail notifications. An example of how the web interface looks like can be found on page 132 in Chapter 6. An example of an e-mail notification is shown on page 133 of the same chapter. More examples can be found in Section B.4 on page 188 and on the SOS website.

B.2 System structure

This section contains an overview of the most important classes within the SOS framework and an explanation of their purposes. Figure B.2 shows the class diagram of the framework, divided in five parts, which are each discussed next.

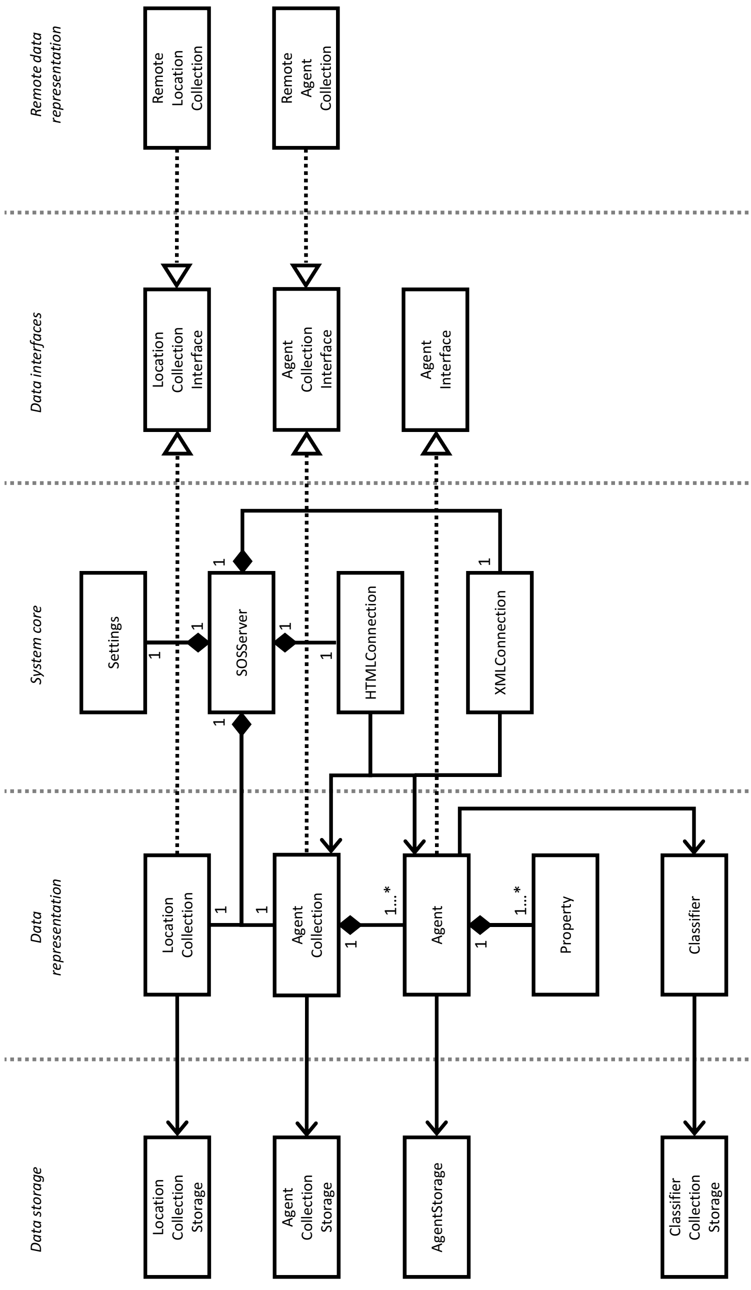

Figure B.2: System structure

B.2.1 System Core

This part of the system holds the core functionality and infrastructure.

SOSServer This abstract class is the starting point of the system. It reads the settings, starts the HTTP and XML listeners, adds the default agents and prepares several collection and storage objects which are used in the system. Also, an AgentsProcessor is created, which manages the execution of agents. Any implementing project has to extend this class, which has to be run in order to start the system.

Settings A class which reads the settings from an .ini file through the use of a Properties object. Predefined names of settings are defined in this class as static strings.

HTMLConnection The main purpose of the HTMLConnection is to provide the web-interface to the system users. It actually consists of two classes, HTTPListener and HTMLGenerator. HTTPListener listens for HTTP connections at a certain port. It handles requests and finds the right agents, instructing them to generate a HTML page through an HTMLGenerator object. This object provides several methods for adding elements to the HTML UI.

XMLConnection The main purpose of the XMLConnection is to enable data from external data sources to be added to the SOS data store. It actually consists of two classes, XMLListener and XMLClientConnection. XMLListener listens on a port for connections, creating a XMLClientConnection. XMLClientConnection handles the reception of commands from a client (which are serialised XMLServerCommands) and translates them to an action performed on the SOS data store.

B.2.2 Data Representation

These structures represent data objects within the system.

Agent An abstract class which acts as a base for all agents. An agent is constructed through its properties, for which the Agent class provides get and set methods. Different access levels are available through the use of interfaces and some common property names are defined as statics strings in the class. Methods for learning, execution and garbage collection are defined in this class. Additionally, generate methods are available which control the generation of the web interface. Any implementing project will have to extend the Agent class to provide its application specific behaviour and interface generation.

Property A Property is a basic data structure which defines a property of an agent. A number of different property types have been defined, such as text, number, time, and location.

AgentCollection An instance of this class is used to retrieve agents from a storage. It implements two interfaces (one through the other) to provide different levels of access. It also has a remote counterpart, to be used for creating data interfaces.

LocationCollection A collection of locations, uses a LocatonCollection-Storage to cache already known addresses and their geographical locations. It implements two interfaces (one through the other) to provide different levels of access. It also has a remote counterpart, to be used for creating data interfaces.

Classifier The Classifier object is responsible for the learning part of the application, and is used by agents to determine their status is problematic or not. For this purpose, it uses a storage to save training instances for each agent type as provided by the system users, which are needed for training the classifier. The WEKA library [63] is used to provide the machine learning classifier.

B.2.3 Remote Data Representation

These structures allow for information exchange between a client and server.

RemoteAgentCollection An extension of AgentCollection, which uses an XML communication with a running server to retrieve Agent objects. This class is to be used for creating data interfaces.

RemoteLocationCollection An extension of LocationCollection, which uses an XML communication with a running server to retrieve locations. This class is to be used for creating data interfaces..

B.2.4 Data Storage

This part of the system manages the storage of the before mentioned data structures. All default implementations utilise a MySQL database.

AgentStorage An implementation of this class provides the storage of individual agents and provides methods to manage and retrieve properties of those agents.

AgentCollectionStorage An implementation of this class provides the storage of a collection of agents. This includes some basic, commonly used properties of the agent.

LocationCollectionStorage An implementation of this class provides the storage for locations.

ClassifierCollectionStorage A collection storing all classifiers and training instances.

B.2.5 Data Interfaces

These interfaces are defined to provide two levels of access to the data structures: The Viewable interface provides reading ("getters") methods, while the Mutable interface allows mutation ("setters").

AgentInterface An interface for Agent. It defines methods the addition and retrieval of agent properties. It actually two interfaces, AgentViewable and AgentMutable, that must be implemented by a class to act as an Agent.

AgentCollectionInterface An interface for AgentCollection. It defines methods for agent addition and retrieval. It actually consists of two interfaces, AgentCollectionViewable and AgentCollectionMutable.

LocationCollectionInterface An interface for LocationCollection. It defines several methods for location retrieval and look-up. It actually consists of two interfaces, LocationCollectionViewable and LocationCollectionMutable.

B.3 System behaviour

This section explains the behaviour of the SOS framework in three different cases. These cases are: a data client adding a new agent, a system user requesting the web interface, and a system user training an agent. Each will be discussed next.

B.3.1 Data client adding a new agent

Figure B.3 shows a UML communication diagram, indicating the different steps and function calls between classes required when a data client is adding a new agent, which represents a real-life object.

B.3.2 System user requesting the web interface

Requesting the web interface consists of two separate HTTP requests, one for the content to be put on map, and one for content of the details pane. Figure B.4 shows two UML communication diagrams, indicating the different steps and function calls between classes required for these two HTTP requests.

B.3.3 System user training an agent

Training an agent whether its current status is problematic or not also happens through the web interface by means of an HTTP request. Figure B.5 shows a UML communication diagram, indicating the different steps and

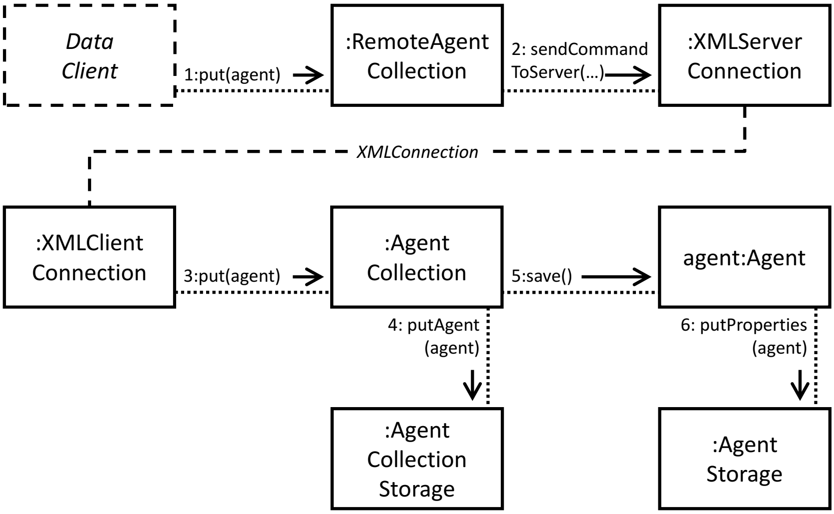

Figure B.3: System behaviour for adding a new agent

(a) Requesting the map content

(b) Requesting the details content

Figure B.4: System behaviour for requesting the web interface

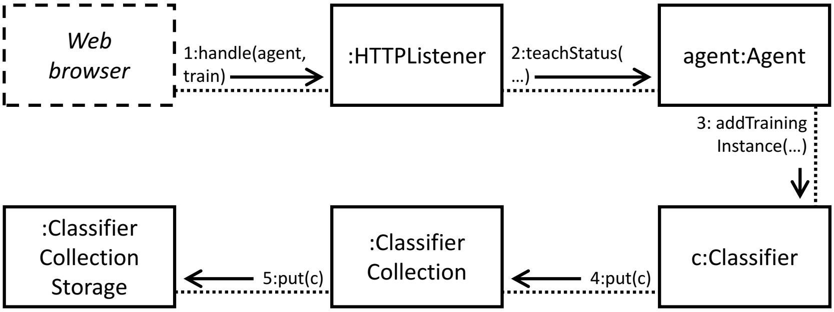

Figure B.5: System behaviour for training an agent

function calls between classes required for the HTTP request when training an agent.

B.4 Screenshots

In this section, some screenshots of demo applications are presented. Figure B.6 shows a screenshot of the Budapest Interactive City Map application. Figure B.7 shows a screenshot of the Dutch Weather Map application. More information on these applications can be found on the SOS website.

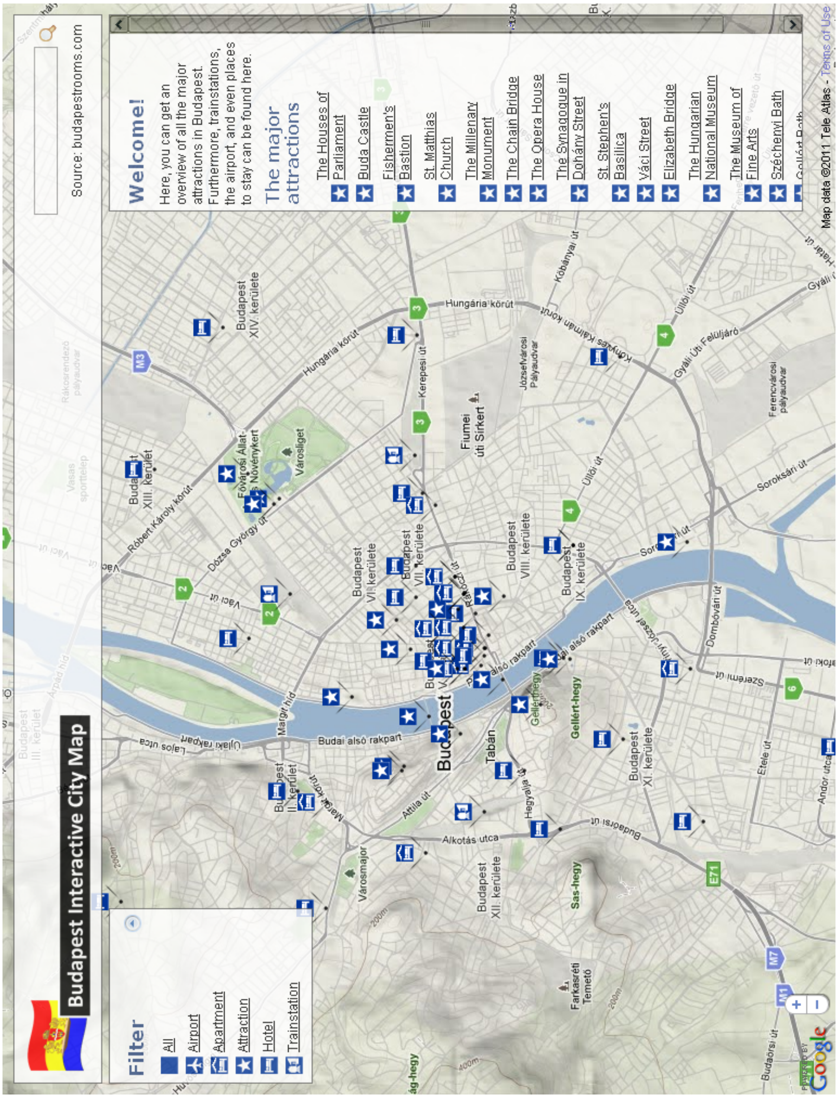

Figure B.6: Budapest Interactive City Map application

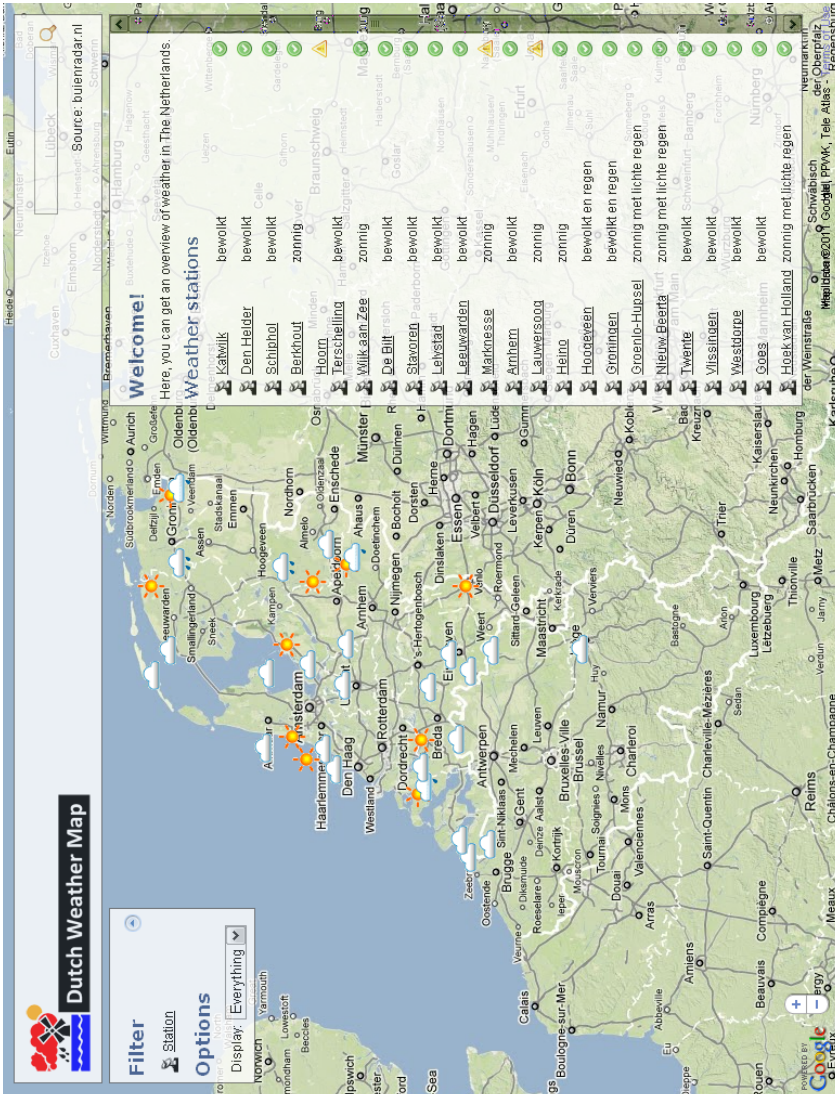

Figure B.7: Dutch Weather Map application

Nederlandse Samenvatting

Naast de operationele planning is voor veel organisaties de dagelijkse beheersing van de uitvoering van plannen eveneens belangrijk. De reden hiervoor is dat tijdens de uitvoering van een plan onvoorziene verstoringen kunnen plaatsvinden, hetgeen menselijk ingrijpen vaak noodzakelijk maakt. Veel organisaties hebben echter moeilijkheden met de beheersing van het operationele werk tijdens de planuitvoering, met als een van de belangrijkste redenen dat de planners tijdige en accurate informatie over de status van de planuitvoering missen. In hoofdstuk 1 zijn de moeilijkheden die zich voordoen bij de dagelijkse beheersing van de uitvoering van plannen geanalyseerd en onderverdeeld in drie categorieën, namelijk moeilijkheden in de beschikbaarheid van informatie, in het detecteren van verstoringen, en in het oplossen van de gevolgen van een verstoring. Het belangrijkste doel van dit proefschrift is om een bijdrage te leveren aan het oplossen van deze moeilijkheden. Daarbij wordt gericht op organisaties die fysieke goederen bewerken of transporteren. De oplossing wordt gezocht in het gebruik van zogenaamde intelligente producten.

Wat zijn intelligente producten?

Het concept achter intelligente producten, de technische grondslagen, en de haalbare praktische toepassingen van intelligente producten worden uitgebreid besproken in hoofdstuk 2. Een intelligent product wordt doorgaans gedefinieerd als de fysieke representatie van een product gecombineerd met een informatie-gebaseerde representatie van het product. Figuur 2.1 op pagina 21 toont een voorbeeld van een dergelijk product. In deze figuur is de pot spaghettisaus het fysieke product, wordt de informatie-gebaseerde representatie van het product in de database opgeslagen, en deze informatie wordt gebruikt door een intelligente softwarematige *agent*. Ondanks het feit dat er al meerdere definities van intelligente producten bestaan, toont hoofdstuk 2 aan dat er een uitgebreidere classificatie nodig is die betrekking heeft op alle aspecten van intelligente producten. De gepresenteerde indeling maakt daarom een onderscheid tussen drie onafhankelijke aspecten: wat is het niveau van de intelligentie van het product, waar bevindt zich de intelligentie, en wordt het product beheerd als zijnde een enkele entiteit of als zijnde een aggregatie van entiteiten.

Intelligente producten in productie

Gecentraliseerde *planning en control*-systemen hebben nadelen aangaande de beheersing van plannen in een productieomgeving, zoals betoogt wordt in hoofdstuk 3, wanneer er vele kleine verstoringen optreden tijdens de uitvoering van de productieplannen. Daarom wordt in dat hoofdstuk een nieuwe systeemarchitectuur voor de beheersing van productieplannen gepresenteerd, welke is gebaseerd op de toepassing van intelligente producten. Deze intelligente producten vormen een uitbreiding van individuele fysieke producten, waarmee elke verandering in status continu lokaal wordt geregistreerd. Wanneer een verstoring optreedt, kunnen intelligente producten de planners direct daarvan op de hoogte brengen. Verder kunnen ze gezamenlijk oplossingen voorstellen om de ernst van de problemen die worden veroorzaakt door de verstoring te beperken.

De implementatie van een prototype van het voorgestelde systeem voor de beheersing van productieplannen wordt gepresenteerd in hoofdstuk 4. Dit prototype is geëvalueerd met behulp van de bestaande en veelgebruikte *TAC SCM* simulatieomgeving, in welke de prestaties van verschillende *planning en control*-systemen binnen een productiescenario vergeleken kunnen worden. Uit de uitgevoerde simulaties is gebleken dat het voorgestelde systeem erg effectief is bij het aanpakken van verstoringen, aangezien ondanks verstoringen het voorgestelde systeem in vergelijking tot andere systemen het beste in staat was alle orders binnen de gestelde tijdslimieten af te ronden. Intelligente producten blijken daarom zeer veelbelovend te zijn voor toepassing in de beheersing van plannen, wanneer robuustheid wordt beschouwd als een belangrijke maatstaf.

Intelligente producten in transport

Planners die werken in de transportsector hebben vaak moeilijkheden met het omgaan met verstoringen, zoals betoogt wordt in hoofdstuk 5, als gevolg van het feit dat ze vaak te laat geïnformeerd zijn en niet over de vereiste informatie beschikken. Daarom wordt in dat hoofdstuk een nieuwe systeemarchitectuur voor de beheersing van plannen in een transportomgeving gepresenteerd, eveneens gebaseerd op de toepassing van intelligente producten. Deze intelligente producten kunnen individuele fysieke producten die worden getransporteerd lokaal en in realtime volgen, planners op de hoogte brengen van verstoringen, en gezamenlijk mogelijke oplossingen aan de planners voorstellen. De evaluatie van de voorgestelde architectuur in hoofdstuk 5 toont aan dat het systeem de bruikbaarheid zal bieden zoals vereist door de gebruikers van het systeem.

Hoofdstuk 6 presenteert een grondige *case* studie uitgevoerd bij een bedrijf gespecialiseerd in wegtransport en met geavanceerde *tracking*-technologie ter beschikking. Ondanks het feit dat de beschikbare tracking-technologie in staat is grote hoeveelheden informatie over de actuele stand van de planuitvoering te vergaren, werd waargenomen dat deze informatie zelden wordt gebruikt voor de beheersing van plannen. Dit is voornamelijk te wijten aan het feit dat de planners moeite hebben met het analyseren van al deze informatie. Daarom blijven de planners doorgaans afhankelijk van handmatige controles op de stand van zake, zoals bijvoorbeeld het bellen met chauffeurs, waardoor de beschikbare informatie grotendeels ongebruikt blijft. Om de aanwezige tracking-technologie beter te kunnen benutten, presenteert hoofdstuk 6 ontwerprichtlijnen welke voorschrijven hoe intelligente producten kunnen worden toegepast om de beheersing van plannen in transportbedrijven te ondersteunen. Voor evaluatiedoeleinden is een prototype gebaseerd op deze ontwerprichtlijnen ontwikkeld. Zowel uit experimentele als observationele evaluatie is gebleken dat de toepassing van intelligente producten volgens deze ontwerprichtlijnen bijdraagt aan het beter benutten van tracking-technologie voor de beheersing van plannen.

Effectieve beheersing van plannen met intelligente producten

Over het geheel genomen stelt dit proefschrift dat de beheersing van de uitvoering van plannen een zeer belangrijk en onderbelicht academisch veld is, waarin veel moeilijkheden de verdere vooruitgang belemmeren. Met als doel om bij te dragen in het oplossen van deze moeilijkheden, presenteert dit proefschrift hoe intelligente producten kunnen worden toegepast in zowel het ontwerpen als implementeren van nieuwe systemen voor de beheersing van plannen. Uit diverse uitgevoerde evaluaties is gebleken dat deze informatiesystemen gebaseerd op intelligente producten erg effectief zijn bij het aanpakken van verstoringen. Dit leidt tot meer effectieve beheersing en daardoor tot een meer robuuste uitvoering van plannen.

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Gerben G. Meyer
Effective Monitoring and Control with Intelligent Products

Monitoring and control of everyday operational plans is an important activity in many organisations. This is due to the fact that disturbances can occur during plan execution, which in turn often require human intervention. Many organisations however face difficulties with the monitoring and control of their operations during plan execution.

The main goal of this thesis is to provide a contribution in overcoming these difficulties. The focus is on organisations which are engaged in the transformation or transportation of physical goods. This thesis presents how intelligent products can be applied in both the design and the implementation of new information systems for monitoring and control. These intelligent products extend individual physical products, enabling local and real-time monitoring of products. When a disturbance occurs, the intelligent products can directly notify the planners and propose solutions on how to reduce the severity of problems caused by the disturbance.

Various performed evaluations show that intelligent products are very effective in handling disturbances. This leads to more effective monitoring and control of operations and thereby to a more robust plan execution.

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