An Analysis of Factors influencing Decentralization in the Context of RFID Systems in Manufacturing

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St. Gallen, May 19, 2009

The President:

Prof. Ernst Mohr, PhD
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Chris Kürschner
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<tr>
<td>Auto-ID</td>
<td>Automatic IDentification</td>
</tr>
<tr>
<td>BRIDGE</td>
<td>Building Radio frequency IDentification solutions for the Global Environment</td>
</tr>
<tr>
<td>Cm</td>
<td>Centimeter</td>
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<tr>
<td>CoBIs</td>
<td>Collaborative Business Items</td>
</tr>
<tr>
<td>DNA</td>
<td>Deoxyribonucleic Acid</td>
</tr>
<tr>
<td>EDI</td>
<td>Electronic Data Interchange</td>
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<tr>
<td>EPC</td>
<td>Electronic Product Code</td>
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<tr>
<td>EPCIS</td>
<td>Electronic Product Code Information Services</td>
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<tr>
<td>ERP</td>
<td>Enterprise Resource Planning</td>
</tr>
<tr>
<td>FEFO</td>
<td>First Expire First Out</td>
</tr>
<tr>
<td>GDSN</td>
<td>Global Data Synchronization Network</td>
</tr>
<tr>
<td>GHz</td>
<td>Gigahertz</td>
</tr>
<tr>
<td>GLN</td>
<td>Global Location Number</td>
</tr>
<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>GTIN</td>
<td>Global Trade Item Number</td>
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<tr>
<td>HF</td>
<td>High Frequency</td>
</tr>
<tr>
<td>IBC</td>
<td>Intermediate Bulk Container</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>JIS</td>
<td>Just-in-Sequence</td>
</tr>
<tr>
<td>JIT</td>
<td>Just-in-Time</td>
</tr>
<tr>
<td>Kbit</td>
<td>Kilobit</td>
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<tr>
<td>Kg</td>
<td>Kilogram</td>
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<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>-----------</td>
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<tr>
<td>LF</td>
<td>Low Frequency</td>
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<tr>
<td>M</td>
<td>Meter</td>
</tr>
<tr>
<td>MES</td>
<td>Manufacturing Execution System</td>
</tr>
<tr>
<td>MHz</td>
<td>Megahertz</td>
</tr>
<tr>
<td>MIS</td>
<td>Management Information System</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology</td>
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<tr>
<td>M-Lab</td>
<td>Mobile and Ubiquitous Computing Lab</td>
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<td>Mm</td>
<td>Millimeter</td>
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<tr>
<td>NFC</td>
<td>Near Field Communication</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<tr>
<td>ONS</td>
<td>Object Name Service</td>
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<tr>
<td>PDA</td>
<td>Personal Digital Assistant</td>
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<td>PLC</td>
<td>Programmable Logic Control</td>
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<td>RFID</td>
<td>Radio Frequency Identification</td>
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<tr>
<td>SCM</td>
<td>Supply Chain Management</td>
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<tr>
<td>SMS</td>
<td>Short Message System</td>
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<tr>
<td>SOA</td>
<td>Service-Oriented Architecture</td>
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<td>SSCC</td>
<td>Serial Shipping Container Code</td>
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<tr>
<td>TAP</td>
<td>Tag Acquisition Processor</td>
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<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
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<tr>
<td>UWB</td>
<td>Ultra Wide Band</td>
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<tr>
<td>WAP</td>
<td>Wireless Application Protocol</td>
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Abstract

Of all the discussions in information technology, few have been as contradictory as that of information technology and (de)centralization. The ultimate goal has been to determine an appropriate arrangement for information technology resources such as hardware, software, communication equipment, data and people within organizations. With the advent of ubiquitous computing technologies, this long-standing debate has become revitalized. Thus, it was the aim of this dissertation to address this topic by investigating the impact of ubiquitous computing technologies and radio frequency identification technology in particular on the decentralization of data and functions in the manufacturing domain.

To answer the identified research question and its sub-questions, a qualitative research approach was used and eleven cases from seven different industries were investigated. In summary, the following steps went into this research: (1) describing ubiquitous computing applications in manufacturing, specifically those that use decentralized data and functions, (2) identifying the factors that have an influence on the distribution of data and functions in the information system architecture, (3) explaining how the different factors influence the information system architecture by comparing both the centralized and decentralized solution, (4) extracting cost components and benefits from the explanation and building an integrated cost-benefit model.

By analyzing the cases of ubiquitous computing applications in the manufacturing domain, six main factors could be identified as having an influence on the distribution of data and functions: (1) synchronization, (2) external data exchange, (3) security, (4) standardization, (5) flexibility and (6) response time. For each identified factor both the centralized and the decentralized solution was investigated, which resulted in the formulation of theses on the (de)centralization decision and in a cost-benefit model. Based on these findings, thirteen management implications were extracted to help practitioners with the decision of how to design a ubiquitous computing application.
I Introduction

The question of whether to decentralize or centralize is an interdisciplinary problem with contributions not only by economists, but also by researchers in political science, management, computer science, operations research and also information systems. With the advent of ubiquitous computing technologies, this long-standing debate is revitalized. Thus, it is the aim of this dissertation to address this topic by investigating the impact of ubiquitous computing technology and radio frequency identification (RFID) technology in particular on the decentralization of data and functions in manufacturing.

This chapter outlines the field of study, which will lead to the focus of the research problem as well as the research question and its sub-questions. This is followed by a presentation of the scope of the study and the theoretical foundation. After that, the research methodology is described and justified in detail. The chapter closes with a detailed structure of the thesis.¹

I.1 Problem statement

Of all discussions in information technology, few have been as contradictory as that of information technology and (de)centralization. The ultimate goal has been to determine an appropriate arrangement for information technology resources such as hardware, software, communication equipment, data and people within organizations.

There has been a steady flow of advice on how to deal with this question – usually prompted by new technological capabilities. The most common view is suggested by proponents of the ‘organizational fit’ concept. They argue that an organization should structure its information technology resources in accordance with its organizational structure; taking into account its decision-making structure, organizational size, managerial philosophy, etc.²

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¹ The primary focus in this thesis is set on RFID technology, which is the central technology of ubiquitous computing. However, in this paper the terms RFID application and ubiquitous computing application are used synonymously.
In general, the (de)centralization debate has tended towards examining trade-offs, in which the organizational advantages of centralized control, standardized operations and economies of scale have been balanced against individual user department requirements, responsiveness and flexibility. However, an appropriate answer to the (de)centralization issue has not been found yet and for information technology departments the dilemma of whether to centralize or decentralize remains a topic of interest. Additionally, with the advent of ubiquitous computing technology and its vision of smart objects equipped with digital logic, sensors and actuators, the complexity of the decision further increases. This is particularly due to the possibility of storing data and executing business logic on a large number of the objects themselves. This and their ability to interconnect significantly contribute to the problem of finding the appropriate level of (de)centralization.

Surprisingly though, most discussions on this issue in the field of ubiquitous computing are dominated by a centralized approach in which object-related data is stored in backend systems and is referenced and manipulated using a unique identification number that is retrieved from the tag. However, reasons for choosing the alternative, decentralized solution, which is distributing data and business logic or functions among objects, can be found in practice but is seldom taken into account in literature. For instance, a recent report shows that out of 128 surveyed respondents, 45 percent preferred centralized data storage and seven percent the decentralized alternative. However, for 48 percent of the respondents the parallel deployment is the ideal solution.

The availability of alternatives is both a blessing and a curse. It may take a long time for the developers to go through the options, understand them and make the best decision for a specific situation. In addition, the impact of bad or wrong decisions may result in severe problems in the future. Thus, it is necessary to establish a common understanding and to look beyond the traditional to the new and more complicated factors that make centralization versus decentralization such a persistent issue.

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4 In this thesis the term function refers to any kind of manipulating data, e.g. filtering, simple rules and business logic.
5 Strüker, Gille, & Faupel 2008
I.2 Research question and target groups

The previous section has shown that a detailed understanding of the (de)centralization of data and functions within ubiquitous computing systems is of high practical relevance and that so far the topic has not been systematically addressed from a scientific perspective. Therefore, it is necessary to further investigate this topic. In this section the research question and its sub-questions are presented. Additionally, the target groups and the benefits they can gain by the presented thesis are introduced.

Research question and sub-questions

This thesis aims at improving the understanding of the factors that determine the degree of decentralization in ubiquitous computing applications, especially in manufacturing. It investigates advantages and disadvantage of alternative solutions and discusses trade-offs that need to be considered when making a decision on the distribution of data and functions in the manufacturing domain. In addition, another goal of the thesis is to develop a cost-benefit model that can help information system developers and designers make proper decisions. For this, the following research question and its sub-questions are addressed:

**What is the appropriate degree of decentralization of data and functions in ubiquitous computing applications within the manufacturing domain?**

To be able to answer the main research question, it is necessary to break it down into several sub-questions which can be answered separately. The defined sub-questions will finally lead to the answers of the overall research question. In this thesis the following sub-questions will be addressed:

1. What are the factors influencing the distribution of data and functions?
2. When is the decentralized solution superior to the centralized solution?
3. What are the costs and benefits of a solution?
4. What recommendations can be given to practitioners?
Target groups

There are two target groups for this thesis. The first target group consists of practitioners. Regardless of the industry and how manufacturing is structured, companies continuously invest to improve efficiency and effectiveness. The ability to obtain and use accurate, timely, granular information based on ubiquitous computing technologies will have a direct impact on the success of these investments. Today, a number of case studies on how manufacturers actually use these technologies are available. However, existing practical publications that describe these applications often fail to provide the level of detail that companies require for a successful implementation.

Manufacturers that gain this understanding on the opportunities and challenges of ubiquitous computing application deployment, and then approach it with a sound plan and realistic expectations, will be best equipped to meet their internal and external requirements. Therefore, the thesis seeks to improve the practical understanding for practitioners who are responsible for the application design as well as software vendors in the manufacturing domain by providing:

- Technological, organizational, operational and economic factors that need to be considered when designing ubiquitous computing applications.
- A description explaining the impact of the identified factors on the degree of (de)centralization of data and functions in ubiquitous computing applications.
- Managerial guidelines regarding the (de)centralization of data and functions in ubiquitous computing applications.

The second target group involves researchers. The research results are expected to offer a supplementary view to the existing research on (de)centralization in ubiquitous computing in particular and in information systems in general. Since the question on whether to centralize or decentralize has emerged as an important issue in ubiquitous computing, and has not yet been sufficiently addressed in existing literature, the research aims at closing this research gap. A framework will be developed that describes technological, organizational, operational and economic factors and their impact on the degree of (de)centralization of data and functions in ubiquitous computing applications in the manufacturing domain. The thesis will also contribute by closing the identified gap in complexity management. Finally, it can also be seen as a basis for a theory of decentralization.
I.3  Scope of the thesis

This thesis explicitly studies the (de)centralization issue in ubiquitous computing applications in manufacturing. To establish a common understanding of the terms ubiquitous computing technologies and (de)centralization, these terms are introduced and explained briefly in the following paragraphs. Furthermore, the motivation for choosing the manufacturing domain is discussed in brief. In addition, to establish a common understanding of ubiquitous computing applications in manufacturing, a short overview of existing and potential applications in this domain is given and illustrated by examples.

I.3.1  The concepts of centralization and decentralization

The long-standing debate on whether to centralize or decentralize has flourished for several decades not only in organizational and political science but also in the information technology community. The widespread discussion about this issue might suggest that there is a mutual consent about the concepts. However, a universally appropriate definition of the terms and their usage have not yet been found. For instance, in organizational science the terms are neither consistent nor operationally defined and various terms such as autonomy, responsibility and decision-making power are used for the same concept.6

Most conceptualizations of centralization and decentralization use the concept of distance, for instance, between different levels of hierarchy within an organization. In this context, Simon7 characterizes the basic relationship between decentralization and hierarchy as follows: “Hierarchy always implies intrinsically some measure of decentralization”. According to this, centralization versus decentralization refers to finding the proper location for actions within a hierarchical system. However, in some situations the hierarchical character is not quite clear. To establish a common understanding, we refer to the definition given by Schneeweiss8 – who defines a hierarchy as “a situation of at least two objects (levels) which exhibit some asymmetric relationship as to their decision rights or their superior information status”.

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6 Beuermann 1992
7 Simon 1965, pp. 103f.
8 Schneeweiss 2003, p. 7
Furthermore, most definitions of the term centralization in a literal sense can be interpreted as the concentration of an attribute or element within a center and the movement to the center respectively. Conversely, the term decentralization can be interpreted as the distribution of an attribute or element among several entities and the movement away from the center respectively. Against this background, there are two distinctive aspects to the concepts of centralization and decentralization within the ubiquitous computing domain – the location of data and functions as well as the communication of data:

- The question of (de)centralization concerns the location of data storage and the execution of manual or automated activities. In this respect, centralization implies storage and execution at a high level of hierarchy, for instance the storage of quality data or the performing of an analysis in an enterprise resource planning (ERP) system. Decentralization, in contrast, implies the storage and execution at a low level of hierarchy, for instance the storage of status data on a tag or the calculation of the average temperature based on sensor data on the tag.

- The question of (de)centralization comprises the timely communication of data. In this respect, centralization refers to the communication of distributed stored or generated data from the distributed entities, such as sensors, to a system located at a high level of hierarchy. Decentralization, on the other hand, refers to the communication of centrally stored or generated data to systems located at a low level of hierarchy. For instance, this information could be the next production step generated by a management execution system (MES), which is then assigned and communicated to an operator on the shop floor.

### I.3.2 Ubiquitous computing technologies

The vision of ubiquitous computing is to seamlessly connect the physical world with its representation in information systems. The following key elements have emerged as enablers of that vision and are referred to as ubiquitous computing technologies:

- **Automatic identification (Auto-ID) technologies**: In order for objects, locations, and people to usefully become part of a wider intelligent, information sharing

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9 Frese 2000, p. 88
10 Weiser 1991
network, it is vital that each item can be uniquely identified. Typical Auto-ID technologies include barcode, RFID, smart card, and biometric systems. Three types of RFID tags can be distinguished – active, semi-passive and passive tags. Whereas active and semi-passive tags use internal batteries to power their circuits, passive tags rely entirely on the reader as power source. Moreover, there are three storage possibilities – read-write, read-only and write-once-read-many.

- **Localization technologies**: In most of the cases, localization is combined with Auto-ID technologies.\(^{11}\) The ability of objects and people to have location information adds another important level of intelligence – location-based tools and services. Hereby, triangulation, scene analysis and proximity are the three principal techniques for automatic location-sensing. Location systems may use them individually or in combination.

- **Sensors**: Having an identity and location information enables a variety of applications and services. Adding a sensing capability can give systems eyes and ears, creating intelligent networks that can collect a range of environmental data. Different sensor types exist to monitor conditions such as temperature, pressure, humidity, sound, light intensity, speed, acceleration, levels of gas concentration, among others. Technical improvements influence the design of new sensors which are becoming smaller in size and consuming less energy.\(^{12}\)

- **Actuators**: In principle, an actuator performs the inverse action of a sensor. An actuator is a mechanical, pneumatic, hydraulic or electrical device that performs a mechanical motion, turns a device on / off or adjusts a device in response to an input signal. Example actuators include motors, lighting, panel screens and relays.\(^{13}\)

- **Communication technologies**: The ability for machines and people to communicate with other machines or people and share information is key in the ubiquitous computing vision. For that, not only mobile and portable devices such as mobile phones or Personal Digital Assistants (PDAs) are needed but also adequate communication systems and software infrastructures. Technologies

\(^{11}\) Hightower & Borriello 2001  
\(^{12}\) Matern 2005  
\(^{13}\) Matern 2005
such as Global System for Mobile Communications (GSM), Ultra Wide Band (UWB), Near Field Communication (NFC), Wireless Application Protocol (WAP), General Packet Radio Service (GPRS), Bluetooth, ZigBee and similar communication standards are the basis for new mobile devices that provide fast and immediate access to the Internet and information systems.\textsuperscript{14}

### I.3.3 Unit of analysis

As shown before, centralization versus decentralization refers to finding the proper location for actions and resources within a hierarchical system. As one of the best known hierarchical systems is the production planning and control system,\textsuperscript{15} ubiquitous computing applications in manufacturing seems to be a suitable subject for analysis.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{Hierarchy model of activities in manufacturing\textsuperscript{16}}
\end{figure}

\textsuperscript{14} Mattern 2005
\textsuperscript{15} Schneeweiss 2003, p. 12
\textsuperscript{16} adapted from ISA 1999
The information technology architecture of an enterprise involved in manufacturing is typically structured as follows.\textsuperscript{17} A physical factory is usually organized in a hierarchy of control modules with different responsibilities supported by information technology allocated to each level (see Figure 1). At the corporate level, software such as ERP and Supply Chain Management (SCM) systems provide a financial and management view into operations, suppliers and customers (level 4 in Figure 1). The goal of these systems is to perform long-term, strategic planning, to optimize the financial returns to the corporation and to manage the supply chain activities as efficiently as possible. The systems of the highest layer communicate orders down to the plant level module, e.g. the MES (level 3 in Figure 1). A MES provides functionalities for optimizing the use of internal manufacturing assets by effectively planning and scheduling the manufacturing operations. At the bottom of the hierarchy (level 1 and 2 in Figure 1) is the process layer with automation systems, which are responsible for machine control, production automation and equipment efficiency.

\textbf{I.3.4 Radio frequency identification applications for manufacturers}

The manufacturing industry faces a rapidly changing competitive environment worldwide. A major challenge for manufacturers is the need to accelerate the pace of innovation – not only in terms of products and services but also in relation to their business models. According to a study\textsuperscript{18} based on a survey of 4,018 executives worldwide, this environment will favor firms that put information technology to maximal use.

Consequently, manufacturers deploy different ubiquitous computing applications to cope with this situation. According to a recent study\textsuperscript{19}, out of eight areas, manufacturing accounts for the second largest number of RFID applications. Yet, the use of RFID in manufacturing is still in its early stage. For instance, Gartner Research\textsuperscript{20} estimates the market penetration of active RFID in manufacturing at five to 20 percent and of passive RFID at less than one percent of the target audience. However, according to two surveys, the deployment of ubiquitous technologies will

\textsuperscript{17} ISA 1999
\textsuperscript{18} EIU 2005
\textsuperscript{19} Strüker, Gille, & Faupel 2008
\textsuperscript{20} Brant et al. 2005
gain momentum in the future: one study\textsuperscript{21} found that only 22\% of 95 respondents have currently RFID applications installed and 80\% evaluate, plan or are in the process of installing such systems. A second report\textsuperscript{22} provides a similar picture. About 10\% of the 275 companies surveyed had already implemented RFID and about 58\% were in the process or were planning to implement RFID.

In the manufacturing domain, applications are implemented in three generic areas, including the inbound process for receiving raw material, the actual production process in which the raw material is transformed into products and the outbound process for shipping the products to distribution centers or customers. This section gives an overview of these applications\textsuperscript{23}:

- **Work-in-progress management**: For build-to-order production and sequencing, manufacturing processes rely on item-level tagging to ensure that the correct base components and raw materials are used. With ubiquitous computing technologies, manufacturers can track and record work-in-progress. Moreover, RFID provides an easy way to verify the use of the correct objects. Additionally, RFID data can be integrated with material handling and production-control systems. By doing so, items are more reliably routed to the appropriate assembly, testing or packaging locations.

  **Example**: Lawsgroup, a Chinese contract manufacturer that produces garments uses RFID technology to automate the tracking of work-in-progress (raw materials, semi-finished components and finished garments). Now, the system provides information on how many pieces are completed and which pieces of an order have reached a certain working station. It also enables the company to produce more garments and react more quickly to changes than before.\textsuperscript{24}

- **Receiving, shipping and picking processes**: When using RFID, pallets can be automatically read at the time deliveries arrive at the warehouse. This allows immediate verification of the contents of the load and real-time visibility to the backend systems. This increases productivity, enables faster invoice settlement, eliminates manual and thus error-prone, time-consuming handling, increases

\begin{itemize}
  \item \textsuperscript{21} ARC 2007
  \item \textsuperscript{22} McBeath 2006
  \item \textsuperscript{23} Bapat & Tinnell 2004; BearingPoint 2005; Lee et al. 2004; McBeath 2006
  \item \textsuperscript{24} O’Connor 2006b
\end{itemize}
inventory accuracy as well as leads to a reduction of inventory levels. Implementing RFID technology in a shipping process ensures proper and swifter shipment and enables the automatic validation of loading sequences for deliveries. In the end, this decreases shipping delays and improves customer satisfaction. Using RFID in a picking process provides faster identification and location of objects, allows emitting alerts when incorrect actions occur and thus eliminates extra time and costs for matching items.

**Example:** In 2004 Gardeur, a German clothing manufacturer, decided to deploy an RFID system to track garments from production to its warehouse using reusable tags. At that time, the company did not know how many products arrived at their warehouses and distribution centers, nor was Gardeur able to confirm that all goods from a production site actually arrived at their planned destinations. Moreover, when a delivery arrived, employees had to spend a lot of time counting and sorting the different product variants. Thus, using RFID manual work and shrinkage was reduced and the efficiency of the underlying processes was improved.\(^{25}\)

- **Asset management:** Firms have physical assets such as tools, returnable containers, machinery, material and other equipment required in the production and delivery of products and services. Knowing where an item is and what state it is in is crucial in a manufacturing process. Challenges faced by manufacturers include low asset productivity, low asset visibility, absence of unique identification as well as thefts and lost assets. By using RFID, companies are able to reduce or even overcome these problems.

**Example:** Nordam Group, an aerospace company that designs, certifies and manufactures integrated propulsion systems, thrust reversers and other aircraft parts, is using RFID to track high-cost molds, tools and parts. The RFID system helps reduce data entry errors, saves labor time and leads to lower expenses as experienced, high-paid technicians spend less time finding required tools. In addition, Nordam is now able to collect data for regulatory agencies.\(^{26}\)

\(^{25}\) Wessel 2006

\(^{26}\) Bachelodor 2006
• **Process control:** Besides its economic potential to optimize the efficiency of manufacturing processes, ubiquitous computing technologies can also improve the planning of logistics and production processes. These technologies have the potential to combine the efficiency of process automation with the flexibility of manual production; leading to complete transparency in manufacturing scenarios that have been hard to control previously. Applying these technologies enables real-time performance of essential functions within process control and quality systems such as identifying incoming products, providing operators with critical information, monitoring and controlling operations during processes, determining pass / fail statuses, moving products to subsequent processes and stopping further processing if products fail predefined quality limits.

**Example:** Like other companies in the semiconductor industry, Infineon Technologies seeks to increase automation in production logistics processes to reduce stock and to improve the efficiency of manual transportation processes. Thus, they developed a real-time identification and localization system. This system combines active and passive RFID tags as well as ultrasound sensors to track plastic wafer boxes and wafer cassettes in the company’s chip-manufacturing process. The implemented solution led to decreased lead times, increased machine utilization and made the entire production process visible and therefore controllable.27

• **Inventory management:** By attaching tags to containers and pallets that are stored in a warehouse, information can be collected when those items move through the facility. Thus, ubiquitous computing based automatic tracking systems can identify and keep track of all movements within a warehouse. The amount of idle inventory can be reduced and managers can be alerted to unscheduled movements that may indicate theft or other forms of shrinkage. Moreover, an RFID solution could potentially eliminate time and cost involved in manually counting stock by collecting the needed data automatically in real time.

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27 Thiesse, Fleisch, & Dierkes 2006
Example: Blommer Chocolate, a cocoa-processing company, implemented an inventory tracking system to improve inventory control and visibility. The project was initiated after the acceptance of the Bioterrorism Act, which requires food suppliers to track the custody and quality of raw materials and finished products in real-time. A system that tracked what ingredients went into each finished goods and which shipments were leaving the plant at what time was implemented. Consequently, the company was able to make its warehouse operations more accurate and efficient. As a side-effect, the company could speed up its loading process and now follows the first-expire-first-out (FEFO) model for ingredients, which means that the oldest ingredients are used first.\textsuperscript{28}

- **Replenishment:** Ubiquitous computing technologies can also be used to provide timely replenishment of materials used in production. These technologies have the potential to bring just-in-time (JIT) replenishment processes such as kanban to new levels of efficiency and responsiveness. Therefore, manufacturers are able to lower their material stocks and thus reduce their operating expenses without the need for reengineering the underlying process.

Example: DaimlerChrysler, one of the big German automakers, implemented RFID to increase visibility of parts in their production sites. In a proof-of-concept project, the company added passive tags to existing kanban parts-management cards. The results of the project showed an improvement of the flow of parts from the on-site storage areas to workstations at the production line. By using RFID the company is now able to track whether parts are in storage or being used on a production line. This increased visibility eliminates the need for labor-intensive and time-consuming annual stock counts. Moreover, by providing an accurate inventory, the automaker is able to automate part orders, requests and inquiries from the suppliers.\textsuperscript{29}

- **Machine monitoring and maintenance:** Machine failures are one of the most expensive forms of breakdowns on critical machines. To cope with this problem, condition-based monitoring systems gather shop floor information such as the state of the machine, flow rates and temperature by means of sensors. This information provides an early warning of abnormal behavior of machines and

\textsuperscript{28} O'Connor 2006

\textsuperscript{29} Collins 2006
processes. In addition, actuators can react to this information in real-time, potentially reducing the magnitude of damage. Furthermore, using diagnostics and predictive analysis software on that information extends the planning horizon for scheduling maintenance and allows prediction of parts failure. As a result, instead of planning with statistical overall average life of equipment, maintenance is performed according to the way it is actually used. In addition, RFID can uniquely identify equipment and store the service history, which is advantageous where personnel may not have access to a backend system. In summary, manufacturers are implementing ubiquitous computing technologies to increase shop floor efficiency, to optimize equipment performance, to reduce unplanned downtime and to cut maintenance costs.\textsuperscript{30}

Example: BP, one of the world’s largest oil companies, started with testing and evaluation of mote technology, a wireless networking technology. Motes can be used to tie sensors into wireless networks and to pass data to backend systems. Although the company intended to use this technology in its industrial production facilities around the world, a first project was conducted on an oil tanker because of its harsh testing conditions – high metal content, high temperature and significant vibration. Within the project a new predictive maintenance system was developed. This system is capable of monitoring critical rotating machinery, e.g. pumps and motors, using vibration data to evaluate operating conditions and wireless communication to send alerts. This data helps to predict when maintenance should be scheduled. As a result, the company could move from time-based maintenance to maintenance when actually required. Thus, the project produced an efficient automated data collection application for machine monitoring and predictive maintenance that eliminated a number of manual error-prone and inefficient processes used in the past.\textsuperscript{31}

- **Labor tracking, safety and security:** When worker badges are equipped with RFID tags that contain worker identification and authorizing data, there are three improvements feasible: first, workers can use their RFID badge to open secure doors, portals, cages, etc. In the end, this will improve security. Second, value added by certain individuals can be captured enabling performance measuring...

\textsuperscript{30} IBM 2006
\textsuperscript{31} Kevan 2006
and new compensation models. Third, attempts to utilize assets during the manufacturing process such as forklifts can be verified against the training record of the worker. By doing so, security can be improved, risk reduced, warranty optimized and legal requirements recorded.

**Example:** BP is piloting ubiquitous computing technologies in the area of health safety, security and environment. Some of their envisioned applications are attaching RFID tags to safety equipment for unique identification and documentation of regular inspections. Other applications include the use of active tags on personnel in order to locate people in the event of an emergency. By doing so the company is able to immediately identify whether someone is missing as well as to safely and efficiently evacuate employees. In another pilot at BP, business logic and data is stored on sensors which are directly attached to chemical drums. In this application, various scenarios are possible. For instance, if two drums filled with reactive chemicals are placed close to each other, an alert is sent to an employee who can then take corrective actions immediately.32

Figure 2 illustrates the example of an existing manufacturing process for confectionary, including the process steps in which RFID might be beneficial. In this process, unwrapped sweets arrive at the production lines where they are wrapped and poured into large containers prior to being committed to packing lines. Depending on the need of the packing lines, the full containers either go directly to packing or are brought to the cold store and kept there until needed on the packing lines. Additionally, containers can be in need of washing. The management of the containers includes knowing their location, their contents and the quality state of the contents. There is also a need to efficiently manage empty containers.

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32 Roberti 2006a
I.4 Theoretical foundation

As pointed out before, the advent of ubiquitous computing and its vision of a large number of smart objects able to interconnect significantly increases the problem of finding the proper location for data and functions within a hierarchical system. The question that arises is what theory can give advice on how to deal with this issue. Answering this question requires the identification of the relationship between a set of numerous interacting entities (vision of ubiquitous computing) and a hierarchical system (centralization versus decentralization). Looking at Simon’s\textsuperscript{33} classic discussion of hierarchy reveals a central theme that runs through his remarks – that complexity frequently takes the form of hierarchy. In this context, he defines a

\textsuperscript{33} Simon 1996, pp. 183-216
complex system as one made up of a large number of parts that have many interactions. Examples of such complex systems include economies, ant colonies, the human brain and companies.\textsuperscript{34} Against this background, it can be argued that ubiquitous computing applications can take the form of a complex system and therefore complexity theory and literature on complexity management should give relevant and applicable input on whether to centralize or decentralize in ubiquitous computing.

Based on findings by the Santa Fe Institute\textsuperscript{35}, Kelly\textsuperscript{36} derives nine principles for designing and managing complex, adaptive systems. Two principles relevant for this thesis are ‘distributed being’ and ‘control from bottom up’. According to these principles, ubiquitous computing systems should be designed so that data and business logic is distributed as widely as possible. However, in a later publication Kelly\textsuperscript{37} admits that although numerous small things connected together into a network generate tremendous power, this power will need some kind of minimal central governance to maximize its usefulness. This means that ubiquitous computing applications should still be designed in a way that maintains some centralized control.

Yet, these two principles are too general to be of particular practical impact. Kelly’s results neither allow drawing conclusions on the type and degree of this centralized control for ubiquitous computing applications, nor do they give quantitative measures with regard to complexity. Thus, based on complexity theory, it is not possible to give practical advice regarding the research question on the degree of (de)centralization of data and functions in ubiquitous computing applications in particular and information systems in general. Rather, with regard to complexity theory, further research is needed. Specifically, making statements on complexity requires an identification of the elements that are part of ubiquitous computing applications as well as their relationships.

\textsuperscript{34} Holland 1992, 1994, p. 185
\textsuperscript{35} www.santafe.edu
\textsuperscript{36} Kelly 1995, pp. 468-471
\textsuperscript{37} Kelly 1998, p. 18
I.5 Research approach

The subsequent sections aim at giving an overview of the research approach and methodology. First, the underlying research classification is outlined. This is followed by a description of the contextual framework, which serves as a simple map of the topic investigated. In addition, the research methods and components used are discussed. Finally, limitations and constraints of the research, which result from the research methodology, are presented.

I.5.1 Research classification

Various ideas of the notions ‘science’ and ‘scientific methods’ exist in the field of business administration. This research follows the tradition established by Ulrich and Krieg, Ulrich and Bleicher, who consider organizations as complex, open, social systems. As an applied social science, business administration research is obliged to remain in close contact with practice and contribute to solving real-world problems. Consequently, research questions are derived from practical challenges. The final goal of this kind of research is to generate normative conclusions and to provide guidance to decision makers within companies. Another important aspect is that theoretical concepts are seen as a tool rather than the goal of the research.

The motivation for this thesis derives from a practical challenge: although potential ubiquitous computing applications for manufactures are known, there is a lack of understanding on how to distribute data and functions within the information technology architecture for these applications. Yet, additional understanding is necessary before companies can decide on how to design the actual application according to their specific requirements, because the impact of bad or wrong decisions may lead to severe problems in the future.

In addition, the thesis aims at increasing the general knowledge on the centralization versus decentralization debate in the area of ubiquitous computing by suggesting a theoretical framework. Both researchers and practitioners may use this framework to get a better understanding of the impact of ubiquitous computing technologies in

38 Raffée 1995; Thommen & Achleitner 2003; Wöhe & Döring 2000
39 Ulrich & Krieg 1974
40 Ulrich 1981
41 Bleicher 1991
42 Bapat & Tinnell 2004; BearingPoint 2005; Lee et al. 2004; McBeath 2006
different contexts and to help improve the quality of recommendations and decisions on the question of whether to centralize or decentralize.

Figure 3: Exploratory research as an iterative learning process

Following Kubicek\textsuperscript{44}, Tomczak\textsuperscript{45} and Gassmann\textsuperscript{46}, the research process is considered to be highly iterative (see Figure 3). Instead of validating hypothesis derived solely from theory, the new knowledge is the result of asking tangible questions based on both practice and theory.\textsuperscript{47} The resulting image of reality created upon the initial framework and data collection is critically tested to reflect differentiation, abstraction and changes in perspective. The new theoretical understanding leads to additional questions which in turn clarify and sharpen the understanding of what’s real. Finally, at the time of writing a publication the research process must be frozen. At that stage all open questions have to be made explicit as part of the research results.

\textbf{I.5.2 Contextual framework}

Theory-building relies on a few general constructs that subsume a set of more specific ones. A conceptual framework explains the main dimensions to be studied and the relationship between them. It serves as a simple map of the issues

\textsuperscript{43} Gassmann 1997, p. 6, Kubicek 1977, p. 14, Tomczak 1992, p. 84
\textsuperscript{44} Kubicek 1977
\textsuperscript{45} Tomczak 1992
\textsuperscript{46} Gassmann 1997
\textsuperscript{47} Kubicek 1977
investigated.\textsuperscript{48} Outlining such a framework can help to understand the overall research approach and to decide what information should be collected and analyzed during the research process.

![Conceptual framework]

\textit{Figure 4: Conceptual framework}

The underlying framework is depicted in Figure 4. The starting point for the examination of the impact of ubiquitous computing technologies on centralization and decentralization is an analysis of applications in manufacturing using such technologies. These applications run on architectures which can be more centralized or decentralized depending on the specific application and contextual factors. The analysis of the different factors will lead to a number of advantages and disadvantages as well as certain trade-offs of the solutions. It can be performed by investigating a single factor and discussing both the centralized and decentralized solution. In the end, this will lead to a cost-benefit model that can serve as a basis for decision making regarding the design of a specific application. In summary, the following steps are required in this research:

1. Describing ubiquitous computing applications in manufacturing, preferably those that decentralize data and functions.

2. Identifying the factors that have an influence on the distribution of data and functions in the information system architecture.

3. Explaining how the different factors influence the information system architecture by comparing both the centralized and decentralized solution.

4. Extracting cost components and benefits from the explanation and building an integrated cost-benefit model.

\textsuperscript{48} Miles & Hubermann 1984, pp. 28-33
I.5.3 Research methodology and components

Answering the identified research question and its sub-questions is a complex and context-bound organizational and technical issue. Furthermore, the nature of the research questions can be described as explorative. Therefore, a qualitative research approach is applicable and used. Yet, while the study is qualitative due to its context, it is situated between deductive and inductive qualitative studies, being neither a check of an already developed theory nor a development of a completely new theory. Rather, it creates knowledge as well as extends existing theories through dialectic interaction between field studies and developed theories.

Figure 5 illustrates the research process, covering research components and results. The structure of the research process aims at maximizing external and internal validity. External validity, in the context of qualitative studies, refers to the extent of transferability of results. Internal validity is the approximate truth about cause-effect or causal relationships.

![Figure 5: Research process](image)

The motivation for this research project traces back to the data-on-tag versus data-on-network discussion and the question on the usefulness of the autonomous control concept. After the identification of these architectural or design challenges the process proceeded to the stage of problem definition. The aim of this stage was to

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49 Yin 2003
50 Strauss & Corbin 1998
51 Lincoln & Cuba 1985
identify a suitable scope for the research which finally resulted in the research question on the appropriate degree of (de)centralization of data and functions in ubiquitous computing applications in the manufacturing domain. In this early stage of research, exploration was needed to develop ideas and sub-questions. Consequently, besides literature reviews and project work, loosely structured exploratory interviews were conducted. Each selected interviewee was directly or indirectly involved in the design process of ubiquitous computing applications in manufacturing.

For the next stage, the research question was broken down into a number of sub-questions which were answered using case study research in a cyclic process. On the one hand, data collection was performed by interviews, group discussions, observation and literature review. On the other hand, data analysis was based on an explanation-building strategy using within and cross case analysis methods.

**Case study research**

According to Leonard-Barton\(^\text{52}\), a case study is a history of current or past phenomena drawn from multiple sources of evidence. The sources can be manifold, including data from direct observation and systematic interviewing but also from public and private archives. In this research project, case study research was applied because of three strengths of the method:\(^\text{53}\)

- **Relevance**: The phenomenon can be studied in its natural setting, which allows generating meaningful and relevant results from the understanding derived through observing actual practice.

- **Completeness**: A case method allows the questions ‘why, what and how’ to be answered with a reasonably full understanding of the nature and complexity of the phenomenon.

- **Area of application**: The case method is useful for early, exploratory investigations where the variables are still unknown and the phenomenon not yet completely understood.

\(^\text{52}\) Leonard-Barton 1990

\(^\text{53}\) Meredith 1998
The cases were selected in a way that a broad spectrum\textsuperscript{54} of both the manufacturing industry and the degree of (de)centralization in the design of the applications are addressed. The number of interviews and cases were increased and analyzed until theoretical saturation was reached.\textsuperscript{55}

Data collection throughout the research was primarily based on interviews and field research (see Table 1), including open-ended interviews, internal data (e.g. manufacturing processes) and physical observations (e.g. factory site visits) as well as academic and other publications (e.g. white papers, reports, presentations).

<table>
<thead>
<tr>
<th>Research context</th>
<th>Duration</th>
<th>Partners</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-Lab (Mobile and Ubiquitous Computing Lab)</td>
<td>11/2004-08/2006</td>
<td>SAP, Gillette, Migros, Deutsche Telekom</td>
<td>Projects on the business potential of ubiquitous computing technologies</td>
</tr>
<tr>
<td>EU Project BRIDGE (Building Radio frequency IDentification solutions for the Global Environment)</td>
<td>09/2006-08/2008</td>
<td>SAP, British Telecom, Nestlé, University of Cambridge</td>
<td>RFID in manufacturing, Discovery service design</td>
</tr>
<tr>
<td>SAP working group manufacturing</td>
<td>10/2006-12/2006</td>
<td>SAP, Humboldt University Berlin</td>
<td>RFID in manufacturing: case studies and recommendations on the manufacturing RFID strategy of SAP</td>
</tr>
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\textit{Table 1: Project environment of this thesis}

Yin\textsuperscript{56} proposes that before data can actually be analyzed, a researcher using case studies should choose from two general analytical strategies. The first strategy is to rely on theoretical propositions. This is the most common and advised strategy and

\textsuperscript{54} Yin 2003, p. 47  
\textsuperscript{55} Glaser & Strauss 1975  
\textsuperscript{56} Yin 2003, pp. 105-108
therefore the one used in this study. The result of this strategy is the collection of data based on research questions taken from previous studies. The findings are then compared with these previous studies. The second strategy is to develop a case description, which would be a framework for organizing the case study. This, however, is less favorable and should only be used when little previous research has been done.

For the analysis, an explanation-building strategy was used which is mainly relevant for exploratory case studies. Explanation-building is considered a form of pattern-matching, in which the analysis of the case study is carried out by building an explanation of the case. To explain a phenomenon means to stipulate a set of causal links about it. These links are similar to the independent variable and may be complex and difficult to measure in any precise manner. Using such a strategy, the researcher does not start out with a theory. Rather, the researcher attempts to induce theory from case examples chosen to represent diversity on some dependent variable. Explanation-building is an iterative process that begins with making an initial theoretical statement about a possible cause constructed through literature review. This is followed by comparing the finding of an initial case against the statement, revising the statement, comparing additional details of the cases against the revision, revising the statement again, comparing the revision to the facts of more cases and repeating this process as many times as is needed.

Basically, the within-case analysis of the data either verifies or falsifies previous research. Applying this approach to multiple cases results in the creation of a cross case analysis with the aim to identify similarities and differences among the cases. The evidence from multiple cases is often considered more compelling and the overall study is therefore regarded as being more robust. However, the explanation-building strategy is known to be a technique that is fraught with problems for the investigator. One of those problems is a loss of focus. Yet, keeping this fact in mind during the research protects the investigator from this problem.

A similar procedure has been commonly cited as part of a hypothesis-generating process in grounded theory literature. This concept originated in the work of the sociologists Glaser and Strauss. Glaser defines this approach as “a general

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57 Yin 2003, pp. 113-115
58 Glaser & Strauss 1975
59 Glaser 1992, p. 16
methodology of analysis linked with data collection that uses a systematically applied set of methods to generate an inductive theory about a substantive area”. The researcher starts with an open mindset, i.e. neither theories nor hypotheses are used as a basis for the investigations. The result of this approach is a theory\(^60\) that is developed inductively from a set of data coming from different sources.\(^61\) However, the goal of grounded theory technique is not to conclude a study but to develop ideas for further study making it necessary to use a slightly different approach in the present work.

I.5.4 Limitations and constraints

Conducting research concerning the centralization versus decentralization issue in the field of ubiquitous computing is not without risk. There are two issues of major relevance: first, although research in the field of ubiquitous computing constitutes an established research stream, a universally appropriate answer to the centralization versus decentralization debate has not yet been found. Second, there are a limited number of real-world ubiquitous computing applications in manufacturing which limits the number of potential data sources. The main argument for exploring the research question at this point in time is the high practical relevance of the topic.

There are three aspects that limit the risk of drawing false conclusions. Two refer to triangulation\(^62\) which is a method used by qualitative researchers to check and establish validity in their studies. The third one is the use of existing theories and concepts.

Data triangulation

Data triangulation involves the use of different sources of data and information.\(^63\) In this research, existing surveys on ubiquitous computing technologies in manufacturing, cases studies conducted by other researchers as well as face-to-face and telephone interviews are used. The interviews are based on a semi-structured interview guideline to ensure that the same areas of information are collected from each interviewee. Furthermore, this guided approach provides more focus than a

\(^{60}\) Punch 1998, p. 166


\(^{62}\) Denzin 1978, p. 291; Jick 1979; Yin 1994

\(^{63}\) Denzin 1978, p. 291; Jick 1979; Yin 1994
A conversational approach in which no pre-determined questions are asked – to remain as open and adaptable as possible to the interviewee's nature and priorities. Therefore, the guided approach allows a degree of freedom and adaptability in getting information from the interviewee.

**Theory triangulation**

Theory triangulation refers to the use of more than one theoretical position in interpreting data. The investigations are based on several paradigms, potentially from different research streams. The idea is to look for theoretical tensions or oppositions and use them to stimulate the development of more encompassing theories and hypothesis. In this research the underlying paradigms relate not only to ubiquitous computing research but also to information system research, distributed systems research, organization science research and research on hierarchical production planning and control systems.

**Relationship to theories and concepts**

The results of this research are derived from existing theories and concepts from various research streams as mentioned above. Consequently, a link is established between the findings of this work and previously conducted research. This not only provides further confidence in the findings but also offers opportunities for future research work, addressing the question whether to centralize or decentralize in different fields of research.

**I.6 Structure of the thesis**

This thesis is organized as follows, and as depicted in Figure 6: chapter I outlines the practical problem and the theoretical gap under investigation which leads to the underlying research question and its sub-questions. In addition, the scope of the study is presented and the applied research methodology is discussed.

To establish a comprehensive view on the centralization versus decentralization debate in the era of ubiquitous computing, it is necessary to look into related research streams and to use their findings as a basis for answering the research question. Hence, in chapter II related literature is introduced and reviewed –

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64 Gioia & Pitre 1990; Lewis & Grimes 1999
including information systems research literature on the various factors affecting the (de)centralization of information technology architecture, ubiquitous computing, distributed systems and organization science literature. In addition, as the focus is set on manufacturing, literature is reviewed in the field of production planning and control systems.

Chapter III aims at developing a descriptive model which describes, without evaluation, how ubiquitous computing technologies are actually implemented in manufacturing. Particularly, the focus is set on the decentralization of data and functions within these applications. The model is primarily derived from four in-depth cases and seven mini case studies from seven industries. Additionally, these

Figure 6: Structure of the thesis

Chapter III aims at developing a descriptive model which describes, without evaluation, how ubiquitous computing technologies are actually implemented in manufacturing. Particularly, the focus is set on the decentralization of data and functions within these applications. The model is primarily derived from four in-depth cases and seven mini case studies from seven industries. Additionally, these
case descriptions form the basis for the explanatory model of the subsequent chapter.

Chapter IV presents an explanatory model which is used for interpreting and discussing the results of the descriptive model. This chapter aims at identifying what factors or drivers actually cause the (de)centralization of data and functions in manufacturing by investigating both the centralized and decentralized solution, in regard to their theoretical grounding, strengths and weaknesses as well as risk factors and trade-offs. As the alternative solutions are investigated, a cost-benefit model is developed which helps to decide on the best solution for an organization. Additionally, the theoretical insights gained by this research are taken a step further to provide guidance for practitioners. Specifically, in this chapter a prescriptive model is presented which suggests how ubiquitous computing applications in the manufacturing domain should be designed with particular focus on the decentralization of data and functions.

In chapter V, the thesis synthesizes the findings of the research. An integrative answer to the research question and its sub-questions is given. Particularly, the chapter contains a summary of the key findings, presents theoretical and managerial implications as well as introduces some future prospects.
II The decentralization versus centralization debate in related research fields

Ubiquitous computing applications can be interpreted as the interplay between technology, information systems and humans embedded into an organization – therefore, establishing a comprehensive view on the centralization versus decentralization debate in the era of ubiquitous computing not only requires the review of related work in the field of distributed systems and organization science but also in information systems research, in the area of ubiquitous computing and, as the focus is set on manufacturing, also in field of production planning and control concepts. The author is aware of the risks associated with a multi-disciplinary approach of this kind. However, a broad understanding is necessary to address the practical problem accordingly.

Unfortunately, there is considerable ambiguity in the meanings ascribed to the terms centralization and decentralization within the different research environments. Therefore, for each research field the focus on the discussion must begin with a definition of terms. This is followed by a more detailed overview of the (de)centralization debate in the respective field. Finally, implications from this previous research are presented.

II.1 Organization science

Although organizations differ greatly in size, function and structure, the operations of nearly all organizations are based on a division of labor, a decision-making structure as well as rules and policies. Against this background, decision-making structures are used to organize authority. Managers hierarchically delegate responsibility to divisional managers and these, in turn, to team managers and so forth. Delegation of decision making power within organizations varies from company to company in their degree of centralization and decentralization. Accordingly, an organization is centralized to the degree to which decisions are made on a high level of hierarchy. In contrast, they are decentralized to the degree to which decisions are made on a low level of hierarchy.

65 Fleisch 2001
Against this background, within organization science there are two research streams which focus on the allocation of decision rights - the ‘organization of knowledge’ and the influence of ‘incentive problems’. In this section, these two streams are investigated which ultimately lead to the optimal degree of decentralization in organizations. Furthermore, implications of the findings on the centralization versus decentralization debate in the field of ubiquitous computing are outlined.

II.1.1 Distributed knowledge

The quality of a decision to be made in organizations depends on the extent to which relevant knowledge is accessible.\(^{67}\) This knowledge, however, tends to be dispersed among multiple individuals throughout the organization. In this context, effective decision making requires collocating knowledge with decision authority. Against this background, Jensen and Meckling\(^ {68}\) propose two distinctive ways to collocate information and decision rights: first, to move the information closer to the decision maker and second, to move the decision rights closer to those having pertinent information. These solutions have been referred to as the ‘Management Information System’ (MIS) Solution and the ‘Organizational Redesign Solution’, respectively.\(^ {69}\) Whereas the MIS solution is usually associated with centralization, the organizational redesign solution usually favors some form of decentralization.\(^ {70}\)

Hayek\(^ {71}\) was an early proponent of the importance of the organizational redesign solution. He argued that an organization’s performance depends on the effective utilization of its resources, particularly knowledge. He stressed the importance of locating information and decision rights together: “If we … agree that the economic problem of society is mainly one of rapid adaptation to changes in the particular circumstances of time and place, … decisions must be left to the people who are familiar with these circumstances, who know directly of the relevant changes and of the resources immediately available to meet them. We cannot expect that this problem will be solved by first communicating all this knowledge to a central board

\(^{67}\) Hayek 1945; Jensen & Meckling 1998
\(^{68}\) Jensen & Meckling 1998
\(^{69}\) Brynjolfsson & Mendelson 1993
\(^{70}\) Nault 1998
\(^{71}\) Hayek 1945
which, after integrating all knowledge, issues its orders. We must solve it by some form of decentralization.”

This statement shows that at a certain degree of complexity of a decision problem, which is for instance caused by high market uncertainty or high product variety, it is required that problems are decomposed into tasks that can be assigned to different agents and solved by these agents. By delegating authority the communication requirements between managers and agents are reduced and the burden of information processing is dispersed among actors within an organization. To conclude, important reasons for the pervasiveness of decentralized decision making within organizations are the limits in communication and the information processing capacities of the actors involved.

II.1.2 Agency problem

The last section might lead to the conclusion that decision rights should be located at the bottom of the hierarchy. However, a possible disadvantage of delegation is that it might lead to incentive problems. This is problematic as the objectives of the principal at the top of the hierarchy and the agents at lower levels may be inconsistent. Agents who have been given authority over a certain decision may pursue their own interest rather than that of the principal. Delegating decision authority to lower-level agents may then allow them to make decisions that are sub-optimal from the organization’s perspective. In literature this problem is referred to as the ‘agency problem’.

Against this background, Alchian and Demsetz as well as Jensen and Meckling propose the view of a company as a nexus of contracts among self-interested individuals. This means, a firm can be seen as a set of agency contracts under which a principal employs agents to perform some tasks on his behalf. An assumption is that an agent’s objective is the maximization of the individual utility, e.g. the agent prefers more rewards and less effort, but pays no regard to the organization’s objectives. This problem can be reduced by providing incentives or by increasing

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72 Hayek 1945, p. 524
73 Hayek 1945; Picot, Reichwald, & Wigand 1996, p. 20; Radner 1992, 1993; van Zandt 1999
74 Calvo & Wellisz 1978; McAfee & McMillian 1990; Williamson 1967; Jensen & Meckling 1998
75 Alchian & Demsetz 1972; Jensen & Meckling 1973; Ross 1973; Wilson 1968
76 Alchian & Demsetz 1972
77 Jensen & Meckling 1973
control. Another method by which the agency costs can be lowered is by optimally locating decision authority at higher organizational levels, where the goals of agents are more aligned with those of the principal. However, in situations where decisions require large volumes of local information this may lead to inefficiencies.78

II.1.3 Determining the optimal degree of centralization and decentralization in organizations

As discussed above, value maximization for organizations is more likely to occur if those with the responsibility for decisions have the knowledge needed for those decisions. Against this background, decision rights can be collocated with knowledge in two ways: transferring the knowledge to the person who has the decision rights, and transferring the decision rights to the person with the knowledge. Whereas the first approach generates knowledge transfer costs, the second leads to agency costs. Therefore, decision rights in an organizational hierarchy should be located where value is maximized, e.g. where the sum of these two cost components is minimized.79

Knowledge transfer costs

If all decisions are made by a central authority, there is a need to process information upward the hierarchy. This inevitably involves a variety of associated information processing costs. These include costs of communication, costs of miscommunication as well as opportunity costs due to delays in communication. Furthermore, decisions made without relevant information may lead to sub-optimal decisions, which cause other kinds of costs.

In general, the sum of these costs increases as decision rights are moved higher in the organizational hierarchy. On the one hand, if knowledge relevant to decisions resides at lower organizational levels, then decentralization of decision authority reduces knowledge transfer costs. On the other hand, the cost of transferring knowledge from higher organizational levels to lower level decision makers reduces the net benefit from decentralization and, everything else being equal, results in less decentralization.80

78 Jensen & Meckling 1973
80 Gurbaxani & Wang 1991; Jensen & Meckling 1973
Agency costs

Agency costs are the sum of monitoring costs, bonding costs and residual losses. Having lower-level agents make decisions in the principal’s interests requires costly systems for measuring and evaluating the agent’s performance as well as rewarding or punishing their actions. Besides these monitoring costs, an agent is expected to report to the principal, consuming time and effort that could be better spent for value generating tasks. This is another type of cost called bonding cost. Furthermore, despite monitoring and bonding costs, the principal may still experience a partial loss of welfare as the agent maximizes his own utility and not that of the organization. This cost is termed residual loss.  

Optimal degree of (de)centralization

Figure 7 provides an intuitive way of thinking about the trade-offs between knowledge transfer costs and agency costs. The vertical axis measures the costs and the horizontal axis measures the degree of (de)centralization of decision authority. Total organizational costs plotted in Figure 7 are the sum of the knowledge transfer

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81 Gurbaxani & Wang 1991; Jensen & Meckling 1973
82 adapted from Beuermann 1992; Jensen & Meckling 1998
costs and agency costs. In short, a centralized system leads to high knowledge transfer costs and low agency costs, whereas a decentralized system leads to the reverse. Therefore, determining the optimal level of (de)centralization requires balancing the two cost types. The optimal location of the decision right and thus the optimal degree of (de)centralization is where the decrease in the cost owing to knowledge transfer just offsets the increase in the cost owing to control issues, e.g. where the total organizational costs are minimized.

II.1.4 Summary and implications

In the field of organizational science, researchers think of (de)centralization in terms of decision making and control. Against this background, a company is centralized to the degree to which decisions are made by an upper level management. In contrast, decentralization is the process of transferring decision making authority to lower levels of the organization.

The primary goal of the research is to determine the optimal degree of the (de)centralization of decision rights. The overall guideline is to locate decision rights in an organization where the sum of the knowledge transfer costs and the agency costs are minimized. Knowledge transfer costs result from processing local information upwards through the hierarchy and include costs for sub-optimal decisions, communication, miscommunication and delays. In contrast, agency costs result from different objectives of the principal at the top of the hierarchy and the agents at lower levels and include costs for monitoring, bonding and residual loss.

Important drivers for decentralized decision making in organizations are limits in communication and information processing capacities of the involved actors. At a certain degree of complexity of a decision problem it is required to decompose it into tasks that can be assigned to actors of lower levels of the hierarchy which are then responsible for the decisions.

From the analysis of related work in organizational science, the following propositions can be inferred concerning the (de)centralization issue:

Proposition 1: Decentralize to minimize the sum of knowledge transfer costs and agency costs.

Proposition 2: Decentralize to cope with limits in communication and information processing capacities of the actors.
II.2 Information systems research

Among other topics, information systems research has focused on the impact of information technology on the centralization and decentralization of decision making authority described in the previous section. Over time, various studies have indicated why it is advantageous and disadvantageous for companies to centralize and decentralize decision making authority by means of information technology. Additionally, various factors affecting the actual information technology architecture within an organization have been proposed which led either to centralization or decentralization. Besides a brief review of these issues, implications of the findings on the centralization versus decentralization debate in the field of ubiquitous computing are presented in this section.

II.2.1 The impact of information technology on centralization and decentralization

The debate on whether information technology architecture should be centralized or decentralized has a long history in information systems research. In fact, it is as old as the technology itself. Ever since Leavitt and Whisler\(^{83}\) predicted that information technology would lead to greater centralization, researchers have speculated about how information technology will effect centralization and decentralization in organizations. The fundamental question is whether information technology will lead to centralized or decentralized decision making\(^{84}\) – with the ultimate goal to determine an appropriate arrangement for information technology resources such as hardware, software, communication equipment, data and people within an organization.\(^{85}\)

Over time, there have been numerous examples demonstrating both directions. In some cases, information technology led to more centralization. In other cases, however, it led to more decentralization. And in still other cases, it appeared to have no effect on the allocation at all. Yet another position makes a fundamental shift in the argumentation, suggesting that information technology reflects rather than causes (de)centralized decision making. Based on this previous research, there seems to be no clear answer to the question on how information technology affects

\(^{83}\) Leavitt & Whisler 1958
\(^{84}\) Dewett & Jones 2001
\(^{85}\) King 1983
the centralization and decentralization of decision making authority within organizations.\textsuperscript{86}

Gurbaxani and Wang\textsuperscript{87} developed a framework that explains why information technology leads to either centralization or decentralization of decision rights depending on the decision related costs. They argue that as decision making rights are pushed downwards through the hierarchy, the costs of communicating information upward decrease while agency costs resulting from goal divergence increase. On the one hand, information technology can reduce communication costs by improving quality and speed of information processing. This would lead to more centralized decision making. On the other hand, information technology can also reduce agency costs by improved monitoring capabilities and performance evaluation schemes. This would lead to more decentralized decision making.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{The impact of information technology on the optimal degree of \((de)centralization\) due to reduced knowledge transfer costs}
\end{figure}

\textsuperscript{86} George & King 1991; Malone 1997
\textsuperscript{87} Gurbaxani & Wang 1991
Coming back to Figure 7, introduced in chapter II.1.3, we see these findings illustrated. What Gurbaxani and Wang\textsuperscript{88} call costs of communication and coordination costs can be seen as knowledge transfer costs and agency costs. Whereas Figure 8 shows the impact of information technology leading to centralized decision making due to reduced knowledge transfer costs, Figure 9 demonstrates the impact of information technology leading to decentralized decision making due to reduced agency costs. By moving the cost curves, it can be shown that a firm may use information technology to centralize some decision rights while decentralizing others, leading to a hybrid structure. The choice depends on the specific cost structures of the firm.

However, the argumentation so far has not included the costs for information technology. Including these leads to higher total costs and thus information technology might not have an influence on the current allocation of decision rights – as the overall costs for information technology outbalance the benefits which can be achieved.

\textsuperscript{88} Gurbaxani & Wang 1991
Another discussion of whether information technology leads to either centralization or decentralization of decision rights is presented by Wyner and Malone\textsuperscript{89}. The critical insight captured in their model is that two kinds of decentralization exist – the unconnected (independent) and the connected decision makers. The model suggests that unconnected decentralized decision makers should be implemented if communication costs are very high. As these costs fall, centralized decision making should become more desirable. Finally, as these costs fall still further, connected decentralized decision making should be used. Even though many factors can affect the (de)centralization of decision making, besides costs of communication, the value of the information is of particular relevance.

II.2.2 Advantages and disadvantages

With the advent of information technology, various studies have indicated why it is advantageous and disadvantageous for companies to centralize and decentralize decision making. The basic analysis contrasts control, efficiency and economy of scale of a centralized solution with flexibility, empowerment and responsiveness of the decentralized counterpart.\textsuperscript{90} The choice of which design principle to follow requires the assessment of how important the advantages of each scheme are to a particular organization.\textsuperscript{91}

As information technology gets implemented in a firm, the amount of available information increases significantly. This leads to better centralized decision making with reduced uncertainty by enabling managers to obtain more information, more quickly and accurately.\textsuperscript{92} However, it may also lead to the phenomenon of ‘information overload’, e.g. an actor receives too much information.\textsuperscript{93} This problem can be solved by decentralizing decision rights, because it reduces the burden on the top management and the communication between different hierarchical levels. Moreover, whereas centralized decision making promotes continuity in the organizational operation as decisions are made at a single level, decision making gets separated from its environment leading to suboptimal decisions.\textsuperscript{94} Also, by

\textsuperscript{89} Wyner & Malone 1996
\textsuperscript{90} Gordon & Gordon 2002; Mertens 1985, pp. 16-22; Stahlknecht & Hasenkamp 2002, p. 446
\textsuperscript{91} Schuff & Louis 2001
\textsuperscript{92} Dewett & Jones 2001
\textsuperscript{93} Brynjolfsson & Mendelson 1993
\textsuperscript{94} Nault 1998
providing centralized control using established technologies and vendors, the technical risks are reduced. Besides that, duplication of effort, resources and expertise is also reduced which saves cost and time.\textsuperscript{95}

At the same time, information technology has made it possible to disseminate and access information easily at lower hierarchical levels leading to decentralization. As a consequence, it enables lower and middle management to make decisions based on local information and information about the organization’s overall situation. This allows for more globally optimized decisions at a lower hierarchical level.\textsuperscript{96} For instance, Anand and Mendelson\textsuperscript{97} have shown for firms competing in different geographical markets that expected profits are generally highest for firms with decentralized decision making structures and access to global information. Besides improved performance, decentralized decision rights possibly encourage innovation.\textsuperscript{98} Furthermore, organizational flexibility and responsiveness is a major advantage brought by autonomy owing to local control of own information systems. However, a lack of centralized control can be disadvantageous as conflicting ideas and policies might lead to inefficiencies.\textsuperscript{99}

Information technology departments that want to manage the distribution and configuration of software across different clients are searching for an acceptable balance of control, speed and reliability. Against this background, Schuff and Louis\textsuperscript{100} analyzed principle advantages of centralized and decentralized software application distribution and configuration. The distribution of application files throughout individual workstations maximizes network performance because it is not required to retrieve the software from a central file server each time it is run. Furthermore, a decentralized approach makes it easier to meet the needs of individual users. On the other hand, placing application files in a few central locations enables information technology departments to control software distribution and configuration. However, this might degrade network performance and eventually lead to user dissatisfaction. In a centralized architecture, the only way to avoid these network bottlenecks without increasing bandwidth and to better

\textsuperscript{95} King 1983  
\textsuperscript{96} Dewett & Jones 2001  
\textsuperscript{97} Anand & Mendelson 1997  
\textsuperscript{98} Nault 1998  
\textsuperscript{99} King 1983  
\textsuperscript{100} Schuff & Louis 2001
meet user requirements is to design highly modular applications so that only the required software modules are transferred. Additionally, a major advantage of a centralized software management is the enforcement of consistent operating systems, hardware driver files and software versions. This not only causes a reduced diversity in workstation software and configuration effort, but files can also be better protected from unintended modification, accidental deletion and corruption. Moreover, if application software is centralized, required software installation, upgrades and patches have to be made in fewer places. As a consequence, fewer technicians are required to update, upgrade and fix software problems. This, in turn, reduces the personnel costs. In general, with centralized software management users should experience a lower number of disruptions and more timely fixes, particularly if the latest versions and updates are received automatically without the need for a technician on site. Finally, centralized servers for data storage simplify the task of increasing network-wide disk storage. This makes it more cost-efficient to increase storage capacity without continuously upgrading individual workstations on the network.

II.2.3 The centralization-decentralization-cycle: Drivers of change

The combination of hardware, software, communication equipment, data and people make up the core of an information system. As each of these dimensions have been developed and integrated, the design and capabilities of information system architectures have undergone considerable changes (see Figure 10). Over time various factors affecting information technology architecture have been proposed, triggering a trend or trend reversal in one or the other direction. Against this background, an inflection point defines a moment in time when a factor was important enough to trigger a trend either towards centralization or decentralization.

Early architectures were of the classic centralized type, and were constrained to large mainframe systems running batch processes. These architectures were characterized by low network connectivity and low information processing decentralization. The early generation of these centralized architectures were modest in size, but grew from small, medium to large centralized mainframes over time. In the early 1960s, information technology architecture was centralized for

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mainly two reasons. On the one hand, the state of the art technology did not allow for alternative solutions. On the other hand, due to high costs of both hardware and communication, only a few central systems were implemented which were well protected and provided only limited accessibility.

Centralized architectures had given way to decentralized information architectures by the mid 1970s. Caused by technological advances leading to less costly and more sophisticated equipment, coupled with an increasing need for flexibility and responsiveness, some degree of decentralization was commonplace. Typically, dumb terminals were connected to the mainframe systems. People were able to send data to the central system electronically and did not have to physically walk to the information technology equipment to process data. Furthermore, with the introduction of the microcomputers in the early 1980s, data processing could be done locally and in a distributed way. This created the so-called end-user phenomenon. Moreover, technology was introduced that provided the ability to connect computers in a network. With this capability, distributed processing was implemented in organizations in the form of client-server computing. Using this

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102 adapted from Evarisot, Desouza, & Hollister 2005
technology, companies began to distribute not only hardware but also software, which gave departments control over their computing activities and resources. At the same time, software had evolved to a point where it was accessible to none-programmers. This enabled end users to develop and implement a set of relatively simple applications.

However, caused by a lack of enterprise-wide standards and quality control, the before mentioned trend towards decentralization led to heterogeneous, not-easily connected hardware and none-integrated software, resulting in data redundancy and therefore in data inconsistency. Enterprise-wide standards, however, were necessary for integrating business functions and supporting new business opportunities. Thus, the need for integration and standardization of the information technology infrastructure created an inflection point in the previously consistent trend towards decentralization. Other factors for centralization efforts were the high costs for separate data processing centers and duplicate software licensing, as well as the need for simplification and reengineering of information technology architecture – which is easier when systems are compatible.

By 1992, the next shift towards decentralization was created, not only through a renewed perception of increased service quality, but also by limitations in communication among the multitude of operating systems available at that time. Furthermore, a push towards web solutions influenced this new trend. Companies such as Amazon began to use ecommerce applications, dispersing their servers to improve response time.

By the late 1990s, the next inflection point heading towards centralization was motivated by the need for instantaneous data access across a multitude of geographically distributed decision-making environments, along with the need for reliability and security. In a decentralized environment, the ability to access data in geographically distant servers may be compromised. The likelihood that a server will not be working or that a connection difficulty will arise increases with the number of servers. As a consequence, complete financial and operational statements may not be retrievable when required. Thus, although the decentralized information system architecture had been promoted as one way to make a system more fault tolerant in case of the elimination of a node, exactly the opposite could also be argued. Furthermore, costs of hardware and communication also played an important role towards more centralized solutions. For instance, it is much cheaper
to create backups and crises centers for a few centralized solutions than for a multitude of decentralized installations.

II.2.4 Summary and implications

In the field of information systems, researchers have focused on the impact of information technology on the (de)centralization of decision rights. Researchers have argued that information technology will lead to either more centralization or decentralization, respectively. In other cases, it has also been argued that information technology does not have an influence on the issue or that this technology reflects rather than causes (de)centralized decision making.

The ultimate goal of research in this field has been to determine an appropriate arrangement of information technology resources such as hardware, software, communication equipment, data and people. The general argumentation is twofold: on the one hand, information technology can reduce knowledge transfer costs and thus leads to more centralized decision making. On the other hand, information technology can decrease agency costs and hence leads to more decentralized decision making.

Over time, several factors have been identified that influence the arrangement of information technology resources leading to certain advantages and disadvantages. Generally, the major advantages of centralized solutions are control, optimality and efficiency. In contrast, key advantages of decentralized solutions are flexibility and responsiveness.

From the analysis of related work in information systems research, the following propositions can be inferred concerning the (de)centralization issue:

*Proposition 3:* Centralize if knowledge transfer costs can be reduced by means of information technology.

*Proposition 4:* Decentralize if agency costs can be reduced by means of information technology.

*Proposition 5:* Centralize to improve efficiency.

*Proposition 6:* Centralize to reach optimality.

*Proposition 7:* Centralize to stay in control.
II.3 Distributed systems

Networks of computers can be found everywhere. The Internet, mobile phone networks, corporate networks, factory networks and in-car networks, to name a few, share essential characteristics that make them relevant subjects for study under the heading of distributed systems. The aim of this section is to explain the characteristics of network computers that impact system designers and implementers likewise. Thereby, a focus is set on the main concepts and techniques that have been developed.

II.3.1 Characteristics of distributed systems

Although the term distributed system has been applied to a variety of computer systems of different designs and purposes, no clear definition exists. Not only is the distinction between distributed and centralized systems not precisely defined, but also there are several contrasting definitions and views on what distributed systems are. Against this background, Coulouris et al.\(^\text{103}\) define a distributed system as “one in which hardware or software components located at networked computers communicate and coordinate their actions only by passing messages”. On the other hand, Tanenbaum And van Steen\(^\text{104}\) define a distributed system as “a collection of independent computers that appear to its users as a single coherent system”. These definitions have the following significant consequences. The various entities in a distributed system can operate concurrently and autonomously. Tasks are carried out independently and actions are coordinated by exchanging messages. Generally, failures are independent and there is no single process or entity that has knowledge of the entire status of the system. Although there are a number of challenges for designers and implementers, the benefits of distributed systems and applications are manifold, making them worthwhile to pursue.

The main goal of a distributed system is to connect users and resources in a transparent, open and scalable way. The term resource is a rather abstract one and

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\(^{103}\) Coulouris, Dollimore, & Kindberg 2001, p. 2

\(^{104}\) Tanenbaum & van Steen 2007, p. 2
includes a range of things that can usefully be shared in a networked computer system – starting from hardware components such as disk space and printers to software entities such as files, database and data objects. Numerous distributed systems are currently in use. An example is a factory system, in which different devices such as robots, production and assembly systems are interconnected for factory automation.

The architecture of distributed systems identifies the main hardware and software components as well as defines the relationship between them. The majority of distributed systems in use are based on the client-server model. One of the main challenges of such a model is drawing a clear distinction between client and server. This ultimately leads to the question on the optimal degree of decentralization, e.g. deciding on the locations at which programs and applications are executed and data are stored. Considering that many applications are targeted toward supporting user access to database, a number of researchers have advocated a distinction between the three components user-interface, processing and data. These three components suggest a number of possibilities for the client-server organization (see Figure 11).

Figure 11: Alternative client-server organizations

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106 Umar 1993, p. 4
107 adapted from Tanenbaum & van Steen 2007, p. 41; Umar 1993, p. 239
One possible organization is to have only the user interface on the client machine (a) and give the applications remote control over the presentation of the data. A first alternative is to place the entire user interface software on the client side (b). A third option is to move a part of the application to the front end (c). An example of such a solution is a form that needs to be filled in completely before it can be processed. The front end can then check the correctness and consistency of the input data. The solutions (d) and (e) are particularly popular in organizations. These solutions are used where the client machine is a personal computer or a workstation connected through a network to a database. Essentially, applications of type (d) are run on the client but all operations on the database are done on the server. For instance, many banking applications run on clients where the user prepares transactions. When finished, the application contacts the database on the server and sends the transaction for further processing. In the case of (e) the client’s local disk holds part of the data, for instance a cache of recently visited web pages.

There has been a trend away from the configurations (d) and (e) in which most processing and data storage is handled at the client. The reason for this is that clients are more problematic to manage. Having more functionality on the client makes the software more prone to error and more dependent on the underlying operating system and resources. Therefore, from a system management perspective having so-called ‘fat clients’ is not optimal. Rather, thin clients (a-c) are much easier to maintain, probably at the cost of less sophisticated user interfaces and user-perceived performance.¹⁰⁸

**II.3.2 Motivation for distributed systems and their drawbacks**

The remarkable growth of distributed systems is primarily driven by the availability of powerful computers which can be interconnected through fast networks. Although building distributed systems is technically feasible, it is not always reasonable to implement them. Rather, a deployment should only be considered if the advantages of the distributed systems outweigh its drawbacks. The following are some of the issues that need to be considered by users and system managers when deciding on the implementation of a distributed system:

¹⁰⁸ Tanenbaum & van Steen 2007, pp. 41f.
• **Sharing of resources**: The main reason for implementing distributed systems is to share resources in a controlled and efficient way. Sharing resources has the potential to reduce costs for expensive components. For example, it is cheaper to let a printer be shared by several users than having to buy and maintain a separate printer for each user. Additionally, it makes it easier to improve collaboration and to exchange information. For instance, the Internet is now leading to numerous virtual organizations in which people work together by means of a groupware system. However, as connectivity and sharing increase privacy and security becomes an issue.109

• **Extensibility / scalability**: It is argued that the place where an object is located in a distributed system should be completely transparent, i.e. the decision of which parts of the software run locally or remotely can be taken after the software has been deployed. Additionally, a properly designed distributed system can be effectively extended as the demand for service grows. Specifically, resources and users can be easily added and administrated without replacing any of the existing components. However, when adding new components to the system, network bandwidth becomes a limiting parameter since each new component adds to the communication load of the network. This is particularly true if only one server is implemented for shared services, data and algorithms. In addition, to reduce complexity, standardized interfaces and communication protocols are required. A lack of standards would create serious compatibility, portability and interconnectivity problems.110

• **Reliability / availability**: If one of the components in a distributed system fails, only the processes running on this component are affected. Such a failure can result in anything from easily repairable errors to catastrophic melt downs. A reliable distributed system should be designed in a way that it is as fault tolerant as possible. The most common approach to handling faults is redundancy in regards to information, re-sending messages and physical redundancy. By doing so, high performance and availability is guaranteed. However, this also results in higher costs as well as synchronization and replication problems.111

110 Coulouris & Dollimore 1991, p. 19; Tanenbaum & van Steen 2007, p. 9
111 Coulouris & Dollimore 1991, p. 19
• **Performance:** In a distributed system there are many computers, each having one or more processors. Hence, parallel execution arises naturally due to the separation of activities and leads to higher throughput. Furthermore, computational load can be balanced among different computers. However, processes may use old data and may make inconsistent updates, the order of updates may or may not matter, the system might deadlock and knowing the exact time might be a challenge.\(^\text{112}\)

Distributed systems differ from traditional software because components are dispersed over the network. Not taking this fact into account when designing such a system leads to needless complexity and results in mistakes that need to be resolved later. The most common false assumptions that lead to badly designed distributed systems or that make such systems infeasible are: the network is reliable, secure and homogeneous, the topology does not change, latency and transportation cost are zero, bandwidth is infinite and there is one administrator.\(^\text{113}\)

### II.3.3 Summary and implications

In general, a distributed system is a collection of hardware and software components that communicate via a network and coordinate their actions by passing messages. The main goal of a distributed system is to connect both users and resources such as disk space, printers, files and data objects. The focus of this research stream is set on the design of a system, namely one that is transparent, open and scalable.

There are several strong reasons for implementing a distributed system. The main reason is to share resources in a controlled and efficient way. Additionally, it is argued that such systems are scalable and easy to extend. Furthermore, as a failure of one component only affects this particular component, a distributed system is reliable and its availability is high. Finally, as resources are duplicated in a distributed system, parallel execution arises naturally leading to a higher performance of the overall system.

From the analysis of related work in distributed systems research, the following propositions can be inferred concerning the (de)centralization issue:

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\(^\text{112}\) Anderson 2001, pp. 115f.
\(^\text{113}\) Tanenbaum & van Steen 2007, p. 16
Proposition 10: Decentralize to share resources in a controlled and efficient way.

Proposition 11: Decentralize to improve extensibility and scalability.

Proposition 12: Decentralize to improve reliability and availability.

Proposition 13: Decentralize to improve responsiveness.

Proposition 14: Centralize to reduce maintenance efforts.

II.4 Production planning and control

Production planning and control is fundamental to the operation of a manufacturing company. The basic challenge is to determine the type and quantity of the products to be produced and to handle disturbances such as machine failure, demand changes or set-ups under consideration of minimal costs."" Wiendahl 1997, p. 250" Thereby, manufacturers have to deal with trade-offs between a number of key performance indicators such as inventory level, lead time, cycle time, delivery time, customer service level and resource utilization. For instance, machines working to capacity lead to a high utilization but also to high inventory levels. In addition to these trade-offs, complexity increases with the number of resources, orders and operations." Zell 1992, p. 17 Thus, production planning and control is a combinational problem in which the number of solutions increases rapidly with the number of parameters relevant for the solution." Ruffing 1991, p. 131

Figure 12 depicts the different distributed manufacturing control architectures. Traditionally, production planning and control was solved using a monolithic model. In this approach, a single detailed model is formulated to determine optimal planning and scheduling decisions. However, such a centralized model becomes practically infeasible for large-scale problems." Bitran & Tirupati 1989 Problems that arise are slow speed of response, difficulty in making changes to the control software and no fault tolerance, i.e. if the central control goes down, the entire system goes down." Babiceanu, Chen, & Sturges 2004

114 Wiendahl 1997, p. 250
115 Zell 1992, p. 17
116 Ruffing 1991, p. 131
117 Bitran & Tirupati 1989
118 Babiceanu, Chen, & Sturges 2004
In contrast, in the hierarchical approach (a) to production planning and control the detailed monolithic formulation is replaced by a sequence of models. Although the hierarchical system is able to obtain global optimization, it also has major disadvantages. Most hierarchical manufacturing control systems tend to have problems with reactivity to disturbances. Therefore, heterarchical control (b) was introduced. While hierarchical control involves a command-response structure between upper and lower level entities, heterarchical control is achieved by allowing a high level of autonomy and decision making for low level entities. Yet, heterarchical control turned out to have problems with predictability and global optimization. This led to a third class of manufacturing control approaches called holarchic control (c) systems. Thereby, entities are provided with a degree of autonomy but are also integrated with the rest of the operations through cooperative mechanisms. Such a system reacts promptly to changes, however it is nearly impossible to reach global optimization.\textsuperscript{120}

Besides a brief review of the hierarchical, heterarchical and holarchical concepts, implications of the findings on the centralization versus decentralization debate in the field of ubiquitous computing are presented in this section.

\textbf{II.4.1 Hierarchical control approach}

The idea of hierarchical production planning and control was formally captured by Anthony\textsuperscript{121} and formalized by Hax and Meal\textsuperscript{122}. Among others, contributors to the development and refinement of the hierarchical production planning model are

\textsuperscript{119} adapted from Bongaerts, Monostori, & Kadar 2000; Dilts, Boyd, & Whorms 1991
\textsuperscript{120} Bongaerts, Monostori, & Kadar 2000
\textsuperscript{121} Anthony 1965
\textsuperscript{122} Hax & Meal 1975
The essential idea of a hierarchical approach is to decompose a global problem into smaller manageable sub-problems. These sub-problems are then to be solved sequentially. Such a model usually consists of three decision levels: strategical, tactical and operational. The three levels have different characteristics in regard to planning horizon, time and cost. Typically, at a higher level, planning is done for aggregated problems related to total manpower requirements and product-line demand, with longer lead times and planning horizons, e.g. several months. In contrast, at the lower level a more detailed plan is provided with shorter lead times and planning horizons related to individual items, machines and workers. Furthermore, each level has its own decision models and solving procedures. The solutions generated by these procedures become a constraint or objective to be satisfied at a subsequent level. Finally, a solution on an upper level can be improved. If the model allows feedback from a lower level, more information will be used in the optimization model leading to better results.

The rationale behind this hierarchical approach is to simplify the overall decision process. The motivation for this is that production planning is a highly complex task and particularly hierarchical planning is a way to reduce and cope with complexity. The reduction of complexity occurs since a large problem is broken up into a series of smaller problems for which the extent of the interdependencies is low. Furthermore, by applying such a model uncertainty can be reduced. A global optimization problem requires the specification of all data well in advance and thus would be subject to a substantial degree of uncertainty. However, not all decisions

123 Bitran & Hax 1977
124 Hax & Golovin 1978
125 Bitran, Haas, & Hax 1982
126 Hax & Candea 1984
127 Leong, Oliff, & Markland 1989
128 De Kok & Fransoo 2003
129 Schneeweiss 2003
130 Neureuther, Polak, & Sanders 2004
131 Dauzere-Peres & Lasserre 2002
132 Dempster et al. 1981; Schneeweiss 2003, p. 158; Soman, van Donk, & Gaalman 2004
133 Kira, Kusy, & Rakita 1997
need to be made at the same point of time. Hence, information demanded at a lower level can be postponed until a point in time relatively close to when execution is required.

The fundamental advantages of the hierarchical planning and control approach to complex problems include: reduction of complexity, coping with uncertainty, fit with hierarchical organization system, improvement of the manager's overall insight due to the use of aggregated figures, reduced need for detailed information and better planning quality.\textsuperscript{134} However, because of its static and deterministic nature, it is difficult to modify the system and to incorporate unforeseen changes into the system. Specifically, practical experience has indicated that many hierarchical systems tend to have problems with reactivity to disturbances.\textsuperscript{135} When a disturbance occurs, it is reported to the appropriate level in the hierarchy and after the schedule has been adapted, the new schedule triggers a new flow of command. Yet, the resulting response time and the robustness of the system are low. Integrated decision models tend to be large, making it difficult or impossible to obtain optimal solutions with reasonable effort.\textsuperscript{136} Additionally, long lead times and high inventories are the most serious problems which many companies face, in spite of the extensive use of hierarchical production planning and control systems.\textsuperscript{137} Moreover, the sequential solution of a hierarchy of sub-problems may lead to sub-optimality, inconsistency and infeasibility. Finally, each method is only suitable for a limited range of planning situations. The identification of the most appropriate method can cause problems to the production planner.\textsuperscript{138}

**II.4.2 Heterarchical control approach**

To overcome the shortcomings associated with hierarchical control, a number of researchers have proposed a heterarchical control approach.\textsuperscript{139} This is a highly distributed form of control, implemented by a system of independent cooperating processes or software agents without centralized or explicit direct control. Instead, control decisions are reached through mutual agreement and information exchange.

\begin{itemize}
\item \textsuperscript{134} Nagi & Proth 1994
\item \textsuperscript{135} Dilts, Boyd, & Whorms 1991
\item \textsuperscript{136} Bongaerts, Monostori, & Kadar 2000
\item \textsuperscript{137} Zäpfel & Missbauer 1993
\item \textsuperscript{138} Vicens, Alemany, Andres, & Guarch 2001
\item \textsuperscript{139} Duffie & Piper 1986; Hatvany 1985; Lin & Solberg 1994; Soman, van Donk, & Gaalman 2004
\end{itemize}
The concept of heterarchical control is inspired by the self-organizing nature of biological systems and market economies. In these systems, reactivity to disturbances emerges almost automatically from simple mechanisms in the behavior of individual agents. It is envisioned for manufacturing systems that heterarchical control architectures offer similar prospects of reduced complexity, increased flexibility, reduced supervisory costs and delay as well as high robustness as found in the biological systems and market economies.

Theoretical considerations and experiments have partially proven these expectations. However, researchers have shown that a control approach with no form of hierarchy has problems in providing globally optimized performance. Even more critical seems to be the fact that the behavior of such a system can be unpredictable, potentially leading to deadlocks. This, however, is contrary to the needs of most manufacturing operations. Finally, heterarchical systems have the tendency to duplicate resources, which is a prerequisite for flexibility. Yet, this potentially leads to conflicting data and therefore inconsistent databases. Furthermore, flexibility in planning and scheduling is necessary but not sufficient. Rather, the underlying production system must be flexible in the same way to be able to execute various alternatives. Overall, literature shows that systems based on heterarchical architecture hardly go beyond the prototypical phase and industry is still far away from the idea of realizing a completely distributed system.

II.4.3 Holarchical control approach

To compensate the drawbacks of both the hierarchical and the heterarchical control approach, researchers have introduced several concepts for designing manufacturing systems based on some analogies with existing theoretical, natural and social organization systems. Those concepts include Fractal Factory, Bionic

140 Lin & Solberg 1994
141 Hogeweg & Hesper 1979; Vámos 1983
142 Bongaerts, Monostori, & Kadar 2000; Crowe & Stahlman 1995
143 Luh & Hoitomt 1993
144 Duffie & Prabhu 1994
145 Bongaerts, Monostori, & Kadar 2000; Crowe & Stahlman 1995
146 Crowe & Stahlman 1995
147 Bussmann 1998
148 Caridi & Cavalieri 2004
Manufacturing and Holonic Manufacturing Systems. A significant amount of research has been conducted in the field of holonic architectures. They have been applied to the planning and scheduling of an assembly shop, to the scheduling and monitoring of a generic shop floor, to engine assembly scheduling and to managing and coordinating manufacturing activities.

The holonic concept refers back to the work of Koestler in which he tried to explain the evolution of biological and social systems. Central to his concepts is the notion of a holon – which means simultaneously a whole and a part of the whole. In manufacturing, a holon can be defined as an autonomous and cooperative building block of a manufacturing system for transforming and transporting, as well as storing physical and information objects. For instance, a single machine, an order, a worker or also a combination of a machine tool, a controller and an operator interacting via an interface can form a holon. A holon might itself consist of other holons that provide necessary processing, information and human interface to the outside world. Hence, a holonic system not only comprises information objects but also the physical world including machines and humans. A system of holons that cooperate to achieve a goal is called a holarchy. Such a system can be created and adapted dynamically depending on the current needs of the manufacturing process.

A holarchical system has both distributed and centralized control capabilities. The autonomous units have a degree of independence and handle contingencies without consulting higher authorities for instruction. This ensures that holons are stable forms which can react more quickly to disturbances. Simultaneously, holons are subject to control from (multiple) higher authorities. This property provides functionality for coordinating and optimizing the performance of the overall system. Furthermore, an advantage of hierarchy in distributed control is the ability to predict the behavior of a distributed system. Finally, such a system eases the migration efforts towards distributed systems as it supports a gradual shift from the current hierarchical to the holarchical system. As the holonic system can be modeled such

149 Tharumarajah, Wells, & Nemes 1996
150 McFarlane & Bussmann 2000
151 Caridi & Cavalieri 2004
152 Koestler 1967
153 Bussmann 1998; McFarlane & Bussmann 2000
that it resembles the hierarchical system, the new control approach performs at least as well as the original system.\textsuperscript{154}

II.4.4 Summary and implications

The fundamental problem of manufacturing companies is production planning and scheduling. The overall goal is to determine type and quantity of products to be produced and to handle disturbances at minimal costs. To solve this problem, different distributed manufacturing control architectures with different advantages and disadvantages have been introduced, namely the hierarchical, heterarchical and holarchical architecture.

The idea of the hierarchical approach is to decompose a global problem into smaller manageable ones. The rationale behind this solution is to simplify the overall decision process. Whereas complexity of the decision problem can be reduced by such a system, it tends to have problems with responsiveness to disturbances. To overcome these challenges, the heterarchical control approach has been introduced. In this highly distributed approach, responsiveness to disturbances is improved. However, without some degree of central control a global optimum is difficult to achieve and the system may lead to deadlocks. This shortcoming has led to holarchical systems which combine both the hierarchical and the heterarchical concepts. On the one hand, autonomous units can make decisions without consulting higher authorities, which ensures high responsiveness to disturbances. On the other hand, these units are subject to higher level control for coordination and optimization of the overall system.

From the analysis of related work in production planning and control research, the following propositions can be inferred concerning the (de)centralization issue:

\textit{Proposition 15}: Decentralize to reduce and be able to cope with complexity.

\textit{Proposition 16}: Centralize to reach optimality.

\textit{Proposition 17}: Decentralize to improve responsiveness.

\textit{Proposition 18}: Decentralize to improve adaptability.

\textsuperscript{154} Bongaerts, Monostori, & Kadar 2000
II.5 Ubiquitous computing

Ubiquitous computing and its vision of smart objects equipped with digital logic, sensors and actuators as well as their ability to interconnect significantly contribute to the problem of finding the appropriate level of (de)centralization. Particularly, three research streams seem to be of relevance for the investigated research question on this issue: the discussion on data-on-network versus data-on-tag, sensor networks and autonomous (production) logistics processes. In this section, these research streams are investigated and summarized. Furthermore, implications of the findings on the centralization versus decentralization debate in the field of ubiquitous computing are outlined.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Data-on-network</th>
<th>Data-on-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic concept</td>
<td>Separation data and object</td>
<td>Collocation data and object</td>
</tr>
<tr>
<td>Access requirement</td>
<td>Network infrastructure</td>
<td>Presence of object</td>
</tr>
<tr>
<td>Data storage location</td>
<td>Database</td>
<td>Tag</td>
</tr>
<tr>
<td>Data on the tag</td>
<td>Unique identifier</td>
<td>Object related data</td>
</tr>
<tr>
<td>Tag storage capacity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Tag costs</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Security</td>
<td>Required at database level</td>
<td>Required at tag level</td>
</tr>
</tbody>
</table>

*Table 2: Characteristics of data-on-network and data-on-tag concepts*\(^{155}\)

II.5.1 Data-on-network versus data-on-tag

RFID data can be stored and communicated by two different approaches. First, the data-on-network concept can be used and second the solution can be based on the data-on-tag concept.\(^{156}\) Most discussions on this debate are dominated by the first, centralized approach in which object-related data is stored in backend systems and is referenced and manipulated using a unique identification number that is retrieved from the tag. However, reasons for choosing the alternative, decentralized solution can be found in practice, but are seldom taken into account in literature. In the following table (see Table 2) the two alternatives are investigated in more detail.

\(^{155}\) adapted from Diekmann, Melski, & Schumann 2007

\(^{156}\) Diekmann, Melski, & Schumann 2007
Data-on-network

Much of the current interest in RFID has been driven by the promise of the 5-cent-tag and the ability to identify any object, anywhere, automatically. Against this background, the most prominent industry standard group EPCglobal was initially founded to develop an open standard architecture for creating a seamless global network of physical objects. The result is the EPCglobal Network, which is defined as a method for using RFID technology in the global supply chain by using inexpensive RFID tags and readers to pass Electronic Product Code (EPC) numbers, and then leveraging the Internet to access large amounts of associated information that can be shared among authorized users. The concept uses unique identification numbers for each object, repositories for storing information about these objects and a discovery service which points to databases containing additional information.157

The data-on-network offers a number of benefits. Storing data on the network has the advantage that data is available even if the object is not.158 Furthermore, this solution allows using tags with low storages capacity, as only a unique identification number needs to be stored on the tag. As the storage capacity directly influences tag prices, costs can be kept relatively low. Other benefits are available standards which allow for compatibility and interoperability as well as give some degree of security for investments.159 Finally, centralized data management is a viable solution where the sensitivity of data demands strictly controlled database access.160

Data-on-tag

The data-on-network approach looks elegant and compelling at first. Having all the information on the network and just linking to it results in a conceptually simple way to identify objects and to gather information about the object. However, a number of cases exist, in which additional data besides a unique identifier are stored on the tag itself (see chapter III). Furthermore, since RFID tags are able to store more data than other identification technologies such as the barcode, it seems to be

157 EPCglobal 2004c
158 Nicolai, Resatsch, & Michelis 2005
159 Diekmann, Melski, & Schumann 2007
160 Mallinson & Parlikad 2005
quite natural to store a subset of useful information onto the tag.\textsuperscript{161} Under certain circumstances, it seems to be even required that data is stored on the tag:

- **Real-time decisions:** Certain processes, for instance in automated manufacturing, require decisions to be made in real-time, e.g. within a fraction of a second. In such situations it might be inefficient to access necessary product and process relevant data from a central database. Rather, data on the tag should be used to support these processes.\textsuperscript{162}

- **Data access at remote locations:** A major advantage of the data-on-tag concept is that information is always available with the object regardless of the ability to access a central database. For instance, an airplane’s entire maintenance history could be stored on the tag so that an employee is able to access this information in remote locations.\textsuperscript{163}

- **Real-time data capture:** There are some situations in which data needs to be recorded in real-time throughout the lifetime of a product, such as temperature variations for perishable goods in the supply chain. A constant networked database access throughout the lifecycle would be impracticable.\textsuperscript{164} Furthermore, product and process information can be changed automatically along the supply chain, which enables the parallel flow of material and information.\textsuperscript{165}

- **Frequency of data access:** Some information about an object needs to be more frequently accessed than others. In situations where the frequency of data access costs outbalances the costs for writing data on the tag, it is sensible to store data on the tag to minimize the overall costs.\textsuperscript{166}

- **Relief of central systems:** Particularly, when large volumes of data need to be processed simultaneously, the decentralized processing of data helps to relieve the central system.\textsuperscript{167} For instance, temperature sensor data can be analyzed in a

\textsuperscript{161} Suzuki & Harrison 2006

\textsuperscript{162} Diekmann, Melski, & Schumann 2007; Mallinson & Parlikad 2005; Vogel 2007

\textsuperscript{163} Diekmann, Melski, & Schumann 2007; Mallinson & Parlikad 2005; Suzuki & Harrison 2006; Vogel 2007

\textsuperscript{164} Mallinson & Parlikad 2005

\textsuperscript{165} Diekmann, Melski, & Schumann 2007; ten Hompel 2005

\textsuperscript{166} Mallinson & Parlikad 2005

\textsuperscript{167} Diekmann, Melski, & Schumann 2007
decentralized component and a message is only sent to the central system in case an exception is raised, e.g. the temperature exceeds a certain limit.

- **Increase of stability:** In a centrally controlled system, the failure or breakdown of the single system results in a disruption of the entire system. However, in a decentralized system the stability can be increased as the failure of a single component within a system does not necessarily result in a failure of the entire system.\textsuperscript{168}

### II.5.2 Autonomous control of logistics processes

Due to increased market dynamics, complexity, demand uncertainty and cost pressure, companies need to become more flexible, adaptive and responsive to market demands.\textsuperscript{169} Against this background, numerous authors report that conventional planning and control methods are efficient under steady operating conditions but cannot handle unpredictable events and disturbances in a satisfactory manner.\textsuperscript{170} A promising solution to this is seen in a paradigm shift from the centralized control of non-intelligent objects in hierarchical structures towards decentralized and autonomous control strategies based on ubiquitous computing technologies.\textsuperscript{171}

**The concept of autonomous control**

The idea of autonomous control has been derived from different concepts and research streams of self-organization such as cybernetics\textsuperscript{172}, dissipative structures in Chemistry\textsuperscript{173}, synergetics in Physics\textsuperscript{174}, autopoiesis in Biology\textsuperscript{175} and chaos theory in Mathematics\textsuperscript{176}. The core of the concept is the creation of order in complex dynamic systems.\textsuperscript{177} Certainly, self-organization is not the only approach for designing, building and controlling systems, but it can be very useful in complex

\textsuperscript{168} Diekmann, Melski, & Schumann 2007
\textsuperscript{169} Drucker 1988; Hayes & Pisano 1994; Kim & Duffie 2004; Windt & Hülsmann 2007a
\textsuperscript{170} Baker 1998; Bongaerts, Monostori, & Kadar 2000; Kim & Duffie 2004; Scholz-Reiter, Windt, & Freitag 2004
\textsuperscript{171} Freitag, Herzog, & Scholz-Reiter 2004, Nelson 1998;
\textsuperscript{172} Ashby 1962; Heylighen & Joslyn 2001; von Foerster 1960
\textsuperscript{173} Glansdorff & Prigogine 1973
\textsuperscript{174} Haken 1981
\textsuperscript{175} Maturana & Varela 1991
\textsuperscript{176} Peitgen & Richter 1986
\textsuperscript{177} Paslack 1991, p. 1
systems where all possible configurations, purposes and problems that the system may be confronted with are not conceivable a priori. Examples of such systems are organizations, traffic control, distributed robotics and complex software systems.\(^{178}\)

Although many researchers use the terms of autonomous control and self-organization, they do not have a general accepted meaning. Their definitions vary depending on their specific discipline.\(^{179}\) However, consensus has been reached on the characteristics complexity, dynamics, non-determinism, autonomy, redundancy, interaction and emergence.\(^{180}\) For (production) logistics processes, autonomous control has been defined as “processes of decentralized decision-making in heterarchical structures. It presumes interacting elements in non-deterministic systems, which possess the capability and possibility to render decisions. The objective of autonomous control is the achievement of increased robustness and positive emergence of the total system due to distributed and flexible coping with dynamics and complexity”.\(^{181}\)

The concept of autonomous control requires that objects such as material, machines and transportation systems are able to gather local information, process this information and make decisions based on this information. This approach can be realized by recent information and communication technologies and leads to a coalescence of material flow and information flow allowing each item to control its manufacturing process itself.\(^{182}\)

**Characteristics of the centralized and decentralized paradigms**

There have been a number of attempts to answer the question of whether the centralized or the decentralized paradigm is superior by referring to the concept of complexity,\(^{183}\) which in itself is complex and theoretical. Yet, a better understanding can be reached by comparing characteristics of both concepts.\(^{184}\)

\(^{178}\) Heylighen & Gershenson 2003  
\(^{179}\) Anderson 2002  
\(^{180}\) Hülsmann & Wycisk 2006  
\(^{181}\) Windt & Hülsmann 2007b  
\(^{182}\) Scholz-Reiter, Windt, & Freitag 2004  
\(^{183}\) Philipp, Böse, & Windt 2006  
\(^{184}\) Anderson & Bartholdi 2000
Table 3: Characteristics of the centralized and decentralized paradigm

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Centralized paradigm</th>
<th>Decentralized paradigm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing unit costs</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Data location</td>
<td>Global</td>
<td>Local</td>
</tr>
<tr>
<td>Data collection costs</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Data processing speed</td>
<td>Slow</td>
<td>High</td>
</tr>
<tr>
<td>System robustness</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Pathological situations</td>
<td>Possible</td>
<td>Not possible</td>
</tr>
<tr>
<td>Global maximum</td>
<td>Possible</td>
<td>Not possible</td>
</tr>
<tr>
<td>Operations</td>
<td>Scheduled</td>
<td>Real-time</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Non-existing</td>
<td>Existing</td>
</tr>
</tbody>
</table>

Table 3 summarizes a number of characteristics of the centralized and decentralized paradigm. The centralized concept is characterized by a complex and omniscient processing unit. Being problem specific, the used algorithms are able to provide the globally optimal solution and not just a local maximum. Finding a global maximum based on a decentralized solution is not easily achievable. To obtain an optimal solution, the central system is required to gather all relevant data from the whole system. However, it cannot easily cope with missing data. Furthermore, having to utilize complex algorithms as well as gather and analyze more information, the centralized controllers are often slower at finding a solution than a decentralized system. Additionally, decentralized components might be linked together forming a network that can react to local conditions in real-time and thus can achieve a desirable adaptive behavior. As the adaptive behavior is an emergent attribute of the overall system, decentralized approaches do not necessarily require complexity at the level of individual components and are therefore less expensive than a single centralized component. Finally, one of the most important differences between the two paradigms is system robustness. Decentralized systems tend to be more robust against failure, due mostly to redundancy. In general, failure of one lower level component will not necessarily cause a system-wide breakdown. Rather, the system

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185 adapted from Anderson & Bartholdi 2000
is able to absorb disruptions and re-adjust quickly. In a centralized system, on the other hand, failure of the centralized processing unit can potentially lead to catastrophic failure of the whole system.

II.5.3 Sensor networks

Sensor networks are a specific instance of ubiquitous computing. They have emerged as a promising way to monitor and study previously unobservable phenomena in the physical world. In general, these networks consist of a large number of autonomous, battery-powered, wireless nodes that have the capability of sensing, processing and communicating.\textsuperscript{186} However, the small size of a node imposes restrictions on its resources. Furthermore, a significant amount of data is being generated within the network, causing data management challenges, e.g. where to store and process data.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectrum_data_management.png}
\caption{Spectrum of data management techniques\textsuperscript{187}}
\end{figure}

Many schemes have been proposed for data management in sensor networks, which differ from distributed storage systems in wide-area networks in two respects. First, energy and storage limitations bring in more rigorous communication constraints.

\textsuperscript{186} Intanagonwiwat et al. 2003
\textsuperscript{187} adapted from Ganesan et al. 2005
Second, data in such networks exhibits spatio-temporal correlations that can be utilized in the storage, processing and querying. According to Ganesan et al., the alternative architectural solutions can be summarized along the axes of communication required for data storage and communication required for query processing. Figure 13 depicts the spectrum of data management techniques, which are described in the following paragraphs.

**Centralized storage and querying**

In the conventional approach to centralized data management, all sensor data of interest are transmitted from the nodes to a central repository. Whereas the sending of data is communication and hence energy intensive, queries over this data do not require additional communication as all data already resides outside the network, e.g. in a central database. An advantage of this solution is that intelligence has access to more resource-rich components, making complicated and complex processing possible. Furthermore, useful information can be stored in one location permanently. However, the major drawback of this solution is power inefficiency. As a consequence, centralized storage and querying is appropriate for low-data rate, small-scale sensor networks where there are infrequent events. With increasing data rates and growing size of the network, centralized storage becomes less feasible due to power constraints on the sensor nodes. Particularly, nodes that are close to the base-station are the bottlenecks because they need to relay data from many nodes within the network. In general, centralized storage and querying seems to be reasonable for a network of a hundred nodes transmitting data over two to three hops to the base-station.

**Local storage and flooding or geography-based querying**

In the local storage and flooding or geographical search scheme all useful sensor data is stored locally on each node and queries are flooded out to the network or are geographically routed. Since data is kept at the sensing nodes, communication costs are involved only on demand, which makes this solution energy efficient. However, an in-network search can potentially incur high energy costs. As data can reside anywhere within the network, a query that does not explicitly constrain the physical search space must be flooded to all nodes within the network. Thus, there are three

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188 Ganesan et al. 2005
189 Bonnet, Gehrke, & Seshadri 2000; Diao et al. 2007; Ganesan et al. 2005; He et al. 2005
drawbacks of such a scheme. First, for queries that are not geographically restricted, search costs might be prohibitive for large networks with frequent queries. Second, data is lost if nodes fail or storage limits are reached. Third, the techniques required for dealing with storage limitations and the fact that nodes need to handle queries put significant complexity into the network. As a consequence, the local storage and flooding or geographical search scheme is appropriate when simple queries are infrequently issued and have limited scope. Additionally, the scheme must be able to deal with node failure.\footnote{Bonnet, Gehrke, & Seshadri 2000; Diao et al. 2007; Ganesan et al. 2005; He et al. 2005}

**Local storage and distributed indexing**

There has been a growing body of work on data indexing schemes for sensor networks.\footnote{Greenstein et al. 2004; Li et al. 2003; Ratnasamy et al. 2002} In this approach not only is data stored locally at each node but also distributed indices are constructed. The advantages are that searching is more efficient and requires less communication compared to flooding or geography-based querying. However, the index structure can only deal with specific attribute-based searches but not with arbitrary signal processing functions over the data. Furthermore, data is lost if nodes fail. As a consequence, local storage and distributed indexing is appropriate when searching can be effectively scoped using simple attributes, for instance if temperature is a good indicator of some other activities.\footnote{Ganesan, Greenstein, Estrin, Heidemann, & Govindan 2005}

**Multi-resolution storage and distributed indexing**

Ganesan et al.\footnote{Ganesan et al. 2005} provide another scheme for data management in sensor networks. The key idea behind their approach is spatio-temporal summarization. Sensor data is stored in a multi-resolution hierarchy and fine-grained data is left on the nodes of the lowest level. Summaries are generated corresponding to different spatial and temporal scales. This coarse-grained data is stored on a higher level, e.g. a higher power node. Queries on the data in the network are posed in a drill-down manner. They are first processed on coarse, highly compressed data corresponding to larger spatio-temporal volumes. The result can be used to make intelligent decisions about what nodes to query subsequently. Another advantage is that even if raw data is
phased out, summaries can still be queried. However, processing and hierarchical storage require power, although not as much as centralized storage. As a consequence, the multi-resolution storage and distributed indexing is appropriate for applications where data sizes are large and patterns need to be found in the sensor data.

II.5.4 Summary and implications

In recent years, research on ubiquitous computing technologies and applications has gained momentum. In this field researchers have focused on different aspects, including autonomous control of logistics processes, sensor networks and the decision of whether to store data on tag or in a centralized database. In all three streams the fundamental question on how to design a ubiquitous computing application is addressed with the ultimate goal to determine an appropriate distribution of data and functions.

Over time, several factors have been identified that influence the arrangement of data and functions leading to certain advantages and disadvantages. Generally, centralized solutions should be preferred if high security and optimality are important issues. In contrast, decentralized solutions should be implemented if real-time decisions need to be made, data needs to be accessed at remote locations, real-time data needs to be captured, central systems need to be relieved and the frequency of data access is high. Additionally, in decentralized systems stability, responsiveness and reliability are increased as well as complexity reduced. Finally, communication is an important factor that may lead to centralized or decentralized solutions depending on the specific application.

From the analysis of related work in ubiquitous computing research following propositions can be inferred concerning the (de)centralization issue:

Proposition 19: Centralize to improve security.

Proposition 20: Centralize to reach optimality.

Proposition 21: Decentralize to improve responsiveness.

Proposition 22: Decentralize to reduce and be able to cope with complexity.

Proposition 23: Decentralize to improve reliability and availability.
Proposition 24: Decentralize to enable real-time decisions.

Proposition 25: Decentralize to enable data access at remote locations.

Proposition 26: Decentralize to enable real-time data capture.

Proposition 27: Decentralize to relieve central systems.

Proposition 28: Decentralize to minimize the sum of data storage cost and query processing cost.

II.6 Summary

Table 4 summarizes the findings of the investigation of related work from the research fields organization science, information systems, distributed systems, production planning and control as well as ubiquitous computing. The summary includes the fundamental question in regard to (de)centralization, the goal that researchers aim at when answering this question, the factors and drivers that have an influence on centralization and decentralization respectively as well as propositions or statements that can be inferred from the investigated literature of the different research streams.

<table>
<thead>
<tr>
<th>Research field</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organizational science</td>
<td><strong>Fundamental question</strong></td>
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<tr>
<td></td>
<td><strong>Goal</strong></td>
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<td></td>
<td><strong>Factors</strong></td>
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<td></td>
<td><strong>Propositions</strong></td>
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<tr>
<td>Information systems</td>
<td><strong>Fundamental question</strong></td>
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<tr>
<td>Research field</td>
<td>Summary</td>
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<tr>
<td></td>
<td>rights?</td>
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<tr>
<td>Goal</td>
<td>Determining an appropriate arrangement for information technology resources such as hardware, software, communication equipment, data and people</td>
</tr>
<tr>
<td>Factors</td>
<td>Efficiency, optimality, control, flexibility, responsiveness</td>
</tr>
<tr>
<td>Propositions</td>
<td>Proposition 3: Centralize if knowledge transfer costs can be reduced by means of information technology.</td>
</tr>
<tr>
<td></td>
<td>Proposition 4: Decentralize if agency costs can be reduced by means of information technology.</td>
</tr>
<tr>
<td></td>
<td>Proposition 5: Centralize to improve efficiency.</td>
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<td></td>
<td>Proposition 6: Centralize to reach optimality.</td>
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<td></td>
<td>Proposition 7: Centralize to stay in control.</td>
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<td></td>
<td>Proposition 8: Decentralize to increase flexibility.</td>
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<td></td>
<td>Proposition 9: Decentralize to improve responsiveness.</td>
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<tr>
<td>Distributed systems</td>
<td>Fundament question</td>
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<tr>
<td></td>
<td>How to design a distributed system?</td>
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<tr>
<td>Goal</td>
<td>Sharing of resources in a controlled and efficient way</td>
</tr>
<tr>
<td>Factors</td>
<td>Sharing of resources, extensibility and scalability, reliability and availability, performance, maintenance effort</td>
</tr>
<tr>
<td>Propositions</td>
<td>Proposition 10: Decentralize to share resources in a controlled and efficient way.</td>
</tr>
<tr>
<td></td>
<td>Proposition 11: Decentralize to improve</td>
</tr>
<tr>
<td>Research field</td>
<td>Summary</td>
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<td>----------------</td>
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</tr>
</tbody>
</table>
| extensibility and scalability.  
*Proposition 12:* Decentralize to improve reliability and availability.  
*Proposition 13:* Decentralize to improve responsiveness.  
*Proposition 14:* Centralize to reduce maintenance efforts. |
| **Production planning and control** | **Fundamental question** | How to design a production planning and control system? |
| **Goal** | Determining the type and quantity of products to be produced and to handle disturbances under consideration of minimal costs |
| **Factors** | Complexity, responsiveness, optimality |
| **Propositions** |  
*Proposition 15:* Decentralize to reduce and be able to cope with complexity.  
*Proposition 16:* Centralize to reach optimality.  
*Proposition 17:* Decentralize to improve responsiveness.  
*Proposition 18:* Decentralize to improve adaptability. |
| **Ubiquitous computing** | **Fundamental question** | How to design a ubiquitous computing system? |
| **Goal** | Determining an appropriate distribution of data and functions |
| **Factors** | Security, costs, real-time decisions, data access at remote locations, real-time data capture, frequency of data access, relief of central systems, stability, complexity, responsiveness, optimality, reliability, communication |
Proposition 19: Centralize to improve security.
Proposition 20: Centralize to reach optimality.
Proposition 21: Decentralize to improve responsiveness.
Proposition 22: Decentralize to reduce and be able to cope with complexity.
Proposition 23: Decentralize to improve reliability and availability.
Proposition 24: Decentralize to enable real-time decisions.
Proposition 25: Decentralize to enable data access at remote locations.
Proposition 26: Decentralize to enable real-time data capture.
Proposition 27: Decentralize to relieve central systems.
Proposition 28: Decentralize to minimize the sum of data storage cost and query processing cost.

Table 4: Summary related work
III  Radio frequency identification applications in practice

In this chapter cases of ubiquitous computing applications for manufacturing are presented. These form the basis for the subsequent analysis. Besides a description of the cases, selection criteria and the overall structure of the case description are presented. The investigated cases are summarized in Table 5.

<table>
<thead>
<tr>
<th>Company</th>
<th>Application</th>
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</thead>
<tbody>
<tr>
<td>Nestlé</td>
<td>Tracking of containers and its contents within confectionary production</td>
</tr>
<tr>
<td>Infineon</td>
<td>Using RFID and ultrasound sensors to improve production in a wafer fabrication</td>
</tr>
<tr>
<td>BP</td>
<td>Distribution of business logic and data to real-world items for hazardous goods and safety management</td>
</tr>
<tr>
<td>Engine cooling modules producer</td>
<td>Using RFID in the production process of cooling modules</td>
</tr>
<tr>
<td>Huf Tools</td>
<td>Using RFID in the production process of car keys</td>
</tr>
<tr>
<td>Aerospace industry</td>
<td>Using RFID in the internal and external supply chain</td>
</tr>
<tr>
<td>HP</td>
<td>Using RFID for tracking printers for production, distribution and reverse logistics</td>
</tr>
<tr>
<td>Airbag producer</td>
<td>Using RFID in the production process of airbags</td>
</tr>
<tr>
<td>Movianto, inet-logistics</td>
<td>Monitoring of cool chains</td>
</tr>
<tr>
<td>Institute for Material Flow at the University of Dortmund</td>
<td>Distributed control nodes for material flow system control</td>
</tr>
<tr>
<td>DaimlerChrysler</td>
<td>Putting RFID tags in kanban cards</td>
</tr>
</tbody>
</table>

Table 5: Investigated cases
III.1 Case study selection and presentation

In this section the case study selection criteria as well as the way of preparing and structuring the case descriptions are presented.

III.1.1 Selection criteria

Building theory from cases is a research strategy that involves one or multiple cases to create theoretical constructs, propositions and theory based on empirical evidence drawn from cases. An important part within this type of research is the selection of relevant cases. Whereas in hypothesis-testing research statistical sampling is crucial, the sampling of cases from a chosen population is atypical when building theory from cases. Rather, such research relies on purposive sampling, i.e. cases are chosen for theoretical but not statistical reasons. This creates a high degree of openness and flexibility – which is required when new fields are being investigated and theoretical constructs and concepts are relatively undeveloped.

Given the limited number of cases that can generally be studied, it is practical to choose cases of polar types or extreme and deviant positions in which the subject of interest is transparently observable. Against this background, the goal should be to choose cases which are likely to replicate or to extend the emerging theory, rather than to obtain accurate statistical evidence on the distributions of variables within a population. Like a series of related laboratory experiments, each instance of a multi-case study can be seen as a discrete experiment that stands on its own as an analytic unit and serves as a replication, contrast and extension to the emerging theory.

Besides the question of case selection, another important question to be answered is how to decide when to stop investigating further cases. Glaser and Strauss suggest the criterion of theoretical saturation: “The criterion for judging when to stop sampling the different groups pertinent to a category is the category’s theoretical saturation. Saturation means that no additional data are being found whereby the sociologist can develop properties of the category.” In summary,

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194 Glaser & Strauss 1975
195 Miles & Huberman 1994, pp. 16-18
196 Pettigrew 1990
197 Yin 2003
198 Glaser & Strauss 1975, p. 61
199 Glaser & Strauss 1975, p. 73
sampling should be finished if nothing new emerges from the investigation of additional cases.

Finally, Morse\textsuperscript{200} defines several generic criteria for good interviewees. First of all, they should have the necessary knowledge and experience of the issue under investigation to be able to answer questions in interviews and in observational studies. Furthermore, participants should also be able to reflect and articulate their ideas, opinions and experiences. Additionally, they should have the time and willingness to participate in the study. If all these conditions are fulfilled, such a case is most likely to be integrated into the study. However, if not all of the before-mentioned criteria are fulfilled, the case should only be used if it is rich in relevant information and contributes to the emerging theory.

As shown earlier, the implementation of ubiquitous computing technologies in manufacturing is a relatively new field of research. Furthermore, although the concepts of centralization and decentralization have emerged in various disciplines, a mutual agreement on these concepts has not yet been found. Thus, a high degree of openness and flexibility is required to answer the posed research question. For this, cases have been chosen based on their likelihood to replicate or to extend the emerging theory. Particularly, the focus was set on an extreme position, e.g. on cases in which data were stored on the tag and where business logic was executed on an object itself. However, cases of the other extreme, e.g. cases in which only a unique identification number was stored on a tag, were also included as this could give insight into when not to decentralize data and functions. In addition, only those cases were taken into consideration for which enough relevant information could be found and for which the interviewees fulfilled the before-mentioned criteria. The reason for presenting mini-cases in addition to full-developed cases in this chapter is that some cases may be able to contribute to the emerging theory even though only limited information could be gathered.

\textbf{III.1.2 Preparation and presentation of the case studies}

This section outlines the structure used for the case study presentation. After a short introduction describing the company, each case is structured along the following elements:

\textsuperscript{200} Morse 1998
• **Initial situation and objectives:** The description starts with an overview of the initial situation of the company. On the one hand, the manufacturing process which was used before the implementation of ubiquitous computing technologies is described. On the other hand, known process issues are outlined which finally led to the decision to introduce new technology. This section will help the reader understand what the process issues of the company are and how ubiquitous computing technologies are expected to improve the situation.

• **Application description:** In this section the new application is described in detail. This includes the new established physical process, the technologies used and the implemented architecture. A special focus is set on the information flow and the location of executed manual and automated tasks and functions. This section will help the reader understand the new solution. Additionally, it will partially help answering the research question on the involved cost factors and benefits of the solution.

• **Decentralization of data and functions:** Based on the previous two parts, this final section focuses on two issues. One the one hand, it analyzes what data is stored and which functions are executed centralized and decentralized respectively. On the other hand, it examines why data and functions are stored and executed on a higher or lower level of the architecture. This section will help answer the research question on the factors that have an influence on the (de)centralization of data and functions as well as the question of how these factors influence the solution. Furthermore, additional cost factors and benefits can be extracted.

### III.2 Food industry: Tracking of containers in confectionary production

Nestlé is the world’s largest food and beverage company and has factories or operations in almost every country in the world. The two main brands of the company are NESCAFÉ and KitKat. Also, Nestlé is one of the major manufacturers for UK's yoghurt and fromage frais sector with brands such as Ski and Munch Bunch. Within the EU project BRIDGE, the company provided access to their facilities, manpower and industrial experience in order to explore the benefits of RFID in manufacturing. In the project, it was examined how RFID could provide accurate and complete batch level information in a timely manner, to enhance the
management of production processes within a factory from raw materials to finished products. The main objective was to enhance manufacturing processes through improved RFID-enabled track and trace of manufacturing resources and work-in-progress products. Based on a detailed analysis and a business case calculation, one application called Intermediate Bulk Container (IBC) management was selected for piloting. The following information was derived from active participation in the project including factory visits, process analysis and discussions with project partners.

III.2.1 Initial situation and objectives

Wrapped Quality Street sweets are semi-finished products, which are stored in large plastic containers prior to being consumed on packing lines. The management of these containers – including filling, transporting, tipping, washing, and storing – is currently managed by a barcode system. The process before the implementation of RFID and the barcode scan points is depicted in Figure 14 and described in the following paragraphs.

Wrapping and filling area

The production process starts at the wrapping and filling area. The sweets on the production line are wrapped and the wrapping machine then pours the sweets into an empty IBC, which can contain about 500kg. When the IBC is full, a sensor on top of the container indicates to the worker that the full IBC is ready to be taken away. This full IBC is picked up with a hand-held trolley and brought to the weight scale at the bottom of a hoist where its contents and weight is recorded. Depending on the current stock buffer at the packing lines, the system indicates that the IBC should either be taken to the buffer in the packaging area or to the cold store. At scan point 1, a barcode plate on the wall is scanned to indicate which line the IBC came from. Additionally, a scan of the IBC captures its unique number. The weight from the weight scale is automatically associated with the IBC and displayed on the scanner where the operator accepts the weight. This associates the weight with the IBC and performs a goods receipt from the wrapping machine as well as creates stock in the MES. After that, a message is sent to SAP with a Serial Shipping Container Code (SSCC) to create stock from the process order which is running on the line. The location of the IBC is set to either ‘in transit to buffer’ or ‘in transit to cold store’ depending on the IBCs destination.
For the wrapping and filling area, there are three locations where empty IBC’s can come from. First, from tipping, where an IBC is scanned (scan point 7) before it is put into the hoist. This scan triggers a location transfer from ‘in transit’ to ‘in wrapping and filling’ in the MES. Second, from cold store, where an IBC is scanned (scan point 13) to ‘filling storage location’ in the MES. Third, from washing, where an IBC is also scanned (scan point 13) to ‘filling storage location’.

**Figure 14: IBC management process before the implementation of RFID**
Packing area

A buffer in the packing area receives full IBCs from the two locations, filling area and cold store. IBCs arriving from these areas are transported by a hoist to the tipping area, where a forklift puts them in the buffer store for intermediate storage. Regardless of where the full IBC comes from, after it arrives in the packing area, a location plate on the forklift truck and the IBC are scanned to transfer stock from ‘in transit’ to ‘in buffer’ (scan point 2).

When a full IBC is needed at a particular tipping line, triggered by an empty IBC at the line, a forklift picks up a full IBC from the buffer area and transports it to the line. At scan point 3, a location plate is scanned which indicates the tipping line number. Additionally, the full IBC is scanned. This sets the status of the IBC to ‘emptying’ in the MES and the message ‘issue full stock to process order on the tipping line’ is sent to SAP. There are always two containers at a line – one in the process of being emptied and a full IBC ready to be emptied. When the IBC is close to empty, a beacon is flashed at the line. The IBC is taken off the line and the worker scans an ‘empty’ barcode plate as well as the IBC (scan point 6). At this point, the system again decides where the empty IBC should be sent. Based on instructions from the system, a forklift truck transports the empty IBC either to tipping or to the cold store. The sweets, which are now in tins, boxes or bags in different sizes and compositions, are transported from the lines to the packaging area. The finished product is then stacked on pallets and prepared for distribution. The pallets are scanned (scan point 8) and processed in the pallet management system, which records the final product receipt. Besides this ideal process, Nestlé needs to be able to handle certain exceptions.

- First, process orders on packing lines run 24 hours and each process order closes at midnight. When an IBC batch spans two process orders, a special set of steps are performed: At midnight, each IBC on the lines is scanned (scan point 4) to ‘transfer to next process order’. After each scan, the worker enters a percentage of how much is left in the IBC. The status of the IBC does not change, but two messages are sent to the SAP system – ‘goods issue reversal’ and ‘goods issue to next process order’.

- Second, sometimes when an IBC is emptying a reason might come up why it needs to be taken off the line before it is empty, for example if the process is stopped. In that case, the worker scans (scan point 5) a ‘goods issue reversal’
barcode plate and the IBC barcode. Again, the worker enters on the scanner the percentage of goods that are left in the IBC. In the SAP system the percentage is reversed out of the process order. In the MES the status of the IBC is changed back to full, but with an adjusted weight and the location defaults to the buffer location. The IBC goes back to buffer stock within the packing area and is used later.

- Third, in packaging some of the sweets might be packaged incorrectly or the packaging might be damaged. Such sweets termed ‘rework’ are collected and periodically tipped into an empty IBC. The first tipping is registered by scanning a location plate and the IBC (scan point 9). Before rework is put into the IBC, the number of bowls being put into the IBC is entered. In the MES the weight is added to the IBC and a ‘rework goods receipt’ transaction is sent to the SAP system. In the MES, the status of that IBC is set to ‘filling’. When the IBC is full, a separate barcode plate ‘full’ is scanned (scan point 10), which sets the status of the IBC to full. The full IBC of mixed, rework sweets is taken either to the buffer or cold store, based on operator decision since the buffer logic is not applied in the rework process.

**Cold store area**

Full IBCs are sent from filling and from rework to the cold store if there is no immediate need for a full IBC in tipping. Also, empty IBCs arrive from either tipping or washing if they are not needed in filling. From filling (scan point 1), tipping (scan point 6) or washing (no scan point), a forklift truck transfers the full IBC to a hoist and it goes up to the cold store. When the container arrives at the cold store, it is placed into a pod (x,y,z coordinates) and scanned to that location (scan point 11). The new location is stored in the MES, but no message is sent to the SAP system. Additionally, within the cold store some IBCs have a quality status of ‘blocked’, for instance because the sweets are badly wrapped. These must not be used in subsequent process steps until released. The information regarding which IBCs are to be taken where is displayed on the buffer screen. The screen also displays information about which pod to remove the IBC from.
**Washing area**

Ideally, if an IBC is used ten times, it should be sent to washing. However, empty IBCs are sent to the washing area for cleaning on visual inspection. Two types of buffer areas exist in washing – one in which the containers wait for the washing process, and one in which containers wait to be transported to the cold store or wrapping area. When an IBC arrives at washing, the container barcode and a location plate are scanned (scan point 12). This sets the location of the IBC to ‘washing’ and a ‘last wash date’ of the IBC attributes is set to the current date and time in the MES.

**Process issues**

In the described manufacturing process, human error during scanning is reported to be the biggest source of material and time waste. Operators may make an error and issue the quality restricted, blocked or even send the wrong sweets to a line. Particularly, due to the seasonal nature of sweet management, agency staff is employed on a temporary basis. As this staff is not as experienced as permanent staff, human error increases during peak production times. Human error during scanning not only has an effect on time and material waste but also has potential to result in quality pitfalls. Scanning is done to track IBCs and IBC tracking is rather complex as there are various states and locations to be included. Another, important part of IBC management is making sure that there are enough empty IBCs at the filling area. Furthermore, although the current system is able to track the maintenance schedule of the IBCs, this functionality is not used. Because of the outlined process issues, the objective of the project was to reduce waste and optimize the circulation of IBCs.

**III.2.2 Solution description**

For the design and deployment of the RFID solution Zetes, a leading pan-European company in the value-added solutions and services industry for automatic identification of goods and people, was selected. The company recognized that a flexible and scalable RFID solution design was extremely important for the project. Therefore, they proposed a design that is a flexible, non-intrusive, rapidly deployable, scalable and cost effective. Such a solution aims at delivering the traceability improvements at low risk and with a quick payback.
Architecture

Figure 15 depicts the general architecture of the solution. Overall, the solution design is flexible, scalable and cost efficient as well as easy to integrate into the existing infrastructure. The existing system, which consists of SAP, MES, SCADA, weighing scales, barcode scanners, label printers and a wireless network, stays in place and only the MES needs to be adapted. At the heart of the Zetes design is the
so-called Tag Acquisition Processor (TAP). This component assigns and operates antennas independent of which reader they are connected to. A wide range of readers and antennas from different manufacturers can be mixed and matched to suit the RFID application and managed effectively by this intelligent network device. Because of this functionality the TAP is ideal to power a RFID pilot, multi-applications and a multi-site rollout. Additionally, TAP supports both standard and application-specific interfaces. It is easily interfaced to management execution and other enterprise systems, which is important to Nestlé since this flexible interface approach facilitates rollout across a wide range of Nestlé’s business systems and applications.

The solution required the mounting of RFID readers and antennas on the forklift trucks together with a compact truck terminal for the user interface. Most importantly, this mobile design is not intrusive and therefore will not impact the day-to-day running of the operation. Additionally, it is a highly flexible solution that meets changing needs of the business both now and in the future. This is particularly important during periods of peak activity. The alternative would have been to install fixed readers and antennas at the filling, weighing and tipping stations. However, the implementation of a large amount of fixed readers and antennas together with the associated data and power cabling would have resulted in a lot of disruption to the operation. Moreover, this solution would have been more expensive and less flexible.

Since IBCs can be read from different sides, each container has three RFID labels with an identical serial number attached to it. Additionally, two rigid RFID tags were embedded in the floor just in front of each filling station. This is required to record when an empty IBC is put onto and removed from a filling point without any manual intervention. If it then came to light that an operator had by-passed the ‘goods receipt’ action earlier in the process at the weigh-scale, it would be possible to trace exactly when and on what line the IBC was filled and the ‘goods receipt’ transaction could be carried out retrospectively.

Process description

When the IBCs are removed from the filling stations, they are transported to the weighing stations. When the antenna of the forklift truck detects that it is positioned at a weighing station, this information is sent to the MES. A record is transmitted to the database with the IBC serial number and the RFID tag serial number at the
weighing scale. As soon as the weight is recorded a message is sent back to the TAP for instructions on where to direct the IBC. The Zetes application reads the record from the MES database and displays the IBC destination information on the screen of the forklift terminal, instructing the operator to remove the IBC and take it to the requested location.

There are more than 70 tipping stations which requires more than 10 fixed RFID readers to be able to identify the IBC tags at the tipping stations. Again, mobile RFID antennas, readers and compact display terminals mounted on the forklift trucks were a more cost effective and flexible solution for the tipping stations. An RFID tag placed on top of the metal floor, but protected behind the guide rails, was used to indicate at which tipping station the truck driver delivers the IBC. This information is sent by the TAP to the MES. A message is returned for display to the operator on the screen of the forklift terminal. This information should be confirmation to the truck driver to pick up the next IBC or an error message.

### III.2.3 Distribution of data and functions

In the described application neither data nor functions were distributed. A number of reasons were identified for this solution. First, the key issue prior to the implementation of RFID technology was the large amount of waste products that had to be scrapped. The major reason for this was incorrect barcode scanning procedures performed by the workers at the filling, tipping and packing lines. Thus, the new RFID system is mainly a replacement of the barcode system to reduce manual, error-prone tasks. Additionally, this barcode system used a wireless network infrastructure to communicate with the backend systems. As this infrastructure could also be used for the RFID system, there were no major infrastructure costs.

Second, as the new system was basically an adaptation of the existing barcode system, some of the functionality was implemented already. However, what was missing was some additional functionality in the MES. Because this MES solution was not a standard software solution but developed for Nestlé explicitly, it was easy to add the missing functionality. Furthermore, there was no need to change the SAP system. However, a software solution was required for integrating RFID readers and for communication with the MES. For this, a software company was selected that was able to deploy a flexible and scalable system, which focused on standard interfaces for communication with the readers and backend systems. Against this
background, the cost for adapting existing software was relatively low and it was easy to extend the legacy system.

Third, even though there would have been scenarios for distributing data and function, most likely Nestlé would not have done so because of synchronization problems between the data on the tag and a central database. Not only are techniques required for synchronizing the two instances, but also a backup of the data on the tag. The tag might get lost or destroyed which would lead to the loss of data unless a copy exists. Thus, for Nestlé the only reason for distributing data and functions is a missing network connection.

III.3  Automotive industry: Production of engine cooling modules

A first-tier automotive supplier, whose name will not be published because of nondisclosure policy, is a globally operating systems partner for the international automobile industry. The company is a specialist in producing engine cooling modules and air conditioning devices for a wide range of automotive companies. It is one of the world’s leading manufacturers and suppliers of original equipment for passenger and commercial vehicles. Their products are either shipped directly to original equipment manufacturers (OEMs) or they enter the aftermarket. At the company, logistics is a key factor in production as it has an effect on almost every type of waste. The company uses just-in-sequence (JIS) and just-in-time (JIT) delivery to guarantee their customers that the correct modules will be delivered at the right time. The company deployed two identical RFID-enabled assembly lines for the production of engine cooling modules in 2003. In this section, the design and implementation of the solution is described. The following information is derived from a report.

III.3.1 Initial situation and objectives

Two identical assembly lines operate twelve hours a day and five and a half days a week. In total, the company produces about 1300 engine cooling modules per day of up to 32 different types. These are put onto a pallet in the order pre-defined by the customer (JIS production). At the end of the production the finished products are put into a truck and instantly shipped to the customer. One order can consist of

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varying amounts of different types of coolers. The two lines work in parallel to fulfill one order each. However, depending on the modules currently produced, the lines vary in their operation speed.

The manufacturing process is coordinated by two software components. First, programmable logic control (PLC) software, which controls a single production line. Second, a centralized JIS software, which is responsible for the correct sequencing of an order on a pallet. Each engine cooling module to be manufactured is put into a carrier which then is moved along the assembly line from workstation to workstation where a worker performs a certain number of tasks. Each of these workstations is able to perform any task which allows for some flexibility in the planning process. One production line is dynamically composed of up to six serial connected workstations. However, if necessary it is possible to have a production line with only three workstations. According to the company, the optimal number is five per line.

The manufacturer introduced RFID technology at the request of one customer who expected improved traceability of the products produced. Tracking and tracing of parts and components is of high importance for OEMs for two major reasons. On the one hand, manufacturers are required to be able to track and trace parts and components by law. On the other hand, they want to improve quality in the long term by identifying faulty parts and components quickly and reliably in the case of a required recall.

III.3.2 Solution description

The following steps are performed at each line during production (see Figure 16). At the beginning of the production process an empty pallet, which can carry up to six finished products, is taken. The PLC software sends a request to the JIS software and retrieves the type and sequence for the next six modules to be produced on the dedicated line. A control label is printed and attached to the pallet. In the next step, the module data for one product and the number of active workstations are retrieved. Based on this information, the required processing tasks for a module are sub-divided and assigned to the active workstations.

For the actual production process, an RFID tag is attached to each carrier but not to the product itself. On the tag, engine cooling module specific data are stored which includes the type of the module and job parameter. During production the
information is constantly updated with the production progress. The module carrier is then put onto the assembly line. At each workstation the job instructions are read from the RFID tag and displayed on a screen. The worker then assembles the required parts and confirms that a task has been completed. This information is written back onto the tag. The semi-finished module is then sent to the next workstation. When all tasks are performed the finished module is taken off the line, out of the carrier and is put onto a pallet. At that point, all data on the RFID tag is transferred to the JIS software. A barcode label containing the module’s serial number is printed and attached to the product. When the pallet is completed, a worker verifies the correct position of the different modules, prints a control label and attaches it to the pallet. A forklift driver scans the barcode on the pallet, determines the position of it on the truck and stores it in the correct position.

![Figure 16: Engine cooling module production process](image)

### III.3.3 Distribution of data and functions

Major reasons for distributing data are implementation costs and difficulty to adapt legacy systems. At each workstation job instructions are read from the RFID tag. Once the task has been completed, this information is written back onto the tag. For each engine cooling module up to 3000 bytes of data are saved. Besides the job parameters and production progress this includes information about the product.

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[202 adapted from Günther & Ivantysynova 2006]
itself, which machines performed which task as well as production errors. At the end of the production process the complete data set is transferred and stored in backend systems and is made available to both the quality assurance and the planning department.

Basically, there are two options for providing workers with the information about the next tasks to be performed: writing data on the tag and retrieving the data from the backend system at the time data is needed. In this application it was cheaper and easier to store the data on the tag than to implement and maintain a connection between the workstations and a central manufacturing execution and other backend systems. Additionally, no functions except reading from and writing data to the tag are now performed locally.

During the project, it was also mentioned that it might be possible to exchange data among supply chain partners using RFID tags rather than integrating backend systems of the different partners. This would ensure an easy and consistent access of product data across its lifetime. However, the data provided on the tag would need to be selected carefully to avoid revealing any confidential information, e.g. on the assembly process. For this, security features need to be incorporated into the solution. Additionally, as the number of companies accessing the data on tag increases, standardization will become a major issue.

### III.4 Semiconductor industry: Production of silicon chips

Infineon Technologies, one of the world’s largest semiconductor manufacturers, offers semiconductor and system solutions for the automotive and industrial sectors, for applications in the wired communications markets, secure mobile solutions as well as memory products. Not only has Infineon opened the RFID Solution Excellence Center and System Lab in Graz, thereby introducing a keystone of the company strategy to provide solutions and presenting a complete RFID system for logistics applications, but also the company is using a combination of radio frequency and ultrasound technologies for continuously monitoring and managing its production of silicon wafers. Infineon Technologies uses in its wafer production...
fabrication facility in Villach, Austria is described. The following information is derived from interviews\textsuperscript{204} and reports\textsuperscript{205}.

**III.4.1 Initial situation and objectives**

Like other companies in the semiconductor industry, Infineon seeks to reduce stock, improve efficiency, decrease lead times, eliminate handling errors and reduce non-value-added activities of its production by automating its processes. While a number of highly automated production system solutions based on conveyor belts exist today, those mostly address the needs of large fabrication facilities with rather static processes, limited product variety and high-volume production. However, factories with a strong customer orientation with a large number of product variations as well as frequent rearrangements of a factory’s machinery and equipment require more flexible, operator-centric automation approaches.

Against this background, Infineon implemented a real-time localization system called LotTrack, which combines active RFID tags, passive RFID tags and ultrasound sensors to precisely locate and track plastic wafer boxes and cassettes in the manufacturing process. The factory develops and produces car components primarily for use in engine management, transmission control as well as comfort and safety management. It operates 24/7 and about 2000 workers are employed at that location. In total, about 800 different products are manufactured, summing up to a volume of 10 billion chips per year. Each product needs to pass through an average of about 400 production steps on 600 machines. This enormous variety of processes does not allow for automation using conveyor belts. Rather, operators transport production lots manually from one machine to another. To illustrate this complexity, Figure 17 shows the path of a product through the factory during the production process. For the production, lots are kept in plastic boxes (see Figure 18), each containing a wafer cassette holder for up to 25 silicon wafers. Between the different production steps and the final tests, these boxes are stored on metal shelves throughout the clean room.

In the past, a central MES planned and scheduled the production procedures for each machine. However, the factory had to deal with two major issues. First, the intermediate transport processes were not transparent and analysis showed that a

\textsuperscript{204} Dierkes 2006, 2007

\textsuperscript{205} Fischer, Dierkes, & Eisen 2006; Thiesse, Fleisch, & Dierkes 2006
higher transparency could increase machine utilization and decrease lead time. Second, for operators the planned operation sequence was hard to follow if a subsequent lot for processing was not in place. Because of these issues, Infineon equipped the factory with a real-time identification and localization system that made the entire production process visible and thus controllable. The project’s main goals were to decrease lead times, eliminate handling errors and reduce non-value-adding activities.

Figure 17: Silicon chips production process

III.4.2 Solution description

At the beginning of the production process, an operator attaches a battery-powered RFID device onto a lot box (see Figure 19). This device is also equipped with an ultrasound sensor for localizing. Additionally, the following features are integrated:

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Dierkes 2007b
• A two-colored light emitting diode (LED) that issues a visual alarm to reduce time for finding a specific box.

• An opto-mechanical signaling device called flipdot for indicating the status of a box, e.g. reserved.

• A no-power display through which workers get information about the next machine, the status of the wafers and the next operations.

• Four keys for user interaction.

![Lot box and wafer cassette holder](image)

*Figure 18: Lot box and wafer cassette holder* 

Besides the DisTag a special hardware and software infrastructure was required. On the one hand, RFID controllers were connected to antennas and ultrasound emitters. On the other other, a central server was implemented managing localization and communication operations as well as communicating with the MES and a visualization tool that gives a graphical overview of all the wafer boxes in the factory.

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207 Thiesse, Fleisch, & Dierkes 2006
The wafer production is organized according to dispatch lists that contain all waiting lots ordered by priority. Within the box, there is a wafer cassette equipped with a passive tag. After selecting the next lot on a screen, the operator picks up the box, brings it to a machine indicated by the display, takes the cassette out of the box, puts it into the machine and starts the processing. A reader on the machine identifies the passive tag attached to the cassette to make sure that no duplicate or missed process step occurs. After processing, the operator takes the cassette out of the machine, puts it back into the box and stores the box on a shelf. There, it waits to be picked up by a worker for the next operation.

**III.4.3 Distribution of data and functions**

Overall, from the factory’s point of view the system implemented is a centralized one. The increasing pressure of costs in the semiconductor industry and an increasing number of custom specific products has led to the more and more complex production processes. This also demands the fast, precisely-detailed planning and scheduling of automation systems because the required tasks can no longer be carried out using conventional, often manual methods. As conventional enterprise resource planning systems are not capable to handle such situations, the MES is very powerful in the semiconductor industry. Therefore, whereas manufacturing master data are retrieved from the enterprise resource planning system, no further integration with this system exists. The MES is solely responsible for planning and scheduling of the production. For this, the system

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208 Thiesse, Fleisch, & Dierkes 2006
stores work plan data, inventory, location of wafer boxes as well as the production plan and is responsible for communicating this information to the worker on the shop floor.

However, in this application at Infineon, two usage scenarios are implemented. On the one hand, data can be retrieved from the backend system when needed, which is the primary solution. On the other hand, data about the production steps is stored on the wafer box. The decentralized stored data serve as a backup. It is needed for displaying the next process step to the operator and is accessed if the network connection fails. This is required because a stopping of the critical production processes would lead to major losses, which should be avoided. Additionally, as the decentralized data is mirrored and not manipulated, no synchronization issues arise and the overall system stays consistent.

III.5 Petrochemical industry: Managing hazardous goods and workplace safety

BP, one of the world’s largest integrated oil companies, believes ubiquitous computing technologies will provide a healthy return on investment by increasing asset utilization, reducing maintenance costs and improving the ability to respond in case of problems in the field. Thus, besides the initiative described next in detail, the company is also piloting advanced wireless sensor networks to monitor the safety of its workers (health, safety and security applications), the location and contents of its railcars (supply chain applications) and the state of heavy machinery on one of its oceangoing tankers (asset life cycle and maintenance applications). The following information is derived from an interview, a factory visit and reports.

III.5.1 Initial situation and objectives

Many products of today’s modern industrial society depend on the use of potentially dangerous chemical substances, and frequently severe accidents occur during their processing and storage. Such accidents not only pose a health and safety hazard to workers and to the public but also lead to high costs for the company operating in

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209 Roberti 2006a
210 Haller 2007
211 Decker et al. 2005; Karnouskos et al. 2007; Nochta, Oertel, & Spiess 2005; Spiess et al. 2005
such an environment. Those costs include reconstruction costs, lost production, court costs and fines. Among others, prominent causes for these accidents are a low perception of the involved risk in certain activities, a poor management of storage and processing of chemicals as well as unreliable and inadequate control systems. Against this background, one goal of the project Collaborative Business Items (CoBIs) was to contribute technologies and services to help manage these prime causes, thereby reducing the number of accidents. Traditionally, software systems that provide various services for enterprises are based on highly decentralized, manual and thus often error-prone data collection combined with centralized data storage and business logic execution. An important intention of this project was to apply recent advances in the area of sensor networks to distribute data and business logic functionality to physical entities. In this way, the actual status of the enterprise, as it is represented in business processes and in the supporting enterprise software systems, can reflect more precisely what is actually happening in the real world.

The overall objectives of the project were twofold. On the technical side, the goals were to provide collaboration concepts and methods, independent from underpinning hardware platform, ensure usability for non-expert users as well as evaluate results in real-world application scenarios. On the business side, the goals were to understand the impact of ubiquitous computing technologies on business processes, optimize existing business processes, show innovative business processes, disseminate project results to external companies and exploit project results through business units of industry partners.

### III.5.2 Solution description

One of the key scenarios of the CoBIs trials was the smart chemical drums application. In this application drums containing hazardous substances were equipped with sensor nodes that are able to determine their location, communicate with other sensors, keep information about their content and raise an alarm in case of critical situations. The rules for these situations were set in a backend system and then pushed down to the nodes using a wireless network. The first on-site application trial was conducted between June, 12th and July 20th 2006 at BP’s Saltend chemical plant in Hull, UK. A second trial was conducted between November, 13th and December 15th 2006. In both trials, around 20 containers with different content were equipped with nodes and three storage locations were set up
within two buildings so that incompatible materials could be stored in different locations. The use cases implemented included the following:

- **Monitoring of storage limit:** This use case was concerned with the detection of the exceeding of pre-defined storage limits in a location. Nodes mounted on the drums communicated to each other and exchange the current amount of the chemical substance within the container. Each of them then sums up the amount of all other amounts received and calculates whether the limit is exceeded or not. In the trial, the limit was set to two drums, e.g. as long as there were less than three drums detected in a location everything was acceptable indicated by a green LED light. However, whenever there were more than two drums detected, a LED turned red and an acoustic signal was raised.

- **Monitoring of incompatible chemicals:** In this use case, the kind of chemical in the drum was used to derive an alert condition. Each node announced the type of chemical it contained by sending a unique identification number. As long as the nodes received no announcements or the announcements of the same identification number, no alert was raised. However, an alert was raised as soon as a node detected the presence of another drum containing a different type of chemical. Like the previous use case, the current status was indicated by a green and red LED light.

- **Monitoring of invalid storage area:** Some chemicals require storage in special areas. The aim of this use case was to prevent drums from entering invalid storage areas. For this, nodes attached to drums stored the type of content and invalid storage areas. When entering an area, a simple check was performed and in the case of an invalid location a local alarm was raised and an alert sent to the backend system. This alarm could be either audible or visual.

- **Monitoring of condition limits:** Certain chemicals are required to be stored under restricted environmental conditions. In this use case, drums were capable of gathering relevant data such as temperature and humidity from its environment using sensors. In case unsafe environmental conditions were detected, an alarm was raised and an alert sent to the backend system. For this, the drums stored critical thresholds at relevant parameters.

The central concept of the project was to use a common service paradigm throughout all layers of the architecture – from the backend applications to the
sensor nodes. One of the ideas behind CoBIs was to take services that are currently provided by a backend system and decompose them into simpler services that can be executed directly on an item. Relocating business process functionality from the backend system to a network of collaborating sensor nodes required the definition, design, implementation and deployment of different services running on the nodes. As a result, a middleware was implemented based on a service-oriented architecture (SOA) paradigm. This software allowed the deployment of business logic to the edge of the network in the form of a service. CoBIs not only focused on providing the service framework but also tools for monitoring and managing the network. Using SOA in the context of distributed systems solved problems usually associated with such systems, particularly the integration of sensors and actuators with backend systems as well as the device management, life cycle management of the nodes, system monitoring, service code deployment and message filtering.

### III.5.3 Distribution of data and functions

It was an essential property of the project that data were stored and processed on a node itself and not in a backend system. However, in addition to distributed data and functions a central monitoring and management system, a central repository for the services as well as information about the properties of dangerous goods was required. The data and code was propagated to the sensor network using middleware software. There were different types of data stored and functions performed on the node:

- **Item data**: Facts describing the physical attributes of the drum or general knowledge, e.g. content, reactivity, weight as well as critical mass and time.

- **Observational data**: Data collected by sensors, e.g. temperature, location and proximity to another drum.

- **Inferred data**: Data derived from item data, observations, previous inference, and data received from other nodes, e.g. time period in a location and average temperature over time.

- **Inference rules**: Rules that describe inference logic of new facts from previously established facts, e.g. total weight of a certain chemical in a location.
- **Actuator rules**: Rules that describe facts that must be true to trigger an action, e.g. send an alert if the weight of a certain chemical in a room exceeds a pre-defined limit.

Factors that influence the storage of data on a node are difficulty to adapt legacy systems, network connection, response time, implementation costs, flexibility, standardization and communication costs. In general, the approach to handle situations locally is more reliable, responsive, scalable and cost efficient. As the total amount of data generated will rise dramatically with the introduction of sensors, it is necessary to process the data directly on the item and to propagate only some data to the backend system. Thus, the software for a sensor network must be organized in a way that makes efficient use of the restricted energy resources, limited bandwidth and memory as well as processing power for both the backend system and the nodes. To reduce cost and to increase flexibility, technical modifications on the existing systems should be limited. Additionally, standards should be used because it greatly simplifies the design of heterogeneous sensor networks. Furthermore, local execution of business logic has the additional advantage that it also works when there is no connection to a backend system available and it can alert nearby workers about a possible hazard immediately. Moreover, in many environments where wireless sensor networks are most useful, regulations prescribe the conditions to be fulfilled by electrical and electronic equipment. Unless devices are adapted to these requirements, productive use is not feasible. Finally, decentralizing data and functions have also the potential to create completely new processes that would not have been conceivable before.

### III.6 Various industries: Mini cases

In the subsequent sections, mini cases are presented which contain valuable information on the distribution of data and functions. As only a limited amount of information on the actual applications could be acquired during research, these cases are not described in detail.

#### III.6.1 Automotive industry: Production of car keys

Huf Tools is a technology company, which among other things specializes in the construction of machines for automation and the development of RFID systems. The company also develops and produces start-stop-buttons for major car
manufacturers. For the fabrication of 14 different variants of car keys, the company uses RFID technology to control the manufacturing process. The production line consists of several workstations and the production of a key can start at different workstations.

Not the products themselves, but rather the container which holds them is equipped with an RFID tag for production. The transponder contains information about job parameters, production progress, production errors and product parameters such as color and frequency at which the key operates. At each switch and workstation this data is used to determine the next workstation and the next production step, respectively. Furthermore, in case of an error, the product is automatically taken off the line and sent to the repair station. There, corrective actions can be performed before putting the product back onto the line.

Factors that influence the storage of data on the tag are response time, implementation costs, difficulty to adapt legacy systems and process flexibility. However, no functions other than reading from and writing data to the tag are performed locally. By storing data on the tag, the production system is faster because data does not need to be sent to a backend system to receive the next production step. In addition, the production is more flexible. There is no need to stop the production line if new variants are introduced or if errors occur. Furthermore, designing the system in a way that integration with the backend system is limited, the solution is less costly and less complex. Besides, it was mentioned during the interview that if production information is stored on the product itself, this data can be used to exchange it among supply chain partners. This would streamline subsequent service processes.\textsuperscript{212}

III.6.2 Aerospace industry: Usage of radio frequency identification technology in the internal and external supply chain

Building an airplane is one of the most complex manufacturing processes. Not only does each plane consist of tens of thousands of parts that must be assembled in a highly orchestrated way, most parts also have to be tracked separately to comply with regulations.\textsuperscript{213} One of the major issues in the aerospace sector is the tracking and tracing of a part during its entire lifetime, even after the plane has been

\textsuperscript{212} Schröter 2007
\textsuperscript{213} Kelepouris et al. 2006
manufactured and is in operation. In this stage maintenance and usage information must be shared among parts manufacturers, plane manufacturer, service centers and the airline according to international requirements.

In this context, the major reason for storing data on the RFID tag is that decisions have to be made and data needs to be captured by different parties without the existence of a network connection. Apart from storing maintenance data on the tag, companies in the aerospace industry require storing configuration and manufacturing data as well as information about part failure and the conditions under which the failure happened. This data is used by several parties for service and maintenance. Another reason given is that the tags can be used to exchange data among business partners without the need for integrating backend systems.\textsuperscript{214}

### III.6.3 Electronics industry: Tracking printers for production, distribution and reverse logistics

HP, one of the world’s largest information technology companies, has gone beyond the phase of just tagging pallets or boxes and is using RFID technology for tagging individual printers. The company RFID-enabled the complete supply chain, including manufacturing, distribution, repair, reverse logistics and recycling. The company’s application is internationally recognized as an outstanding RFID implementation, having won the first RFID Journal Award.

RFID data are used to gain a deep insight into the actual manufacturing process. By tagging each printer, HP now knows how long a product spends at each station on the assembly line and how long it sits in a temporary storage area. Using analysis and reports software gives insight into asset timeline utilization, visual track and trace, historical analysis, real-time visibility in assets and their contents as well as status and exception reports to highlight process anomalies.

At the start of the manufacturing process, an RFID tag is attached to the printer’s chassis. During different stages of the assembly process, testing is carried out and test results are written onto the tag. If a component fails a test, the printer is taken off the production line and examined, while passing printers are routed to next production step. Each tag is read again when the unit is shipped and the information is compared against the purchase order to make sure the appropriate units are on the

\textsuperscript{214} Alderson 2003
pallet. In addition to test results, a unique serial number, firmware version, cartridges install-by date and product destination are stored on the tag. Doing so enables HP to create a so called product DNA (deoxyribonucleic acid) that travels with the printer through manufacturing and the supply chain.

The information on the tag is used for different purposes. The destination information on the tag is used to make sure that the units are shipped to the proper countries. Having a full record of the printer’s history enables HP to improve its repair service and allows them to return printers to customers much more efficiently. Furthermore, relevant information can be accessed at remote locations without the need to integrate the backend systems of all partners, if no network is available. This information can also be used to improve reverse logistics processes.215

III.6.4 Automotive industry: Production process of airbags

A first-tier automotive supplier, whose name will not be published because of nondisclosure policy, is a globally operating systems partner for the international automobile industry manufacturing airbags. The production of car airbags consists of seven steps. The process starts with the injection of plastic into a mold, which is then formed to a cover (injection molding). In a subsequent step, flash is removed from the parting lines (flash removal). For some products, the surface is provided with a special treatment in a third step to increase the quality of varnishing (surface treatment). Subsequently, the covers are sent to the varnishing workstation (varnishing). In the next step the emblem of the car brand is mounted and the covers, cushions and inflators are assembled together (assembling). In the final step, the finished airbags are packed, labeled and sent to the warehouse (shipping).

Currently, RFID is not used in production, but barcodes are used for data management and tracking of products. However, in a case study potential costs and benefits as well as implications for the information technology architecture were analyzed. The main reason for considering RFID is to reduce manual, time-consuming and error-prone barcode scanning processes. Furthermore, by using RFID technology the manufacturer would be able to reduce the load of process control on backend systems. Currently, the existing infrastructure is at its limits for processing plausibility checks, resulting in an intolerable response time. Workers

215 Gambon 2007; OATSystems 2007; Roberti 2006b
have to wait before they can carry out their next task. Whereas the extension of the existing solution would require initial investments in the server infrastructure, an RFID solution would require tag and deployment costs. The latter solution could process consistency checks independently of the backend system. For this, job parameters need to be stored on the tag.216

III.6.5 Pharmaceutical industry: Monitoring of cool chains

Not only benefit manufacturers from ubiquitous computing technologies on the shop floor, but also throughout the supply chain. Movianto, a Europe-wide logistics service provider in the pharmaceutical industry, serves some of the world’s top pharmaceutical manufacturers including Bayer and Sanofi Aventis. The company launched a joint RFID-project with inet-logistics, a provider of standard software solutions for supply chain execution. The core of the project was the active and consistent temperature monitoring and tracking of transported pharmaceutical products on the basis of a combination of ubiquitous computing technologies, e.g. RFID, sensors, GSM, GPS and GPRS. The implementation is realized by means of a so-called Shipment Localisation Kit.

One of the challenges in the pharmaceutical industry is the ability to monitor the entire cool chain. Traceability is not only important due to legal requirements but also due to quality, cost and optimization issues. By means of ubiquitous computing technologies attached to transportation units, temperature data can be recorded during the entire transportation process. This data can be transferred to a backend system for evaluation at pre-defined read points or by means of a GSM module via Short Message Service (SMS). In any case, temperature data is recorded and temporarily stored locally until it is sent to the backend system. As soon as data indicates a critical status of products, corrective actions can be performed in real-time reducing subsequent costs. Furthermore, by sending location information a central system is able to find the optimal route for the transport. Additionally, a lamp attached to the Shipment Localisation Kit indicates if temperature exceeded or fell below a certain range during transportation. This allows a worker to react properly without the need to connect to a backend system.

For this solution, the storage of information in a central system is required for optimization issues and for giving access to supply chain information to a multitude

216 Ivantysynova et al. 2007
of participants with different roles in the process flow. Furthermore, temperature data needs to be stored and processed locally to reduce communication costs and to optimize energy usage, which is generally highest for communicating data. Finally, storing temperature data and allowed temperature ranges as well as analyzing and indicating discrepancies locally does not require the adaptation of existing information technology systems, while resulting in a highly flexible and scalable solution.217

III.6.6 Research: Distributed control nodes for material flow systems

The Institute for Material Flow and Logistics at the University of Dortmund, together with its industrial partners, developed and implemented a decentralized material flow control system based on RFID. This prototype, consisting of a unit load conveyor and sorters, has been built for a proof of concept and will be used for further research in this field. The first step towards the realization of this prototype was to break down the whole system into several components. Each of these segments had to get its own software module to control the material flow of the underlying mechanical parts. The hardware platform for running the different modules are small embedded systems linked together via an Ethernet. As the decentralized modules operate autonomously, there is no need for a supervising control system.

In the described setting, RFID technology is applied for the identification of unit loads and for the dynamical routing of the packages. For this, job information is stored on the tag and contains a list of system segments that need to be passed by a package. However, it is not sufficient for a module to know where a package should be routed to, but also alternative routes to increase the flexibility of the overall system. In the case of alternatives, the decision about the next destination has to be made based on priorities. Against this background, the allocation of the path priorities can be either static or dynamic. In the latter case additional information about the states of subsequent segments are to be communicated. The advantages of such a decentralized control approach are seen in its flexibility, e.g. reconfigurations due to changing demands can be done quickly and cost-efficiently.218

217 Werle & Böckle 2006
218 Libert 2006; ten Hompel, Libert, & Sondhof 2006
### III.6.7 Automotive industry: Putting transponders in kanban cards

DaimlerChrysler, one of the leading car manufacturers worldwide, has looked into using RFID to improve the flow of materials from its own onsite storage areas to workstations on its production lines. At its production site in Untertürkheim, the company uses a kanban management system for replenishment. Kanban is a concept related to lean and JIT production. In a kanban system, material is delivered to a workstation along an assembly line only when the worker sends a request by signaling that a container is empty. This is done by means of cards which identify both the type of part and the workstation where this part is used. These cards are collected by a worker and transferred to the supplying location which delivers the requested material to the consuming location.

Previously, information for kanban processes had to be manually scanned, causing a potential source of errors. The new RFID-enabled procedure automates these processes and creates a direct connection between the physical goods movement and its representation in the enterprise resource planning system benefiting reliability and costs. For this, kanban containers were equipped with reusable tags that could be uniquely identified. RFID readers were installed at each pick-up and drop-off location. During a movement of a container, it passes through an RFID gate and its status is changed in the backend system. Whereas upon the detection of an empty container a replenishment order is triggered, upon the detection of a full container, goods receipt information is sent to the backend system. Additionally, a dashboard displays the status of any container in the system. The fully automated replenishment brings the following benefits: prompt delivery of containers, reduced shrinkage due to fraud or theft, reduction in labor costs as well as reduced stock in transfer.

In the DaimlerChrysler case, neither data nor functions were distributed. Only a unique identifier is written onto the transponder. Similarly to the food manufacturer case described above, the new RFID system is mainly a replacement of the barcode system to reduce manual, error-prone tasks. The required business logic already existed in the backend system and the existing infrastructure could also be used for the RFID-enabled system.\(^\text{219}\) Another factor that influences the storage of data on a tag is standardization. If no standards for readers exist, companies cannot be sure of

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\(^{219}\) Collins 2006; Kilian 2007
their ability to handle the data on the tag in the future. Thus data should not be stored on the tag because of this uncertainty. As seen in previously described cases, the only reason for distributing data and functions is a high response time, e.g. the time it takes for reading data, sending this data to a backend system, calculating the response and sending the result back.

In the interview it was also mentioned that the more data is stored on the tag, the longer it takes to read the data. Additionally, the more complex the data structure on the tag, the more complex algorithms are required to extract the right information and the higher the response time.

### III.7 Summary

In the previous sections, eleven cases of ubiquitous computing applications in manufacturing were presented. These cases are summarized in Table 6 giving information on the company or industry, the actual application as well as decentralized data and functions. Thereby, functions can be anything from simply reading the data from the tag to performing business rules on the tag. Additionally, factors that influence the centralization and decentralization of data and functions are presented.

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<tr>
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<th>Results</th>
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<td>Nestlé</td>
<td>Application Tracking of containers in confectionary production</td>
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<td>Decentralized data Identification number</td>
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<td>Decentralized functions Reading data from the tag</td>
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<td>Factors</td>
<td>Legacy systems, Synchronization, Data access / capturing without network connection</td>
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<td><strong>Airbag producer</strong></td>
<td>Application: Using of RFID in the production process of airbags</td>
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<td>Decentralized data: Identification number, Job parameters</td>
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<td>Decentralized functions: Reading data from the tag, Writing data onto the tag, Displaying data to worker</td>
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<td>Factors: Implementation costs, Load on backend systems, Response time</td>
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<td><strong>Movianto, inet-logistics</strong></td>
<td>Application: Monitoring of cool chains</td>
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<td>Factors: Communication costs, Legacy systems, Process flexibility</td>
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<td><strong>Institute for Material Flow and Logistics at the University of</strong></td>
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<td>DaimlerChrysler</td>
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*Table 6: Factors influencing the (de)centralization of data and functions*
IV  Factors influencing the decision on distributing data and functions

In the last chapter, cases have been investigated and core factors that influence the decision whether to centralize or decentralize data and functions have been identified. The aim of this chapter is twofold. First, arguments are derived from the case studies that give a first advice on the question whether to centralize or decentralize. Second, these arguments are then explored in more detail, taking into account objections, complications and alternative solutions. Specifically, for each factor the two alternative solutions – centralized architecture and decentralized architecture – are analyzed in regard to theoretical grounding, strengths and weaknesses, advantages and disadvantages, risk factors as well as trade-offs. As the alternative solutions are explored, cost components and benefits are extracted which ultimately will lead to a cost-benefit model. This model forms the basis for implementers and designers to decide on the best solution for a specific application.

IV.1  Case study results

From the previous chapter, several factors that influence the distribution of data and functions have been identified. The case study results can be summarized by six arguments. Thereby, one or more given factors extracted from the case studies form a specific argument.

- *Synchronization argument*: Do not decentralize data if synchronization issues cannot be solved because this may lead to inconsistent databases.

  In the Nestlé case it is argued that if data gets replicated and stored on a tag, this data needs to be synchronized with the backend database at some point in the process. For this, synchronization techniques and protocols are needed that keep the enterprise database consistent. However, Infineon replicated data and stored it on the tag as a backup. This data is needed for displaying the next process step to the operator and is accessed if the network connection fails. As this data is only mirrored and not manipulated, no synchronization problems will ever occur and the overall system stays consistent.

  The next questions that arise are: in what situations will synchronization problems occur, and how can these problems be solved? This analysis is performed in chapter IV.2.
• **External data exchange argument:** Decentralize data to exchange this data with supply chain participants in forward and reverse logistics because this reduces backend integration efforts as well as streamlines reverse logistics and service processes.

HP, the engine cooling manufacturer and companies in the aerospace industry argue that exchanging data using an RFID tag does not require the integration of backend systems of the different supply chain partners and ensures an easy, consistent access of product data across its lifetime. As mentioned by HP, this data can also be used for reverse logistics processes. Additionally, as seen in the HP and Huf Tools cases, service processes can be streamlined.

The next questions that arise are: what kind of information is exchanged among supply chain partners and which systems already exist for exchanging this information? This analysis is performed in chapter IV.3.

• **Security argument:** Do not decentralize data if security problems cannot be solved because this may lead to data corruption and a loss of access control.

In the case of the engine cooling modules producer it was mentioned that the data provided on the tag needs to be selected carefully to avoid revealing any confidential information, for instance information on the assembly process. For this, security features need to be incorporated into the solution.

The next questions that arise are: what are potential threads and attack models in ubiquitous computing applications and what security primitives are available on both the tag and the enterprise level? This analysis is performed in chapter IV.4.

• **Standardization argument:** Do not decentralize data and functions if standardization problems cannot be solved, because this may lead to compatibility and interoperability problems as well as increased investment risk.

In the DaimlerChrysler case it was mentioned that if no standards for readers exist, companies cannot be sure to be able to handle the data on the tag in the future. Another aspect is given in the case of the engine cooling modules producer. There, it is argued that as the number of companies accessing the data on the tag increases, standardization will become a major issue. Similarly, BP mentioned that standards greatly simplify the design of heterogeneous sensor networks.
The next question that arises is: what standards do exist or are currently under development on both the tag and enterprise level? This analysis is performed in chapter IV.5.

- **Flexibility argument:** Decentralize data and functions because this increases the ability to cope with changes at low cost and low effort.

Flexibility can be defined as the ability to add, modify and remove any software, hardware or data components with ease and low cost to cope with changes. Based on this definition, there are three factors which were mentioned in the case studies that can be discussed under the heading flexibility, namely process flexibility, legacy systems and implementation costs.

Both the Institute for Material Flow and Logistics at the University of Dortmund and Huf Tools argue that there is no need for stopping the manufacturing process if a new variant is introduced into the currently running production process. The same is true if production errors occur on products and if reconfigurations of the production system are required. Also, BP and Movianto mentioned that the decentralization of data and functions leads to increased flexibility of the physical process.

The cooling engine module producer, BP, Huf Tools, Movianto and the Institute for Material Flow and Logistics at the University of Dortmund mentioned that a decentralized solution was easier, cheaper and quicker to develop than a centralized solution. On the other hand, in the cases of Nestlé and DaimlerChrysler the opposite was the case. As the new system was basically an adaptation of the existing barcode system most of the required functionality was implemented already and only a few changes had to be made on the legacy systems.

In four case studies it was mentioned that a decentralized solution was less costly than a centralized solution. Whereas in the Movianto case the aim was to reduce communication costs by storing temperature data locally, the goal in the BP case was to reduce the cost for technical modifications on existing systems. BP also mentioned that regulations on hardware used in certain environments ultimately lead to higher costs of the decentralized solution. Furthermore, for the engine cooling modules producer it was cheaper to store the data on the tag than

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220 Duncan 1995
to implement and maintain a connection between the work stations and a central MES and other backend systems. The relevant trade-off for the airbag producer was cost for server infrastructure of the centralized solution versus cost for tag and deployment of the decentralized solution.

The next question that arises is if the centralized or decentralized solution is more flexible in regard to process flexibility, legacy systems and costs? This analysis is performed in chapter IV.6.

- **Response time argument:** Decentralize data and functions because this reduces response time.

In general, response time is defined as the time required responding to a request or event, particularly the time it takes for reading data from the tag, communicating data to an application, calculating the response and sending it back. Response time as a factor was mentioned by BP, the airbag producer and DaimlerChrysler. However, two additional factors mentioned in the case studies can be discussed under the heading response time, namely network connection and load on backend systems, because both factors greatly influence the response time.

The extreme case is that no network connection exists, which ultimately leads to high response times. In the aerospace and HP cases, decisions have to be made and data has to be captured or accessed by different parties without the existence of a connection to the backend system. The decentralized data and functions in the Infineon case are needed for displaying the next process step to the operator – and this data is accessed if the network connection fails. This ensures that critical production processes do not need to be disrupted. For BP, local storage of data and execution of business logic on the item has the advantage that it also works if there is no connection to a backend system available. It enables the company to alert nearby workers about a possible hazard immediately. For DaimlerChrysler and Nestlé, the only reason for distributing data and functions would be a missing network connection.

The second factor that is related to response time is the load on the backend systems which also may lead to longer response times. BP mentioned that, as the total amount of data generated will rise dramatically with the introduction of

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221 Smith & Williams 2001, p. 3
sensors, it is necessary to process the data directly on the item and to propagate only some data to the backend systems. Particularly, bandwidth as well as memory capacity and processing power of the backend systems are limiting factors. A similar argument is given by the airbag producer. By decentralizing data the manufacturer is able to reduce the load of process control functionality on backend systems. Currently, the existing infrastructure is at its limits for processing plausibility checks, resulting in a non-tolerable response time because workers have to wait before they can carry out their next task.

The next question that arises is: what components of a ubiquitous computing system have an influence on the response time? This analysis is performed in chapter IV.7.

IV.2 Synchronization argument

The synchronization argument reads as follows: do not decentralize data if synchronization issues cannot be solved, because this may lead to inconsistent databases. As mentioned in section IV.1, the following subsequent questions arise: in what situations will synchronization problems occur and how can these problems be solved? To answer these questions, first a definition on the term synchronization is given. This is followed by the analyses of the synchronization argument by discussing the centralized and decentralized scenario. Finally, the discussion will ultimately lead to management implications including costs, benefits and issues that need to be considered when evaluating a solution.

IV.2.1 Definitions and concepts

Systems that comprise multiple databases or data storage locations are likely to feature some form of replication and synchronization. Replication refers to the periodic or continuous copying of selected data between databases or storage locations. The concept of data synchronization refers to the idea of keeping multiple copies of a dataset coherent and thus to maintain data integrity.

Data replication allows users and applications to work with offline data and to make independent edits, e.g. additions, deletions and updates, to that data while disconnected from the network. These manipulations are later synchronized with a central database. Whereas replication reduces point failure dependencies, increases performance and serves as a mechanism to distribute master data without the
absolute requirement of dedicated connections, synchronization is the enabling mechanism that removes the stringent requirement of maintaining constant connectivity.

However, along with these advantages, in some scenarios replication might bring complications. Whenever one replica is updated, the others also need to be refreshed to keep the overall system consistent and to base all decisions within the company on the same and up-to-date data. Therefore, in systems built on replication, sophisticated synchronization mechanisms are critical.222

**IV.2.2 Discussion**

In general, for ubiquitous computing applications there seems to be several levels or degrees of synchronization223 which require more or less sophisticated synchronization protocols. Identifying and analyzing the characteristics of the different levels helps with the decision of whether to centralize or decentralize. Once these characteristics are known, costs and benefits can be derived and decision support can be given to the management.

**Centralized solution**

Basically, the centralized solution is the data-on-network scenario as described in section II.5.1 and an environment without data replication. In this scenario, object-related data is stored in backend systems and is referenced and manipulated using a unique identification number that is retrieved from the tag. Applications that are based on this concept assume that everything participating in a transaction is connected to the network by default. However, this does not necessarily mean that the different components are always connected, because the network may occasionally be unavailable. Rather, the system is designed to recover from such situations by making use of techniques to increase system availability such as redundant connectivity or message queues, e.g. messages placed onto the queue are stored until the recipient retrieves them. Synchronization issues will never arise in such a scenario because data is only stored in one location.

Two of the investigated applications in chapter III are solely based on this centralized scenario. Nestlé equipped its containers with three RFID labels holding

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223 Shigeya & Harrison 2006
an identical serial number. Similarly, DaimlerChrysler attached reusable tags that can be uniquely identified to kanban containers. In both cases, all object related data are stored and all business functions are performed in a central system.

The major cost component of the centralized solution is the cost for setting up and maintaining a fault tolerant network infrastructure so that no disruptions occur. The total cost of this depends on the cost for a cabled or wireless infrastructure including the implemented techniques to increase system availability and recovery. Interestingly, in the Nestlé case the factory was already fully equipped with a wireless network that could be used for the RFID implementation and therefore the cost for the network infrastructure could be kept low.

The major benefits of the centralized solution is that low-cost tags and readers can be used because only a unique identification number is stored on the tag, and data is only read from but not written onto the tag during the production process. Additionally, no non-value added software is required for the synchronization of data and all business functions. Furthermore, as data is stored in one place, a consistent and homogenous system is established. Finally, another benefit of the centralized solution is that decisions can be made on global, up-to-data data resulting in globally optimal decisions.

**Decentralized solution**

For the decentralized solution, three major environments are conceivable, namely an environment with data replication but treating tag data as cache of central data, an environment with data replication but treating tag data as a cache of local data, and an environment with local and global data updates while disconnected:

- In an environment with data replication but treating tag data as cache of central data, master data is always available in the backend system at any time. The data on the tag is only a copy of the master data or a subset of it. Designing a system this way enables the client application to access the tag data conveniently without the need to connect to the backend system. Updates are always made first in the backend system and then this data is copied onto the tag. Synchronization issues will not arise if the master data on the tag are valid until the underlying physical manufacturing process using this data is finished.

Some of the investigated applications in chapter III make use of this approach. For instance, the engine cooling modules producer, Infineon, BP, Huf Tools, the
airbag producer and the Institute for Material Flow and Logistics store product parameters and/or job parameters on the tag. This data is accessed during the execution of the process and can be deleted when the process is finished.

- In an environment with data replication but treating tag data as a cache of local data, the tag may contain some data that is more recent than the corresponding data in the backend system. An example of such a scenario is that the tag memory contains recent data received from an attached sensor. The data will be replicated to the central system when a network connection is available or if local rules trigger the transfer. Data synchronization issues will never arise in such a scenario as the tag memory functions as a buffer of data.

Some of the investigated applications in chapter III make use of this approach. For instance, in the cases of BP and Movianto, environmental data are locally gathered and simple checks on that data are performed. Only in critical situations data is sent to the backend system. In the case of the engine cooling modules producer information about the production progress is stored locally and sent to the backend system after the process is finished.

- In an environment with local and global data updates while disconnected, both the database and the tag data can be updated simultaneously. However, fundamental problems in such situations are the conflicts which generally occur when two different systems have the right to update the same data set. In this environment, such a problem has potentially serious consequences. Conflicts cause users and systems to make decisions based on incorrect data. Additionally, they can cause the system to lose important inputs because some data might be discarded later due to conflicts. Thus, in certain situations, synchronization becomes an important issue. When synchronizing data, a sophisticated policy is required about how data can be merged. Resulting actions may be to reject the update or to raise an alarm if there are conflicts between tag data and the backend system. These policies might be complex or the merge might be practically unsolvable.

None of the investigated applications in chapter III make use of this approach, because of the before mentioned problems that may arise. Additionally, for Shigeya and Harrison, it is not clear whether this kind of update is even necessary.

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224 Dahlin et al. 2000
225 Shigeya & Harrison 2006
The major costs involved in the decentralized solution are the costs for intelligent readers and tags with user-memory. Furthermore, software is required for extracting data from the backend databases, for writing data onto and reading data from the tag as well as for processing and interpreting data locally. Additionally, in an environment with local and global data updates while disconnected, sophisticated software is required for synchronizing locally with centrally stored data sets. In such a scenario, cost may arise from decisions based on not up-to-date data both locally and globally.

The major benefit of the decentralized solution is that if all required data is stored on the tag, no cabled or wireless network connection is necessary for each workstation. This reduces costs and efforts for deploying and operating the network infrastructure. Additionally, if tag data are treated only as a cache of local and global data, software costs for extracting data from and writing data into central databases is straightforward and of low effort.

IV.2.3 Management implications

In the last section the synchronization argument, ‘do not decentralize data if synchronization issues cannot be solved because this may lead to inconsistent databases’ was investigated in more detail by analyzing the different levels or degrees of synchronization. The research shows that the initial argument needs to be revised and can now be formulated into the following thesis:

Synchronization thesis: Decentralization can be a solution in situations in which the tag data and the same data in the database are not manipulated simultaneously.

Against this background, there are two important management implications concerning the decentralization issue:

- Although it is argued that decentralization leads to synchronization issues, this is only the case if the tag data and the same data in the database are manipulated simultaneously.

In general, for ubiquitous computing applications there are several levels or degrees of synchronization which require more or less sophisticated synchronization protocols. In the centralized solution, no synchronization issues arise because only the unique identification number is stored on the tag. In environments in which the tag data is used as a cache of global or local data,
synchronization refers to the fact that this data needs to be updated in a timely manner so that decisions are always based on up-to-date data. In contrast, sophisticated synchronization algorithms are required if both the data on tag and the same data stored in a backend database are manipulated simultaneously.

- The decentralized solution can be implemented if locally generated data and data extracted from the backend system is treated as cache.

On the one hand, in an environment in which tag data is treated as cache of central data, master data is always available in the backend system at any time. The data on the tag is only a copy of the master data or a subset of it. Designing a system this way enables the client application to access the tag data conveniently without the need to connect to the backend system. On the other hand, in an environment in which tag data is treated as a cache of local data, the tag may contain some data that is more recent than the corresponding data in the backend system, e.g. data received from a sensor. The data will be replicated to the central system when a network connection is available or if local rules trigger the transfer. In both cases, tag data is treated only as cache. Synchronization means extracting data from the tag or database and writing data onto the tag or into a central database. This, however, will never lead to inconsistent databases because of simultaneously manipulated instances of a data set.

IV.3 External data exchange argument

The external data exchange argument reads as follows: decentralize data to exchange this data with supply chain participants in forward and reverse logistics, because this reduces backend integration efforts as well as streamlines reverse logistics and service processes. As mentioned in section IV.1, the following subsequent questions arise: what kind of information is exchanged among supply chain partners and which systems already exist for exchanging this information? To answer these questions, definitions on relevant terms and concepts are given. This is followed by the analyses of the external data exchange argument by discussing both the centralized and decentralized scenario. Finally, the discussion will ultimately lead to management implications including costs, benefits and issues that need to be considered when evaluating a solution.
IV.3.1 Definitions and concepts

Companies require the exchange of detailed information about their products with trading partners to facilitate commercial transactions and the movements of goods. Discussing the external data exchange argument requires a solid understanding of supply chain management and reverse logistics. More importantly, to evaluate whether a data-on-tag solution is beneficial, an analysis must be made of what information needs to be exchanged and what information systems exist to exchange this information. Therefore, in this section background information is given on supply chain management, reverse logistics, Global Data Synchronization Network (GDSN), EPCglobal Network and data that are exchanged using these systems.

Supply chain management

In recent years, the concept of supply chain management has gained increasing popularity. Simchi-Levi et al.\textsuperscript{226} define supply chain management as “a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time in order to minimize system-wide costs while satisfying service level requirements.” Stern and Weitz\textsuperscript{227} point out that “now, the focus of the logistics decision has shifted to a broader level concerned with costs throughout the whole value chain. Programs such as ‘continuous replenishment’, ‘just-in-time,’ ‘quick response’, and ‘efficient consumer response’ emphasize the need to coordinate inventory levels, delivery patterns, transportation methods, and storage functions throughout an entire distribution system”.

In several instances, information from different parts of the supply chain needs to be available to ensure coordination.\textsuperscript{228} One well-known example in which supply chain performance can be improved by coordination via information sharing is the bullwhip effect.\textsuperscript{229} Global availability of data (e.g. point-of-sale data) can improve supply chain performance measures (e.g. product availability), even when the individual companies in the supply chain use decentralized control mechanisms (e.g. retailer and manufacturer independently decide on inventory levels).

\textsuperscript{226} Simchi-Levi, Kaminsky, & Simchi-Levi 2000, p. 1
\textsuperscript{227} Stern & Weitz 1997
\textsuperscript{228} Simchi-Levi, Kaminsky, & Simchi-Levi 2000, p. 100
\textsuperscript{229} Lee, Padmanabhan, & Whang 1997
Reverse logistics

Logistics is defined by the Council of Logistics Management as “the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements”. According to Rogers and Tibben-Lembke reverse logistics includes all of the activities but as they operate in reverse. Therefore, they define reverse logistics as “the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value or for proper disposal”.

A reverse logistics system consists of a number of activities such as collection, cleaning, disassembly, testing and sorting, storage, transport and recovery operations. These activities can be performed by traditional manufacturers, retailers, logistics service providers or specialized parties. Additionally, the reverse distribution can take place through the original forward channel, a separate channel or a combination of both channels. Main options for recovery include repair, reuse, resale, refurbishing, remanufacturing, cannibalization, recycling, landfilling and incineration. Finally, the following are the key characteristics of reverse logistics: uncertainty of quantity, quality, configuration, location and timing of the product returns. Analog to the forward supply chain, information from different parts of the supply chain needs to be available to ensure efficiency.

Global Data Synchronization Network

Every company maintains databases containing information about the products they make, sell and buy. These databases serve as product catalogues that customers can use to place orders. Difficulties arise when product attributes change or new products are introduced, because this information needs to be communicated to all affected supply chain parties to make sure that all partners are using the same information. Additionally, an update is also required if companies change the

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230 Rogers & Tibben-Lembke 1999, p. 2
231 Rogers & Tibben-Lembke 1999, p. 2
232 Fleischmann et al. 1997
233 Thierry et al. 1995
234 Spengler, Stötting, & Ploog 2007; van Hillegersberg et al. 2001
location of its headquarters where invoices are to be sent or if they open a new store where deliveries need to be dropped off. Communicating those updates to all affected parties can be a daunting task.

The GDSN responds to this problem by ensuring consistent and high-quality information among supply chain partners, utilizing global identification numbers for legal entities, trading partners, locations, products and services as well as messaging and data standards. The global identification numbers of the network are the Global Location Number (GLN) and the Global Trade Item Number (GTIN). The network provides a single entry point for trading partners to synchronize static information using data pools. Companies register their product information with the data pool and authorize a list of partners to receive their information. When a company makes changes to their data in their data pool, the entries are checked for compliance and published in the recipient’s data pool. By utilizing the GDSN, companies are able to greatly improve the accuracy of orders, shipments and receivings while reducing costs.\textsuperscript{235}

\textbf{EPCglobal Network}

The EPCglobal Network is a collection of interrelated standards for hardware, software and data interfaces that aims at enhancing the supply chain through the use of EPCs. An EPC is a globally unique and standardized identifier contained in each RFID tag for labeling a product. More specifically, the components of the EPCglobal Network provide the functionality to capture and share object-related information in today’s complex trading networks.\textsuperscript{236}

The network consists of three main components: the Object Name Service (ONS), the EPC Information Services (EPCIS) and the EPC Discovery Service. ONS is the authoritative directory of information sources available to describe an EPC associated with a product - typically this is the manufacturer. EPCISs are the actual repositories at each company’s site that store data about unique items in the supply chain. The EPC Discovery Service component is essentially a chain-of-custody registration service that enables companies to find detailed, up-to-date data related to a specific EPC and to request access to those data.\textsuperscript{237}

\textsuperscript{235} GS1 2008
\textsuperscript{236} Armenio et al. 2005
\textsuperscript{237} EPCglobal 2004b
Retrieving information about physical objects involves several steps: \(^{238}\) (1) A company – hereafter referred to as client or information requester – asks for information about a specific EPC-equipped product. It sends its query request to the Discovery Service. (2) The Discovery Service looks up all EPCIS addresses that hold data about the provided EPC number. (3) The Discovery Service sends the related addresses back to the requesting company. (4) The client queries the given EPCISs directly. (5) The queried information providers check the client’s access rights. (6) Given that the client is authorized to get information, the query result is sent by the information providers.

**Information requirements**

Both the GDSN and the EPCglobal Network are major infrastructure initiatives of GS1, a leading global organization dedicated to the design and implementation of global standards and solutions to improve efficiency and visibility in supply chains. The two networks serve related but slightly distinct purposes (see Figure 20).

![Figure 20: Information in the EPCglobal Network and the Global Data Synchronization Network\(^ {239}\)](image)

Whereas both systems are built around data exchange, the GDSN intends to facilitate the exchange of master data on products and locations. Master data can be

\(^{238}\) Armenio et al. 2005; Beier et al. 2006; GS1 2005; VeriSign 2005

\(^{239}\) adapted from EPCglobal 2004a
divided into two different types, namely neutral data and relationship-dependent data. Neutral data are generally shared between multiple parties and are relationship-independent. The three categories of neutral data include core product data that apply to all instances of any product (e.g. description, brand name, packaging dimensions), category-specific data that only apply to specific product categories (e.g. color) as well as target market data that are specific to products in a particular market (e.g. packaging indicators in a specific country). In contrast, relationship-dependent data include data attributes that concern bilateral agreements such as marketing conditions, price information and logistics agreements.

The EPCglobal Network provides dynamic data about the history of an individual product. Three categories of information about each item can be retrieved using this network: core product information that applies to all instances of any product (e.g. description, brand name, packaging dimensions), manufacturing time information (e.g. things known about an item at the time of manufacturing such as lot number and expiration data) and lifecycle history information (e.g. track and trace details of the lifecycle of a product such as date and time received at a certain location, maintenance history and parts replacement history).

IV.3.2 Discussion

In general, there are two major options for exchanging data among supply chain partners. First, data can be exchanged via a network, which is the traditional approach, and second via the tag, which is now possible because of the latest developments in ubiquitous computing technology. For a company to be able to evaluate the two solutions, it is necessary to describe both approaches in detail, including the system components and the information flow. Once this is known, costs and benefits can be assigned to each approach and decision support can be given to the management.

Centralized solution

Figure 21 schematically shows how companies may exchange information via a network. To capture data, tags carrying unique EPCs are affixed to containers, pallets, cases and individual items respectively. Furthermore, strategically placed
readers throughout the supply chain will read the tags and communicate the EPC as well as date, time and location to the internal database (EPCIS). Once history and instance data are captured, the EPCglobal Network is used to share this information among authorized trading partners as described above. Additionally, manufacturers publish their product master data to their data pool in the GDSN. This data is then synchronized with interested trading partners.

Besides the data exchange via the GDSN and EPCglobal Network, there is additional electronic data interchange (EDI) that is unaffected by the two networks. EDI is a set of standards for the electronically exchange of structured information among businesses, organizations, government entities and other groups in a compact, concise and precise way. Any standard business document that one company would exchange with another company such as purchase orders, invoices, shipping schedules, inventory inquiries and claim submission can be exchanged via EDI between two parties as long as both have set up proper systems. For the exchange of data, EDI provides different transaction sets for various types of business activities within forward and reverse logistics processes.

Figure 21: Information flow via network

242 adapted from Tellkamp 2006, p. 52
The major cost involved in the centralized solution is the cost for the implementation and maintenance of both the EPCglobal Network and the GDSN. As discussed above, both systems are built around data exchange which requires the establishment of standardized interfaces, databases and sophisticated software for collecting and integrating all required data that resides in different databases within the company. Particularly challenging is the decision of which data should be stored in which database. For instance, as described above both networks are designed to store master and core data about products which ultimately leads to duplicated data and synchronization issues. Additionally, annual fees have to be paid to use the services of the networks. Finally, all partners in the supply chain have to make sure that their databases can be accessed any time, because it is unknown when trading partners will want to access the data. This also includes setting proper access rights which might be challenging, particularly if trading partners are unknown in advance.

One benefit of the centralized solution is that low-cost tags and readers can be used, because only the unique identification number needs to be stored on and read from the tag. Additionally, with the GDSN an established and proven network for exchanging static data can be used. Similarly, for the EPCglobal Network standards have been developed for exchanging dynamic data among business partners via backend systems.

**Decentralized solution**

Figure 22 schematically shows how companies may exchange information via tags. Apart from the capability of storing only the identification number on the tag as practiced in the centralized scenario, RFID offers the possibility to store more data if extra user memory is available. In the decentralized approach, tags that are affixed to containers, pallets, cases and individual items respectively carry unique EPCs and additional data. This data may be anything from master and history data to instance data. Furthermore, strategically placed readers throughout the supply chain will read the content of the tags. The read information can be used without the need to connect to a backend system. Besides reading, supply chain partners may have the right to delete, update and add data on the tag. Similarly to the centralized

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244 In this picture the EPCglobal Network and the GDSN are omitted to illustrate the extreme case. Most likely, there will be a hybrid solution in practice.
There is a number of major cost components involved in the decentralized solution. First of all, intelligent readers and tags with user memory are required, which adds to the hardware cost. Additional costs arise for the implementation of sophisticated security mechanisms including the costs that arise if data on the tag is misused. However, security is limited by the user memory available on the tag and by a lack of robust and sophisticated security features, e.g. it is very little space available on tags for digital signature and it is difficult to manage individual access rights. Furthermore, standardized data syntax and semantics on the tag level are needed to gain further acceptance on the market and to be able to interpret the data stored on the tag. This would lead to costs for the development of tag level standards. Finally, disruption costs need to be taken into account if data on the tag is not accessible due to unknown syntax and semantics of the stored data or due to lost, destroyed or manipulated data. The solution to this problem may be to duplicate the data and to introduce security features on the tag. However, duplication might lead to synchronization issues. Furthermore, if the backup is stored on the network, the question arises of why to decentralize in the first place.

The major benefit of the decentralized solution is the possibility to exchange data among supply chain participants without the need to integrate backend systems. There is no need to implement and maintain both the EPCglobal Network and the GDSN to exchange data.
IV.3.3 Management implications

In the last section the external data exchange argument ‘decentralize data to exchange this data with supply chain participants in forward and reverse logistics because this reduces backend integration efforts as well as streamlines reverse logistics and service processes’ was investigated in more detail by analyzing the system components and the information flow of both the exchange of data using a network approach and tag approach.

The research shows that the initial argument needs to be revised and the following thesis can now be formulated:

External data exchange thesis: Decentralization can be a solution in situations in which data should be exchanged among supply chain participants without integrating inter-organizational backend systems.

Against this background, there are two important management implications concerning the decentralization issue:

- Exchanging data via tag may be an option if the GDNS and EPCglobal Network have not been implemented yet, a low number of partners are involved and less critical data are exchanged.

  With the GDSN and the EPCglobal Network, two networks have been developed for exchanging a high volume of static and dynamic information among supply chain partners in a standardized and secure way. In contrast, using a tag only a limited amount of data can be exchanged because of the restricted storage space on the tag. Additionally, high effort is required to establish tag level data standards for data exchange because different interests of the participants have to be taken into account. Furthermore, the data on the tag needs to be secured. Finally, if tags get lost or destroyed, data would also be lost unless a copy exists in the backend system. This data would therefore not be available for decision making.

- Although there is a lack of information systems that support reverse logistics processes, data for these processes should not be exchanged via tag because of security, standardization and data volume issues.

  Whereas the GDSN provides static data about a product, the EPCglobal Network is used to store and exchange dynamic data about the history of an individual product. Both types of data are required to efficiently execute reverse logistics
and subsequent processes. Additionally, both networks together allow for exchanging a high volume of data about a product. The storage capacity of the tag memory, in contrast, would not be enough to hold all that information. Moreover, for companies it is easier to establish access rights in a backend system than to implement them on the tag itself.

IV.4 Security argument
The security argument reads as follows: do not decentralize data if security problems cannot be solved because this may lead to data corruption and a loss of access control. As mentioned in section IV.1, the following subsequent questions arise: what are potential threads and attack models in ubiquitous computing applications and what security primitives are available on both the tag level and enterprise level? To answer these questions, first definitions on relevant terms are given. This is followed by the analyses of the security argument by discussing tag and EPCIS security. Finally, the discussion will ultimately lead to management implications including costs, benefits and issues that need to be considered when evaluating a solution.

IV.4.1 Definitions and concepts
Analyzing the security argument requires the understanding of two things. On the one hand, it is important to know about potential threats and attack models. On the other hand, current security capabilities need to be outlined.

Potential threads and attack models
In general, threats are potential events that cause a system to respond in an unexpected or damaging way. According to Thompson\textsuperscript{246} six categories of threads exist:

- **Spoofing**: Spoofing describes an event where an attacker successfully acts as an authorized user of a system. For instance, an attacker can query the tag for the EPC number as most tags respond to any reader. Because of its standardized format, an attacker can then determine the manufacturer and possibly the product number.

\textsuperscript{246} Thompson, Chaudhry, & Thompson 2006
• **Tampering:** Tampering describes an event where an attacker manipulates data, e.g. modifies, adds, deletes or reorders data. For instance, an attacker removes or physically destroys the tag or erases all data stored on the tag.

• **Repudiation:** Repudiation describes an event where a user denies an action and no proof exists to prove that the action was performed. For instance, a retailer denies the receiving of a certain pallet or the owner of an EPC number denies having information about an item.

• **Information disclosure:** Information disclosure describes an event where information is disclosed to an unauthorized user. For instance, an attacker performs an unauthorized inventory count in a storage location by scanning all tags to determine the types and quantities of items.

• **Denial of service:** Denial of service describes an event where a valid user is unable to use a certain service. For instance, a shoplifter shields the tag from being read or carries a blocker tag that disrupts reader communication to hide a stolen item.

• **Elevation of privilege:** Elevation of privilege describes an event where unprivileged users gain higher privileges than they are authorized. For instance, a user can become an attacker by raising his / her status in the information system to an administrator and writing malicious data into the system.

In a recent survey\textsuperscript{247} companies were asked to name their most important security concerns. These included disclosure of confidential information, security of internal systems, consumer privacy, injection of false information, process hold-ups, theft, counterfeits, repudiation of changes and missing control over information.

**Security primitives**

The security issues described in the previous section can be solved using a set of security mechanisms. In general, security mechanisms are combinations of cryptographic algorithms and protocols used to provide the security of information systems related to aspects such as confidentiality, data integrity, entity authentication and data origin authentication. Cryptographic tools are based on some mathematically difficult problems, and their level of security depends on the difficulty of the mathematical problem. A mathematical problem is said to be difficult if the time necessary for solving the problem is immense compared to the

\textsuperscript{247} Aigner et al. 2007
size of the input parameters to the problem. Thus the level of security provided is often expressed in the number of operations required to break the cryptographic system.\textsuperscript{248}

Three major security primitives can be distinguished – symmetric key primitives, asymmetric key primitives and primitives without using keys.\textsuperscript{249} These mechanisms can be evaluated with respect to various criteria such as level of security, functionality, performance and ease of implementation. The relative importance of these criteria is very much dependent on the available resources of the software system.

- \textit{Symmetric key primitives:} In symmetric key protocols the identical key is used for both encryption and decryption. This implies that this key has to be shared among all parties that are communicating via a secure network. In large networks, however, there are many key pairs to be managed which require effective key management.

- \textit{Asymmetric key primitives:} Asymmetric key protocols are arrangements that make use of a public and a private key. Companies keep the private key secret and publish the public key. A message is encrypted using a public key and can be decrypted using the private key. Even if this message may be overheard, the attacker cannot read the message because the attacker does not have the private key. In other words, the two parties that are communicating do not need to share secrets. A major problem with this kind of encryption is proving that a public key is authentic and has not been tampered with or replaced by a malicious third party key. Compared with symmetric key encryption, the key sizes are typically much larger and the throughput rates are much slower.

- \textit{Unkeyed primitives:} These primitives do not require any keys. An example is arbitrary length hash functions, the main subclass of unkeyed algorithms. Hash functions work by generating a hash value, a binary string of a fixed length, from binary strings of arbitrary length. The basic idea is that this hash value serves as a compact representative of an input string. To be of cryptographic use, a hash function is chosen such that it is infeasible to find two distinct inputs which lead to the same hash value. For example, hash functions are used with digital signatures. Using this primitive, a message is hashed and signed only with the hash value. The receiving party then hashes the received message and verifies

\textsuperscript{248} Ranasinghe, Engels, & Cole 2004
\textsuperscript{249} Menezes, van Oorschot, & Vanstone 1996, pp. 15-33
that the received signature is correct. Typically, the used hash functions are publicly known. This method is usually used to detect whether a message input has been manipulated.

IV.4.2 Discussion

Basically, there are two options for exchanging RFID data. First, the data can be exchanged via tag and second, the data can be exchanged by means of the EPCglobal Network as described in chapter IV.3.1. For companies to be able to evaluate both solutions it is required to identify and analyze current security capabilities and issues for both options. Once this is known, costs and benefits can be assigned to each solution and decision support can be given to the management.

Centralized solution

The EPCIS provides an opportunity for trading partners to share information about objects. To retrieve the information stored in the repositories, it is necessary to locate the corresponding EPCIS servers first. This is done by invoking the Discovery Service. Because of the above mentioned security threats, it is essential that the information exchange is done in a secure way. Against this background, there are various aspects of security that need to be considered:

- First, authentication is the verification of a claimed identity. Usually, a set of credentials, e.g. a password, is used to fulfill this verification. For instance, a client application, which presents the identity of an organization attempting to access the Discovery Service or the EPCIS, needs to be verified. Asymmetric cryptography is often used for this.

- Second, authorization is the process of verifying that a known person has the authority to perform a certain operation. For example, an authenticated client application must be authorized before revealing the content of the Discovery Service or the EPCIS.

- Third, access control is the process of preventing unauthorized access to resources. This is usually achieved by implementing access control policies, which can be as simple as lists that specify authorized clients, but may also include other attributes of a client. For instance, fine-grained access control policies may express conditions regarding any attribute of a record in the

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250 Konidala, Kim, & Kim 2006
Discovery Service or the EPCIS; such as, a client is only allowed to access the records of a specific EPC range.

- Fourth, confidentiality is the property that data is not disclosed to unauthorized entities during transmission. For instance, transmitting EPCIS and Discovery Service data can be performed using asymmetric cryptography.\textsuperscript{251}

The EPCglobal Network approach seems to be compelling at first. However, it has two major shortcomings. First, a complex key management overhead is necessary to support symmetric and asymmetric key primitives. Particularly, keys need to be made available to all relevant parties within the supply chains. However, distributing keys among unknown supply chain participants seems to be challenging. This leads to the second weakness. Defining fine-grained access rights at the EPCIS and Discovery Service level is a challenging and time consuming task. Additionally, sophisticated methods need to be developed to assign access rights to unknown supply chain partners.

The major cost involved in the centralized solution is the cost for implementing the EPCglobal Network and particularly the security mechanisms on the Discovery Service and EPCIS level. Unfortunately, the EPCglobal Network security mechanisms have not been fully developed yet, so no standardized solution exists. Furthermore, defining and maintaining access rights at both levels requires high efforts and cost. This is particularly true if fine-grained access rights need to be assigned manually to trading partners, e.g. a certain company is only allowed to access information on specific EPCs. Similarly, key management adds significantly to the costs of the solutions and involves aspects such as generation, exchange, storage, safeguarding, vetting and replacement of keys for asymmetric and symmetric cryptography.

A major benefit of the centralized solution is that well-established security mechanisms can be used to protect the data in the backend system. The asymmetric, symmetric and unkeyed security mechanisms have been successfully implemented to secure data exchange via the Internet. Additionally, in the centralized solution it is possible to assign fine-grained access control policies in the backend system, which means that the latest access rights policy is used upon a request from a company.

\textsuperscript{251} Burbridge et al. 2007
Decentralized solution

The most straightforward approach for the protection of data on a tag is to destroy the tags before they are placed into unauthorized hands. By killing a tag all data is lost and can not be reconstructed. This approach was originally designed for deactivating tags upon purchasing in a supermarket.\textsuperscript{252} However, there are some applications emerging in which this is undesirable, particularly if it comes to the exchange of data in forward and reverse supply chain processes.

A better approach would be to include access control and authentication mechanisms for the read and write memory on the tag. In this context, the strength of memory access control procedures varies depending on the used method, e.g. password, challenge-response protocol.\textsuperscript{253} Not only can the security primitives described above be used for authentication purposes, but they can also be used for encrypting the content on the tag.\textsuperscript{254}

However, the decentralized approach has three major shortcomings. First, supporting strong cryptography is beyond the resources of low cost tags, although solutions do exist for more expensive tags.\textsuperscript{255} Second, the schemes presume a centralized model, namely that readers have continuous access to a central database. This makes sense for security models for the Internet. However, for ubiquitous computing systems, around-the-clock access is usually too strong an assumption.\textsuperscript{256} Third, as specified in the centralized solution, to support key primitives, a complex key management overhead is necessary.\textsuperscript{257} For instance, keys need to be made available to all relevant parties within the supply chains. However, challenges might arise when keys need to be changed because then tags with previous keys might be within the supply chain. Additionally, distributing keys among unknown supply chain participants seems to be challenging.

Major costs of the decentralized solution include the cost for intelligent readers and tags with user-memory. Not only does the additional data stored on the tag require more expensive tags, but the embedded security mechanisms also require memory

\textsuperscript{252} Sarma, Weis, & Engels 2002
\textsuperscript{253} Knospe & Pohl 2004
\textsuperscript{254} Sarma, Weis, & Engels 2002
\textsuperscript{255} Knospe & Pohl 2004; Ratnasamy et al. 2004
\textsuperscript{256} Juels 2006
\textsuperscript{257} Sarma, Weis, & Engels 2002
which adds to the costs. Particularly, the more sophisticated the security mechanism is, the more memory is required. Similarly, the readers need to be able to handle the implemented security features. Another important cost factor is the disruption costs which occur if data on the tag is not accessible. Data on the tag may not be accessible if the security mechanism does not allow access to the data because no access rights are given or the wrong key is used. To overcome this problem, a permanent connection to the backend system would be required. However, in this case the decentralized solution as such must be questioned. Finally, maintaining access rights of tags that are not in possession of the company may be challenging because the latest policy must be written onto the tag.

The major benefit of the decentralized solution is that data stored on the tag can be protected to a certain extent if no permanent network connection is available. That means, however, that from a security perspective the centralized solution should be preferred and only if such a solution is not feasible the decentralized solution should be implemented.

**IV.4.3 Management implications**

In the last section the security argument ‘do not decentralize data if security problems cannot be solved because this may lead to data corruption and a loss of access control’ was investigated in more detail by analyzing security threats and capabilities on the Discovery Service / EPCIS and tag level. The research shows that the initial argument needs to be revised and the following thesis can now be formulated:

*Security thesis:* Decentralization can be a solution in situations in which no permanent network connection is available and non-critical data are to be exchanged.

Against this background, there are two important management implications concerning the decentralization issue:

- Fundamentally, security schemes presume a centralized model, making a decentralized model less secure or harder to manage.

  Using asymmetric and symmetric primitives implies that keys must be shared among supply chain partners via a secure way. Additionally, a company has to make sure that only the latest access rights policy is used throughout its partner
network. A pre-requisite for both issues is a secure always-on network. In an environment in which the network is not always available, a company cannot make sure that the latest access policies are used. Furthermore, in a decentralized model, updating access policies on tags that are distributed within the supply chain seems to be challenging or even infeasible. Thus, from a security perspective data can be decentralized if it is non-critical data, because then only primitive security mechanisms, if any, are required. Data can also be decentralized if no permanent network connection is available, but then this data must be of high relevance for the underlying business process.

- Both solutions require a complex key management and challenges arise from assigning fine-grained access rights.

Three major security primitives can be distinguished – symmetric key primitives, asymmetric key primitives and primitives without using keys. These security mechanisms require the exchange of security information among the supply chain partners, be it a key or the used hash function. No matter which of the solutions is used, a complex key management overhead is necessary to support the security primitives. Another challenge for both solutions is to assign fine-grained access rights to all supply chain partners. Particularly, maintaining access rights of tags that are not in possession of the company may be challenging because the latest policy must be written onto the tag.

IV.5 Standardization argument

The standardization argument reads as follows: do not decentralize data and functions if standardization problems cannot be solved, because this may lead to compatibility and interoperability problems as well as increased investment risk. As mentioned in section IV.1, the following subsequent question arises: what standards do exist or are currently under development on both the tag level and enterprise level? To answer this question, first a definition of the term standard is given and factors are presented that influence the adoption of a standard. This is followed by the analyses of the standardization argument by discussing existing standards on both the tag and backend system level. Finally, the discussion will ultimately lead to management implications including costs, benefits and issues that need to be considered when evaluating a solution.
IV.5.1 Definitions and concepts

Discussing the standardization argument and giving managerial implications requires the understanding of the term standard, factors influencing the adoption of standards and the standards that exist for RFID solutions on both the tag and enterprise level.

A definition of the term ’standard’

In a global business environment, interoperability among information and communication technologies is a fundamental requirement for companies.\textsuperscript{258} However, many kinds of heterogeneity result from technological differences, for instance differences in software, hardware and communication systems.\textsuperscript{259} Therefore, for integrating these heterogeneous information systems, a common understanding of the syntax and semantics of the exchanged information is necessary.\textsuperscript{260}

To overcome this issue, standards have been developed and implemented in the industry. In general, standards are defined as "documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose".\textsuperscript{261} A series of related standards generally allow for modular construction of the overall system in which a group of products and services are combined using standardized interfaces.

Factors influencing the adoption of standards

In some cases, standards are mandated by an institution or industry association. However, often standards are selected in the marketplace through the adoption decisions of organizations or individuals. Economic theories provide well-developed concepts and empirical results which are useful for the study of technology evaluation, adoption and implementation.\textsuperscript{262} Probably the most influential economic theory of standard adoption is that of positive network effects. This theory proposes that, the utility that a subscriber derives from a system

\begin{flushleft}
\textsuperscript{258} Schmitt, Thiesse, & Fleisch 2007  \\
\textsuperscript{259} Sheth 1999  \\
\textsuperscript{260} Hasselbring 2000  \\
\textsuperscript{261} Bryden 2003  \\
\textsuperscript{262} West 2003
\end{flushleft}
increases as others join the system.\textsuperscript{263} Other studies propose various classes of factors responsible for the adoption such as technological (e.g. relative advantage, complexity and compatibility), organizational (e.g. top management support and organizational size) and environmental characteristics (e.g. external pressure and competition).\textsuperscript{264}

Information technology standards involve a high upfront investment and resource commitment from organizations involved in the standardization process.\textsuperscript{265} The development requires a great deal of intellectual effort by skilled team members which results in high upfront costs. Additionally, these investments represent sunk costs if this standard does not become the dominant standard.

The problem with coexisting standards that are still under development is that they might lead to switching costs.\textsuperscript{266} This term is used in various areas such as microeconomics, strategic management and marketing to describe any impediment to a customer’s changing of suppliers. For instance, mobile telephony service is one example. Once subscribed, a user receives a number and usually signs a long-term contract. Yet, in the absence of number portability or due to costs for terminating the contract, a consumer faces switching costs.\textsuperscript{267} In his model, Klemperer\textsuperscript{268} classifies switching costs into three categories: learning costs (e.g. costs for learning to use a substitute), transaction costs (e.g. costs of uninstalling equipment of one supplier and installing equipment of the new supplier) and contractual costs (e.g. costs for unused repeat-purchase coupons).

Additionally, in an adoption decision, companies are likely to consider both network effect and switching costs. In situations where one standard holds a majority share, the combination of network advantages and installed based switching cost will tend to enable the leading standard to get even further ahead.\textsuperscript{269} However, in a rapidly growing market the effect of the installed base switching costs might be dwarfed by the decisions of a larger population of new and potential customers.

\textsuperscript{263} Rohlfs 1974
\textsuperscript{264} Schmitt, Thiesse, & Fleisch 2007
\textsuperscript{265} Arthur 1996; Shapiro & Varian 1998, p. 352
\textsuperscript{266} Kilian 2007
\textsuperscript{267} Klemperer 1995
\textsuperscript{268} Klemperer 1987
\textsuperscript{269} Arthur 1996
adopters.\textsuperscript{270} As a consequence, there is some degree of uncertainty surrounding which standard will finally win over the other, depending on key innovative attributes such as relative advantage, compatibility and complexity.

**Existing standards**

The RFID market consists of a massive amount of diverse players such as chip and transponder manufacturers, software providers, system integrators and consultancies. All of them offer different and often proprietary products and services. Not only is it difficult for potential customers to acknowledge the distinct benefit of a particular solution, but also this requires a huge effort in terms of standardization for securing the high investment.\textsuperscript{271} In this section, international standardization initiatives which cover standards of different layers of an RFID solution are presented.

Unfortunately, different standards coexist or are still under development. Additionally, different actors with divergent interests influence the standard definitions. Currently, there are two major organizations working towards international standards for RFID technology. These two organizations are the International Standards Organization (ISO) and EPCglobal.\textsuperscript{272}

ISO is a network of national standards institutes from 157 countries, and the world's largest developer and publisher of international standards. Its RFID standards are defined on a rather generic level and are fairly application-independent with regard to processes and industry-specific context. ISO standards cover the areas of technology, data content and structure, conformance and performance as well as applications.\textsuperscript{273} Technical standards specify issues such as operating frequencies and air interface protocols. Data content and structure standards define standardized tag data such as GTIN and SSCC. Conformance and performance standards define specific methods against which devices can be compared with standards. Application standards specify how RFID is used to track and trace entities such as containers and animals.

\textsuperscript{270} Liebowitz & Margolis 1990; West & Dedrick 2000
\textsuperscript{271} Gerst, Bunduchi, & Graham 2005
\textsuperscript{272} Wu et al. 2006
\textsuperscript{273} Schmitt, Thiesse, & Fleisch 2007
In parallel with the ISO standardization effort, the Massachusetts Institute of Technology (MIT) together with a number of industrial partners set up the Auto-ID consortium for the development of the EPCglobal Network. Thanks to their work, the rapid diffusion of RFID was particularly driven by the development of the EPC, a worldwide unique code for the identification of physical objects.

IV.5.2 Discussion

Basically, there are two options for exchanging RFID data. First, the data can be exchanged via tag, and second data can be exchanged by means of the EPCglobal Network as described in chapter IV.3.1. For a company to be able to evaluate a solution in terms of standardization issues, it is necessary to describe both solutions in more detail. Once this is done, costs and benefits can be assigned to each approach and decision support can be given to management.

Centralized solution

A large number of RFID applications have been developed for operations within a single company. For instance, some manufacturers are using RFID tags to track items moving through a manufacturing or distribution facility. But most applications to date have not yet addressed the challenges of tracking products as they cross the physical boundaries between trading partners. Against this background, the EPCglobal Network can be seen as the next logical step in the evolution of supply chain management and information exchange. The standard-based platform of the EPCglobal Network ensures compatibility and scalability across a diverse set of participating companies, allowing an efficient and secure flow of information.

To take RFID beyond the usage within a single organization and create value for the entire supply chain participants, two things are needed. First, there must be a standardized way of uniquely identifying items. Second, there must be a standard means of discovering and sharing the data that describes each item. The first requirement is addressed through EPCs. EPCs are virtual unique license plates for products that identify the manufacturer, product class and serial number. By means of such an EPC, members of the supply chain can easily identify and locate information about a particular object. The second requirement to extend RFID value

274 VeriSign 2005
across trading partners is a standards-based method to discover and share data about objects. This is the role of the EPCglobal Network as described in section IV.3.1.

![Figure 23: EPCglobal Network and standards](image)

On top of the EPC, a whole set of software and hardware standards have been developed and now the network consists of three layers (see Figure 23):

- **EPC physical object exchange standards**: The standards on the lowest level ensure that when a supply chain participant exchanges a physical object with a supply chain partner, the latter company will be able to determine the EPC of the item and interpret it properly. For this, a number of tag air interfaces for tag-reader communication have been developed.

- **EPC infrastructure standards**: On the middle layer the EPCglobal architecture defines standards for the major infrastructure components which are required to gather and store EPC data. This allows EPCglobal subscribers to build their internal system based on interoperable components. For this, access to the readers is defined by the reader protocol. Additionally, the filtering & collecting

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275 adapted from EPCglobal 2007
276 EPCglobal 2007
interface allows for aggregating tag events from different readers over time. Finally, the EPCIS interface specifies how the EPC data can be transmitted to the EPCIS for storage and retrieval.

- *EPC data exchange standards:* Standards for data exchange provide a means to share EPC data within pre-defined user groups or with the general public. This allows companies to increase visibility over the movement of goods across the supply chain and is supported by the EPC query interface. Besides standards for inter-organizational data exchange, service interfaces allow access to EPCglobal services such as subscriber authentication and discovery service.

The major cost components of the centralized solution include the implementation of the EPCglobal standards. On the one hand, companies need to purchase EPC numbers which may require a renumbering and redesign of the internal databases. On the other hand, they must build their internal system based on the interoperable standard EPCglobal interfaces, which may require a redesign of the existing software components and the purchase of EPCglobal-conform readers.

The major benefit of the centralized solution is that global standards will be used, which have been developed by potential industrial users of the standards. This not only secures the investment, but also provides an efficient way to exchange information among new business partners in the future.

**Decentralized solution**

The ISO and EPCglobal standards primarily cover air interface, data protocol and network standards. Data content and structure standards which define the data stored on the tag and its format only cover existing numbering schemes such as GTIN and SSCC. Application- or industry-specific data are not included in these specifications.²⁷⁷ Therefore, to ensure interoperability between both internal and external systems, standards need to be developed. If RFID technology is deployed in a closed-loop manufacturing process, then industry data standards do not necessarily need to be considered unless the application will be extended in the future. However, if data is exchanged among supply chain partners, industry-specific standards must be used. Although the aerospace and automobile industries have developed data standards which specify the data schemes for electronically shared information, standards for data stored on an RFID tag have not yet been

²⁷⁷Harmon 2006; Want 2004
ratified. However, if no standards for data on the tag exist, not only the business data but also metadata describing this data need to be stored locally. Only this way is the software able to interpret the data, particularly if more than one format can be used. This, in turn, requires additional storage space on the tag which adds to the cost of the tag.

The major costs involved in the decentralized solution include the cost for intelligent readers and tags with user-memory. Furthermore, to ensure interoperability between internal and external systems, data standards need to be developed – which requires high investment and resource commitment from the organization. Finally, in the worst case, companies are required to exchange hardware and software for existing ubiquitous computing applications in the future in case a standard emerges that replaces the used format.

The major benefit of the decentralized solution is that company-internal syntax and semantics can be used. There is no need to implement the standards that are still under development or that have been already developed by ISO and EPCglobal. However, using internal syntax and semantics may not be the best solution in the long term, particularly if the application will be extended in the future.

**IV.5.3 Management implications**

In the last section, the standardization argument ‘do not decentralize data and functions if standardization problems cannot be solved because this may lead to compatibility and interoperability problems as well as increased investment risk’ was investigated in more detail by analyzing standardization on the tag and backend level. The research shows that the initial argument needs to be revised and the following thesis can now be formulated:

*Standardization thesis:* Decentralization can be a solution in situations in which data and interface standards exist for an application.

Against this background, there are two important management implications concerning the decentralization issue:

- The EPCglobal Network is the most comprehensive set of software and hardware standards for RFID applications and should be used.

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The EPCglobal Network standards comprise EPC physical object exchange standards, EPC infrastructure standards and EPC data exchange standards which enable companies to exchange information among supply chain partners in an efficient and secure way. These standards have been developed by the MIT together with a number of industrial partners so that practical relevance is given. Additionally, these standards allow for modular construction of the overall system. Although, a number of factors exist that influence the adoption of standards, it seems that the EPCglobal standard becomes the dominant standard.

- Design a ubiquitous computing system based on existing standards to keep the cost down and to secure the investment.

Not using the existing standards would require the development of a unique standard to ensure interoperability between internal and external systems. However, the development of information technology standards requires a high upfront investment and resource commitment from organizations involved in the standardization process. Additionally, these investments represent sunk costs if this standard will not become the dominant standard. If RFID technology is only deployed in a closed-loop manufacturing process, then the development does not seem to be a major problem. However, if data is exchanged among supply chain partners, industry-specific standards must be used. Finally, a company might face switching costs if a new standard needs to be implemented in the form of learning costs, transaction costs and contractual costs.

IV.6 Flexibility argument

The flexibility argument reads as follows: decentralize data and functions because this increases the ability to cope with changes at low cost and low effort. As mentioned in section IV.1, the following subsequent question arises: is the centralized or decentralized solution more flexible in terms of process flexibility, legacy systems and costs? To answer this question, first definitions on relevant terms are given. This is followed by the analysis of the flexibility argument by discussing the centralized and decentralized scenario. Finally, the discussion will ultimately lead to management implications including costs, benefits and issues that need to be considered when evaluating a solution.
IV.6.1 Definitions and concepts

Analyzing the flexibility argument requires consideration of two things. On the one hand, it is important to define the term flexibility. On the other hand, infrastructure components and their characteristics that have an influence on flexibility need to be outlined.

Flexibility

Manufacturing flexibility is a key strategic objective of many manufacturing companies besides costs, time and quality. In the past, the situation was characterized by stable demand, low product variety as well as long life cycles and lead times. Today, however, the ability to absorb fluctuations in demand economically as well as to develop and introduce new products and services quicker is an important issue. To achieve this, manufacturing processes must be more flexible in the face of uncertainty.²⁷⁹

An early definition of manufacturing flexibility by Gupta and Goyal²⁸⁰, who credit Mascarenhas²⁸¹, describes the term as “the ability of a manufacturing system to cope with changing circumstances or instability caused by the environment”. Similarly, Cox²⁸² defines manufacturing flexibility as “the quickness and ease with which plants can respond to changes in market conditions” and Schneeweiss²⁸³ defines it as “the ability of a system to cope with unforeseen changes”. Adopting a more operational view, Nagarur²⁸⁴ defines the term as “the ability of the system to quickly adjust to any change in relevant factors like product, process, loads and machine failure”. This leads to the more comprehensive view which describes flexibility as “the ability to change or react with little penalty in time, effort, cost or performance”.²⁸⁵ While these definitions are by no means exhaustive or particularly comprehensive, they illustrate three important points. All definitions refer to the ability to respond to changes, reflect the diversity in the understanding of the issue and point to the use of flexibility to cope with uncertainty.

²⁷⁹ Beach et al. 2000
²⁸⁰ Gupta & Goyal 1989
²⁸¹ Mascarenhas 1981
²⁸² Cox 1989
²⁸³ Schneeweiss 2003, p. 210
²⁸⁴ Nagarur 1992
²⁸⁵ Upton 1994
A number of authors have presented taxonomies of flexibility dimensions. For instance, Vokurka and O’Leary-Kelly \(^{286}\) collected a set of 13 dimensions of flexibility from some of the more well-known taxonomies. These dimensions and their definitions are machine (range of operations that a piece of equipment can perform without incurring a major setup), material handling (capabilities of a material handling process to move different parts throughout the manufacturing system), operations (number of alternative processes or ways in which a part can be produced within the system), labor (range of tasks that an operator can perform within the manufacturing system), process (number of different parts that can be produced without incurring a major setup), routing (number of alternative paths a part can take through the system in order to be completed), product (time it takes to add or substitute new parts in the system), delivery (ability of the system to respond to changes in delivery requests), volume (range of output levels that a firm can economically produce products), expansion (ease at which capacity may be added to the system), program (length of time a system can operate unattended), production (range of products the system can produce without adding new equipment) and market (ability of the manufacturing system to adapt to changes in the market environment).

**Infrastructure components**

Important infrastructure components of ubiquitous computing applications that have an influence on flexibility are tags, readers and software. In general, the more functionality a component provides, the more flexible it is. In this section these components are investigated in more detail:

- **Tags**: Tags come in two distinct types – active and passive (see Table 7). Whereas an active tag has a local power source, a passive tag has no battery source on the tag. Active tags provide much higher functionality than passive tags, including longer read range, ability to integrate sensors, data security through encryption, ability to transmit in a noisy environment and the ability to communicate with other tags to form an ad-hoc network. However, active tags are not only more expensive than passive tags, but also have a shorter lifespan. Although passive tags have less functionality than active tags, they provide a number of advantages over active tags. They are smaller in size, cheaper, have a

\(^{286}\) Vokurka & O’Leary-Kelly 2000
longer lifespan and are easier to deploy in the field with very little maintenance requirements throughout operational life.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Active tag</th>
<th>Passive tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>433 Mhz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Read range</td>
<td>&lt; 100 m</td>
<td>&lt; 100 m</td>
</tr>
<tr>
<td>Memory size</td>
<td>2 kbits</td>
<td>2 kbits</td>
</tr>
<tr>
<td>Physical size</td>
<td>5 cm x 5 cm</td>
<td>5 cm x 5 cm</td>
</tr>
<tr>
<td>Lifespan</td>
<td>1-5 years</td>
<td>3-5 years</td>
</tr>
<tr>
<td>Cost</td>
<td>$5-$50</td>
<td>$5-$50</td>
</tr>
</tbody>
</table>

![Table 7: Types of RFID tags and key attributes](adapted from INEMI 2008)

- **Reader:** A reader is a device which is used to communicate with RFID tags and may include reading, writing and updating data. It is equipped with one or more antennas that emit radio waves and receive signals back from the tag. Besides that, a reader is also able to communicate with backend systems. The most fundamental characteristic of an RFID reader is the frequency or frequencies at which the reader can communicate. This is important because readers and tags must communicate at the same frequency. Additionally, most readers communicate exclusively with active or passive tags. Today, various types of readers are available which are provided by different manufacturers. Some of them only read passive tags that are produced by the same manufacturer; others can read any tag by the same specific standard. Similarly, most manufacturers of active tags implement their own proprietary communication protocol.

RFID readers come in different sizes, frequencies and with different data processing and reporting capabilities. Against this background, many people use the term **intelligent reader** to describe a device that has the ability not just to run different protocols, but also to filter data and even run applications. Essentially, it can be described as a computer that communicates with the tags. In contrast, a so called **dumb reader** is a simple device that might read only one type of tag.
using one frequency and one protocol. Typically, this type of reader has very little computing power and thus cannot filter reads, store tag data and so on. In general, more sophisticated readers are more expensive than simple readers and fixed devices are less expensive than mobile devices.\textsuperscript{288}

- **Software:** At the heart of ubiquitous computing applications is a powerful middleware, which is designed for use in facilities that require multiple reader deployments, including manufacturing plants, where processed RFID data need to be integrated into local and enterprise applications. This middleware is able to coordinate and control both fixed and mobile RFID readers via wired and wireless networks. Additionally, the software is capable of intelligently processing high volumes of RFID data at a site-wide level, correlating tag reads and utilizing user-defined locations. Also, it provides RFID data to backend applications, isolating them from interactions and physical changes at the tag identification layer. Besides that, a console and dashboard enables administrators and managers to remotely configure, deploy and monitor site operations at each facility.\textsuperscript{289}

The cost for the middleware varies from company to company depending on number of sites, number of connected readers and configuration effort. The local storage of data and the distribution of business logic require a much more sophisticated middleware because the management, monitoring and administration of such a system are much more complex than a centralized system. Thus, the middleware must be able to deploy, remove and upgrade services on the item to adapt the system to changing application or business needs. In addition, a central repository of available services must be maintained.\textsuperscript{290} Finally, RFID and sensor data are only useful if they are used in business processes. For this, functionality in the backend systems must be available or must be developed.

\textsuperscript{288} Banks & Thompson 2008; INEMI 2008  
\textsuperscript{289} Reva 2008  
\textsuperscript{290} Haller 2007
IV.6.2 Discussion

Information technology is one method for delivering flexibility besides organizational structures, labor and process technology because it may be possible to equip the system with a certain degree of self-diagnostic and adaptive control capabilities. According to a number of authors, information technology infrastructure flexibility allows organizations to respond to new market conditions while providing for future integration. An important quality of a flexible infrastructure is modularity, which is the ability to add, modify and remove any software, hardware or data components with ease and with no major overall effects.

However, it seems that flexibility still presents something of a conundrum, a concept where researchers and practitioners cannot agree on answers to the most basic questions, e.g. what is flexibility and how can it be implemented. Thus, discussing the question of whether data and functions on a tag or in the backend system increases manufacturing flexibility can contribute to answering some of the open questions. The question under investigation is, which option enables an organization to respond and adapt to changing business conditions by adding new functionality to the system with lower effort and at lower cost – the centralized or decentralized solution?

Centralized solution

In the centralized solution, information technology resources and activities are located in one location at a high level of hierarchy. An example of a centralized solution is the Nestlé case. In this application, only the unique identification number is stored on the tag and any business function is performed in the central system.

The effort needed to adapt the existing system includes the following activities. First, new items in the system must be equipped with an RFID tag containing a unique identification number. Second, additional read locations require the installation and configuration of readers. For this, the readers must be connected to

291 Beach et al. 2000
292 Nagarur 1992
293 Byrd & Turner 2000
294 Duncan 1995
295 Oke 2005
the middleware via a network connection. Third, in the middleware, rules for the communication with the backend system must be defined. Forth, usually the most complex and most costly part is the development of the backend functionality. This is particularly true for custom software which is developed only for one company. This effort can potentially be reduced if configurable standard software is used, as long as the required functionality is provided by the software vendor. Finally, new functionality sometimes requires new user interfaces at the shop floor, which need to be developed and hardware, e.g. terminals, which need to be deployed.

Major cost and effort of the centralized solution is the development and deployment of new backend functionality. This may be the installation and configuration of standard software or the development of individual software. Another type of cost is the cost for deploying readers and other devices such as monitors, as well as attaching tags to objects. Additionally, the configuration of the readers and the definition of business rules in the middleware layer can be done easily by means of sophisticated middleware solutions. All this requires a network infrastructure that connects the devices to the backend system.

The major benefit of the centralized solution is that low-cost tags and readers can be used, because only a unique identification number is stored on the tag and data is only read but not written from the tag. Additionally, sophisticated, standardized middleware solutions allow for an easy configuration of the devices and integration with backend systems. Finally, the solution is able to adapt to changes based on the latest global data.

**Decentralized solution**

In the decentralized solution, information technology resources and activities are distributed among different locations at a low level of hierarchy. Not only the unique identification number but also additional data are stored on the tag. Besides that, business functions might be executed locally. For instance, BP equipped all chemical drums with motes which hold a unique identification number and additional master, environmental and locally manipulated data. Furthermore, not only is functionality required for analyzing and manipulating data locally, but also for communicating with other motes.

The effort needed to adapt the existing system requires the following activities. First, new tagged items must be equipped with an RFID tag, containing not only a
unique identification number but also additional data and eventually functionality. For this, software in the backend is required that extracts relevant data and writes that data on the tag. A sophisticated middleware solution is not necessary for this. However, if business logic needs to be performed locally, additional software is required for maintaining the services and for writing these onto the tag. Second, new read locations require the installation and configuration of readers. In the decentralized scenario these readers do not need to be connected to a backend system as all required data and functions are provided via the tag. However, in the cases where there is no network connection, updates of software packages cannot be performed centrally – resulting in high efforts. The same is true for the configuration of the readers which cannot be done centrally unless mobile readers are used.

The major cost of the decentralized solution is the software for extracting and writing relevant data for storage on the tag as well as writing data back into the backend system. Additionally, if business logic is performed, these software components need to be distributed and maintained. Furthermore, besides more expensive tags, more sophisticated readers are also necessary to perform the filtering of raw data. Finally, new functionality sometimes requires new user interfaces at the shop floor, which need to be developed and deployed.

The major benefit of the decentralized solution is that no network infrastructure is required if all required data is stored on the tag and functions are performed locally on one item. Additionally, extracting data from backend systems and writing this data on the tag is a straightforward and low-cost process. Finally, the solution is able to adapt to changes based on available local data.

IV.6.3 Management implications

In the last section the flexibility argument ‘decentralize data and functions because this increases the ability to cope with changes at low cost and low effort’ was investigated in more detail by analyzing the centralized and decentralized solution. The research shows that the initial argument needs to be revised and the following thesis can now be formulated:

*Flexibility thesis:* Decentralization can be a solution in situations in which the development or deployment of a centralized software package and / or the deployment of a network are not feasible.
Against this background, there are two important management implications concerning the decentralization issue:

- Whereas the decentralized solution is able to cope with local uncertainty based on locally available data, the centralized solution is able to cope with both local and global uncertainty based on system-wide data.

  In the decentralized solution, data is stored on the tag and business functions are executed on the tag. This means that the decentralized solution reacts quickly based on available local data and business logic. Global data are only taken into account if this data is stored on the tag. In contrast, the centralized solution is flexible in the sense that the latest global data can be used to adapt to changes. This will lead to globally optimal decisions.

- The decentralized solution should be implemented if flexibility is a key performance indicator and the adaptation of legacy systems and network infrastructure is not feasible.

  In cases where a network infrastructure already exists and the backend systems can be extended at low cost and effort, a centralized solution should be favored. Against this background, the major problem with the flexibility of a centralized solution is that the required software is not available or expensive to develop. This is particularly true if custom software is used. However, it will become less of a problem if modular and customizable standardized software packages exist that allow for an easy implementation of the software. In contrast, in some scenarios it is easier and cheaper to deploy a decentralized solution, particularly if data is only extracted from the backend system and read at the point of action but not manipulated. In this case no additional software is required and no network connection has to be established.

**IV.7 Response time argument**

The response time argument reads as follows: decentralize data and functions because this reduces response time. As mentioned in section IV.1, the following subsequent question arises: what components of a ubiquitous computing system have an influence on the response time? To answer this question, first definitions on relevant terms and concepts are given. This is followed by an analysis of the response time argument discussing both the centralized and decentralized solution.
Finally, the discussion will ultimately lead to management implications including costs, benefits and issues that need to be considered when evaluating a solution.

**IV.7.1 Definitions and concepts**

The real-time availability of RFID data is critical for many ubiquitous computing applications in manufacturing systems. In such systems, the physical process control usually requires real-time RFID and sensor data as an input for decision making. The result of the decision will then be executed in real-time to control the physical process flow in order to meet certain hard time constraints. These information processing time constraints are usually set by the dynamics of the physical process under control. In general, the time constraint is that the control information flow must be faster than or at least as fast as the physical flow. Apparently, response time is closely related to performance and real-time systems. Therefore, in this section background information is given on performance and real-time systems.

**Performance**

Performance is an important design factor for all software implementations but is often overlooked until it becomes a serious problem. In order to design for performance, it helps to understand what performance is. According to Smith and Williams\(^\text{296}\) performance is “an indicator of how well a software system or component meets its requirements for timeliness”. Timeliness can be measured in terms of response time and throughput. Response time is the time required to respond to a request or event. For instance, an online system may be required to provide a result within half a second after the user presses the ‘enter’ key. Throughput is the number of requests that can be processed in a pre-defined time frame. For example, an online system may be required to process 100,000 customer requests per hour. In addition, software timeliness has two important dimensions – responsiveness and scalability. Responsiveness describes the ability of a software system to meet its objectives for response time and throughput. Scalability is the ability of a software system to continue to meet its requirements for response time and throughput as the demand for software functions increases.

\(^{296}\) Smith & Williams 2001, p. 3
Figure 24 depicts the scalability curve. As long as the load on a system is below a certain threshold, increasing the load does not have a major effect on the response time. In this region response time increases linearly with the load on the system. However, once the threshold is reached, a small increase in load has a major effect on the response time. In this region, response time increases exponentially with the load on the system. This effect is usually caused by the fact that a system resource, e.g. computer processing unit, disk space or network bandwidth, is close to one hundred percent utilization.\textsuperscript{297}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{scalability_curve.png}
\caption{Scalability curve\textsuperscript{298}}
\end{figure}

**Real-time system**

Timeliness is an important quality of real-time systems, because such a system must react to stimuli within time intervals dictated by its environment. A solid understanding of the economic and technical factors which characterize such a system helps to interpret the demands that a system designer must cope with. According to Kopetz\textsuperscript{299}, a system is said to be real-time if the correctness of the system behavior depends not only upon the logical results, but also on the physical instant (deadline) at which these results are produced. If the result has utility even after the deadline has passed, the system is classified as a soft real-time system. For example, a software system that maintains and updates the flight plans for commercial airlines is a soft real-time system. On the other hand, if a catastrophe

\textsuperscript{297} Smith & Williams 2001, pp. 3-8  
\textsuperscript{298} Smith & Williams 2001, p. 5  
\textsuperscript{299} Kopetz 1997, p. 2
may result if the deadline is missed, the system is called hard real-time system. Consider a railway crossing a road with traffic lights. If the signal does not change to ‘red’ before a train arrives, a catastrophe might occur. The design of a soft real-time system is fundamentally different from that of a hard real-time system. Whereas it is acceptable for a soft real-time system to miss a deadline occasionally, a hard real-time system must sustain a guaranteed temporal behavior under all specified load and fault conditions. Therefore, hard real-time systems are typically found at a low level of hierarchy in embedded systems.\textsuperscript{300}

\textbf{IV.7.2 Discussion}

Ubiquitous computing systems consist of a combination of different hardware and software components that are triggered by incoming event streams and that communicated via some form of communication network. The main question of the design of such a system is whether or not a particular distribution of data and functionality will meet the overall time requirements. System level performance analysis is one proposed technique to answer this question.\textsuperscript{301} For this, the first step is to decompose the overall system into sub-systems or processes. Once these are identified, it should be analyzed which components have an influence on performance in the centralized and decentralized solution respectively.

\textit{Figure 25: Time delay diagram}\textsuperscript{302}

\textsuperscript{300} Kopetz 1997, pp. 3-5  
\textsuperscript{301} Wandeler et al. 2006  
\textsuperscript{302} Wang 2003
System components influencing response time

According to Wang\textsuperscript{303}, a ubiquitous computing system can be decomposed into the following time delay blocks – RFID tag read time delay, RFID data processing time delay, network communication time delay, decision-making process time delay and actuator decision execution time delay (see Figure 25). Basically, an RFID tag holds information that is read by readers. This information is then pre-processed to eliminate duplications, redundancies and misreads. Based on this information and eventually additional information extracted from backend databases, decisions are made. The result of this decision is communicated to specialized information technology systems or to actuators which are used to influence the physical process. Finally, in some circumstances data is written back onto the RFID tag.

Centralized solution

In the centralized solution, all delay blocks depicted in Figure 25 have an influence on response time. Standard RFID tags offer only a limited amount of memory – just enough to store a unique identification number. The advantage is that the time required for reading and processing the data from one tag is low. However, to retrieve additional information the RFID system must link to local or remote databases. For this, a robust network infrastructure that guarantees secure, reliable and timely access to a central database is required. This also means for field service applications that the access provided via a mobile service provider guarantees full coverage and proper response time. For decision making, additional data is extracted from the database and the decision is executed. There is no need to write data back onto the tag.

The described process seems to be straightforward and preferable. However, as shown before, response time for database queries and decision making increases linearly with the load on the system and once a certain threshold is reached, a small increase in load has a major negative effect on the response time, which is caused by the fact that a system resource is close to one hundred percent utilization. Usually, RFID traffic in manufacturing environments competes for limited bandwidth of the wired or wireless networks with other legacy enterprise applications such as SCADA and MES.\textsuperscript{304} Similarly, new implemented RFID

\textsuperscript{303} Wang, McFarlane, & Brusey 2004
\textsuperscript{304} Liu 2007
functionality in the backend systems competes with the limited processing power of those systems. Particularly, if the legacy systems are not scaleable, limited resources become a bottleneck for both existing functionality and new implemented RFID functionality.

The major cost involved in a centralized solution is the cost for extending legacy backend systems. On the one hand, this involves providing a robust network infrastructure that is able to handle the additional RFID traffic. On the other hand, backend legacy systems need to be extended with the required RFID functionality, and processing power for handling this additional functionality must be provided. Obviously, extending legacy systems is easier if those systems are scaleable and have a modular design. In addition, in cases of hard real-time systems, costs need to be included for the catastrophic behavior due to missed deadlines.

There are a number of benefits to the centralized solution. First of all, the cost for tags and intelligent readers can be kept low. Additionally, centralized servers allow for a higher volume of data storage, which may lead to better decision making. Finally, as all functionality is performed and all data is stored in one place, a consistent and homogenous system is enforced. If application software is centralized, required software installation, upgrades and patches have to be made in only one place. As a consequence, fewer technicians are required to update, upgrade and fix software problems.

**Decentralized solution**

In the decentralized solution, the following delay blocks depicted in Figure 25 have an influence on response time: data communication for reading data from the tag, data processing, decision making as well as decision execution. Data is read from the tag and processed locally. Based on the read data, decisions are made and executed. An important factor in regard to response time is the speed at which data can be read from a tag. For instance, Helmigh reports that it takes about four seconds to read the complete content of a temperature sensor. In the case of an assembly line moving at a constant speed of one meter per second, the reader must cover four meters of the line. However, if a reader with a read range of 1.4 meters is used, only 30 percent of the data can be read. This means that the time it takes to read data from the tag depends on the volume of the data.

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305 Helmigh 2006
Furthermore, the time for data processing needs to be considered. Usually, the more data is stored on the tag, the more data processing is required and consequently the more powerful these decentralized systems must be. Against this background, the organization of the user memory on tag influences the time it takes to extract and process the data. Memory can be structured as a single block that must be read in its entirety by the application. Once the data has been read, specific pieces of information can be extracted. The total time it takes to get meaningful information using this technique depends upon the amount of data stored in the user memory and the time it takes for the application to extract the required information. Additionally, the syntax and semantics of the stored data must be known. Alternatively, specific pieces of data can be assigned to a given memory location on the tag. This, however, is only feasible if all parties were looking for the same piece of information. Furthermore, where there was a lack on homogeneity, users would permit blank fields of data to consume memory space. Yet another option is to develop industry-specific memory maps. In this scenario, memory would begin with a code that would identify which memory map was being used.

There is a number of major cost components involved in the decentralized solution. Although, decision making may take less time because decisions are based on a rather small amount of data extracted from the tag, it may be possible that not all relevant global data are included in the decision making algorithm. This would lead to costly sub-optimal decisions. Additionally, not only data but also processing and decision rules need to be distributed and updated among dispersed systems, which may result in high maintenance cost. Furthermore, costs need to be included for catastrophic behavior due to low tag performance and inaccessible tag data. Finally, intelligent readers and tags with user memory are required, which adds to the hardware costs.

The major benefit of the decentralized solution is the avoidance of network and backend system bottlenecks without increasing bandwidth and backend system resources. This means that legacy systems and network infrastructure stay untouched. What is required is the extraction of data from existing databases for writing this data on the tag and vice versa.
IV.7.3 Management implications

In the last section, the response time argument ‘decentralize data and functions because this reduces response time’ was investigated in more detail by identifying ubiquitous computing system components that have an influence on response time and by analyzing which components have an influence on performance in the centralized and decentralized solution respectively. The research shows that the initial argument needs to be revised and the following thesis can now be formulated:

*Response time thesis:* Decentralization can be a solution in situations in which network and backend system bottlenecks should be avoided without adapting legacy systems and extending the infrastructure.

Against this background, there are three important management implications concerning the decentralization issue:

- Although it is argued that response time is shorter in a decentralized solution, this is not always the case because the time needed for reading data from the tag increases with the amount of data stored on the tag.

  Ubiquitous computing applications can be decomposed into the following delay blocks – transponder read time delay, data processing time delay, network communication time delay time, decision-making process delay time and actuator decision execution time delay. Whether the decentralized or the centralized solution is the better choice depends on the cumulated delay times. In the decentralized solution the time delay is primarily determined by the amount of data that need to be extracted from the tag. In the centralized solution the time delay mainly depends on the throughput of the network and the speed of database queries.

- Design a ubiquitous computing system based on peak loads and not average loads if response time is critical for a process because response time increases dramatically when a certain thresholds is reached.

  It is important to know for the design of the system, that as long as the load on a system is below a certain threshold, increasing the load does not have a major effect on the response time. However, once this threshold is reached, a small increase in the load has major effects on the response time. Therefore, the basis for the design must be the peak loads, rather than the average loads on the
system. This is particularly true for hard real-time systems, e.g. for systems that lead to major losses or problems if timeliness is not achieved.

- The decentralized solution should be implemented if response time is a key performance indicator and the adaptation of legacy systems and network infrastructure are prohibitively expensive.

Because of the benefits of the centralized solution, the management should first focus on this solution. Only if the adaptation of the legacy systems and network infrastructure are not feasible, the decentralized solution should be taken into account because its major benefit is the avoidance of network and backend system bottlenecks without adapting legacy systems and extending the network infrastructure. Particularly, if local decision making requires only a low volume of data which can be provided via tag and if the tag read rate is close to 100 percent, the costs of the decentralized solution can then be kept low.

### IV.8 Summary

Table 8 summarizes the findings of the research by presenting a main thesis, major costs and benefits of both the centralized and decentralized solution as well as management implications for each identified factor.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thesis</td>
<td>Decentralization can be a solution if the tag data and the same data in the database are not manipulated simultaneously.</td>
</tr>
<tr>
<td>Costs</td>
<td>Cost for fault tolerant network infrastructure</td>
</tr>
<tr>
<td>Benefits</td>
<td>Low-costs tags and readers</td>
</tr>
<tr>
<td>No non-value added software for synchronization</td>
<td></td>
</tr>
<tr>
<td>Consistent and homogenous system</td>
<td></td>
</tr>
<tr>
<td>Optimal decision making based on system-wide, up-to-date data</td>
<td></td>
</tr>
<tr>
<td>Factor</td>
<td>Summary</td>
</tr>
<tr>
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</tr>
</tbody>
</table>
| **Costs** | Cost for intelligent readers and tags with user memory  
Cost for software for writing data onto and reading data from the tag, processing data locally as well as synchronizing data  
Costs for decisions based only on locally available data |
| **Benefits** | No network connection is necessary during production process  
If tag data is treated only as a cache of local and global data, software costs for extracting data from and writing data into central databases is straightforward |
| **Management implications** | Synchronization issues may only arise if the tag data and the same data in the database are not manipulated simultaneously.  
The decentralized solution can be implemented if locally generated data and data extracted from the backend system is treated as cache. |
| **External data exchange** | Thesis  
Decentralization can be a solution in situations in which data should be exchanged among supply chain participants without integrating inter-organizational backend systems. |
<p>| <strong>Costs</strong> | Cost for the establishment and maintenance of the GDSN and the EPCglobal Network |</p>
<table>
<thead>
<tr>
<th>Factor</th>
<th>Summary</th>
</tr>
</thead>
</table>
| solution benefits | **Benefits**  
Low-cost tags and readers  
Usage of an established and proven GDSN for static data exchange  
EPCglobal standards have been developed for dynamic data exchange |
| Major costs & benefits decentralized solution | **Costs**  
Cost for intelligent readers and tags with user memory  
Cost for implementing security mechanisms  
Cost for standardization initiatives  
Cost of disruptions due to inaccessible data |
| Management implications | **Benefits**  
Data exchange among supply chain participants without the need to integrate backend systems |
| Security | **Thesis**  
Decentralization can be a solution in situations in which no permanent network connection is available and non-critical data are to be exchanged. |
<table>
<thead>
<tr>
<th>Factor</th>
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<tr>
<td><strong>Major costs &amp; benefits centralized solution</strong></td>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td></td>
<td>Cost for implementing the EPCIS and particularly security mechanisms on Discovery Service and EPCIS level</td>
</tr>
<tr>
<td></td>
<td>Cost for key management</td>
</tr>
<tr>
<td></td>
<td>Cost for maintaining fine-grained access rights</td>
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<tr>
<td></td>
<td><strong>Benefits</strong></td>
</tr>
<tr>
<td></td>
<td>Well-established security mechanisms can be used</td>
</tr>
<tr>
<td></td>
<td>Fine-grained access control possible</td>
</tr>
<tr>
<td><strong>Major costs &amp; benefits decentralized solution</strong></td>
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<td><strong>Benefits</strong></td>
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<tr>
<td></td>
<td>Protection of data to a certain extend if no permanent network connection is available</td>
</tr>
<tr>
<td><strong>Management implications</strong></td>
<td>Fundamentally, security schemes presume a centralized model making a decentralized model less secure or harder to manage.</td>
</tr>
<tr>
<td></td>
<td>Both solutions require a complex key management and challenges arise from assigning fine-grained access rights.</td>
</tr>
<tr>
<td><strong>Standardization</strong></td>
<td>Thesis</td>
</tr>
<tr>
<td></td>
<td>Decentralization can be a solution in situations in which data and interface standards exist for an application.</td>
</tr>
<tr>
<td>Factor</td>
<td>Summary</td>
</tr>
<tr>
<td>--------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Major costs &amp; benefits centralized solution</td>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td></td>
<td>Usage of EPC numbers</td>
</tr>
<tr>
<td></td>
<td>Implementation of the EPCglobal standards including redesign of databases and software systems &amp; architecture</td>
</tr>
<tr>
<td></td>
<td><strong>Benefits</strong></td>
</tr>
<tr>
<td></td>
<td>Usage of global standards for information exchange and securing investment</td>
</tr>
<tr>
<td>Major costs &amp; benefits decentralized solution</td>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td></td>
<td>Cost for standard definition</td>
</tr>
<tr>
<td></td>
<td>Cost for switching standard</td>
</tr>
<tr>
<td></td>
<td>Cost for intelligent readers and tags with user memory</td>
</tr>
<tr>
<td></td>
<td><strong>Benefits</strong></td>
</tr>
<tr>
<td></td>
<td>Usage of company-internal syntax and semantics</td>
</tr>
<tr>
<td>Management implications</td>
<td>The EPCglobal Network is the most comprehensive set of software and hardware standards for RFID applications and should be used.</td>
</tr>
<tr>
<td></td>
<td>Design a ubiquitous computing system based on existing standards to keep the cost down and to secure the investment.</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Thesis</td>
</tr>
<tr>
<td></td>
<td>Decentralization can be a solution in situations in which the development or deployment of a centralized software package and / or the deployment of a network are not feasible.</td>
</tr>
<tr>
<td>Major costs &amp; benefits</td>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td>Factor</td>
<td>Summary</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>centralized solution</strong></td>
<td>Cost for development and deployment of backend software</td>
</tr>
<tr>
<td></td>
<td>Cost for middleware configuration</td>
</tr>
<tr>
<td></td>
<td>Cost for network infrastructure</td>
</tr>
<tr>
<td><strong>Benefits</strong></td>
<td>Low-cost tags and readers can be used</td>
</tr>
<tr>
<td></td>
<td>Sophisticated, standardized middleware solutions allow for an easy configuration of the devices and integration with backend systems</td>
</tr>
<tr>
<td></td>
<td>Solution is able to adapted to changes based on the latest global data</td>
</tr>
<tr>
<td><strong>Major costs &amp; benefits</strong></td>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td>decentralized solution</td>
<td>Cost for intelligent readers and tags with user memory</td>
</tr>
<tr>
<td></td>
<td>Cost for software development deployment of backend and local systems</td>
</tr>
<tr>
<td><strong>Benefits</strong></td>
<td>No network infrastructure is required if all necessary data is stored on the tag and functions are performed locally on one item</td>
</tr>
<tr>
<td></td>
<td>Extracting data from backend systems and writing this data onto the tag is a straightforward and low-cost process</td>
</tr>
<tr>
<td></td>
<td>Solution is able to adapt to changes based on available local data.</td>
</tr>
<tr>
<td>Factor</td>
<td>Summary</td>
</tr>
<tr>
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<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Management implications        | Whereas the decentralized solution is able to cope with local uncertainty based on locally available data, the centralized solution is able to cope with both local and global uncertainty based on system-wide data.  
<pre><code>                            | The decentralized solution should be implemented if flexibility is a key performance indicator and the adaptation of legacy systems and network infrastructure is not feasible. |
</code></pre>
<p>| Response time                  | Thesis                                                                                                                                                                                                 |
|                                | Decentralization can be a solution in situations in which network and backend system bottlenecks should be avoided without adapting legacy systems and extending the infrastructure.                          |
| Major costs &amp; benefits         | Costs                                                                                                                                                                                                 |
| centralized solution           | Cost for adapting legacy system                                                                                                                                  |
|                                | Cost for extending infrastructure                                                                                                                                  |
|                                | Cost of catastrophic behavior due to low network and database performance                                                                                                    |
|                                | Benefits                                                                                                                                                                                               |
|                                | Low-cost tags and readers                                                                                                                                        |
|                                | Optimal decision making based on a high volume, system-wide data                                                                                                                                 |
|                                | Consistent and homogeneous system                                                                                                                                    |
| Major costs &amp; benefits         | Costs                                                                                                                                                                                                 |
| decentralized solution         | Cost for intelligent readers and tags with user memory                                                                                                           |
|                                | Cost for sub-optimal decision making based on locally available data                                                                                          |</p>
<table>
<thead>
<tr>
<th>Factor</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost for maintaining distributed data as well as processing and decision making rules</td>
</tr>
<tr>
<td></td>
<td>Cost of catastrophic behavior due to low tag performance and inaccessible tag data</td>
</tr>
<tr>
<td>Benefits</td>
<td>Avoidance of network and backend system bottlenecks without adapting legacy system and extending infrastructure</td>
</tr>
<tr>
<td>Management implications</td>
<td>Although it is argued that response time is shorter in a decentralized solution, this is not always the case because the time needed for reading data from the tag increases with the amount of data stored on the tag.</td>
</tr>
<tr>
<td></td>
<td>Design a ubiquitous computing system based on peak loads and not average loads if response time is critical for a process because response time increases dramatically when a certain thresholds is reached.</td>
</tr>
<tr>
<td></td>
<td>The decentralized solution should be implemented if response time is a key performance indicator and the adaptation of legacy systems and network infrastructure are prohibitively expensive.</td>
</tr>
</tbody>
</table>

*Table 8: Summary of the findings*
Summary and conclusions

This thesis aimed at providing new insights into the centralization versus decentralization debate in the field of ubiquitous computing in the manufacturing domain. The following and concluding chapter summarizes the most important findings, reflects their theoretical and practical implications, and briefly outlines promising future fields of research.

V.1 Key findings of the thesis

This thesis dealt with the following research question: what is the appropriate degree of decentralization of data and functions in ubiquitous computing applications within the manufacturing domain? To answer this question, it was broken down into sub-questions and the following answers were found:

What are the factors influencing the distribution of data and functions?

By analyzing eleven cases of ubiquitous computing applications in the manufacturing domain, the following main factors that have been identified as having an influence of the distribution of data and functions:

- **Synchronization**: The concept of synchronization refers to the idea of keeping multiple copies of a dataset coherent and thus maintains data integrity.

- **External data exchange**: External data exchange refers to the efficient and secure distribution of master data and dynamic data among supply chain partners.

- **Security**: Security mechanisms are combinations of cryptographic algorithms and protocols used to provide security of information systems related to aspects such as confidentiality, data integrity, entity authentication and data origin authentication.

- **Standardization**: Standards are defined as documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose.

- **Flexibility**: Flexibility refers to the ability to add, modify and remove any software, hardware or data components with ease, at low cost and with no major overall negative effect as well as to cope with uncertainty.
• **Response time:** Response time refers to ability of a system to meet the overall time requirements of the underlying physical process.

**When is the decentralized solution superior to the centralized solution?**

To answer the question when the decentralized solution is superior to the centralized solution, for each identified factor both the centralized and the decentralized solution have been investigated:

- **Synchronization:** Decentralization can be a solution in situations in which the tag data and the same data in the database are not manipulated simultaneously.

- **External data exchange:** Decentralization can be a solution in situations in which data should be exchanged among supply chain participants without integrating inter-organizational backend systems.

- **Security:** Decentralization can be a solution in situations in which no permanent network connection is available and non-critical data are to be exchanged.

- **Standardization:** Decentralization can be a solution in situations in which data and interface standards exist for an application.

- **Flexibility:** Decentralization can be a solution in situations in which the development or deployment of a centralized software package and/or the deployment of a network are not feasible.

- **Response time:** Decentralization can be a solution in situations in which network and backend system bottlenecks should be avoided without adapting legacy systems and extending the infrastructure.

**What are the costs and benefits of a solution?**

Based on the descriptions of both the centralized and decentralized solution for each identified factor following costs and benefits have been extracted (see Table 10).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Cost &amp; benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronization</td>
<td>Costs</td>
</tr>
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<td></td>
<td>Cost for faulty tolerant network infrastructure</td>
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<td></td>
<td>No non-value added software for</td>
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<tr>
<td>Factor</td>
<td>Cost &amp; benefits</td>
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</tr>
<tr>
<td></td>
<td>synchronization</td>
</tr>
<tr>
<td></td>
<td>Consistent and homogenous system</td>
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<tr>
<td></td>
<td>Optimal decision making based on system-wide, up-to-date data</td>
</tr>
<tr>
<td>Major costs &amp; benefits decentralized solution</td>
<td>Costs</td>
</tr>
<tr>
<td></td>
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<td>Costs for decisions based only on locally available data</td>
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<tr>
<td>External data exchange</td>
<td>Costs</td>
</tr>
<tr>
<td>Major costs &amp; benefits centralized solution</td>
<td>Cost for the establishment and maintenance of the GDSN and the EPCglobal Network</td>
</tr>
<tr>
<td>Benefits</td>
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<tr>
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<td>Cost of disruptions due to inaccessible data</td>
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<tr>
<td>Benefits</td>
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<td>Data exchange among supply chain participants without the need to integrate backend systems</td>
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<tr>
<td>Security</td>
<td>Costs</td>
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<td>Major costs &amp; benefits centralized solution</td>
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<td>Cost for implementing the EPCIS and particularly security mechanisms on Discovery Service and EPCIS level</td>
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<td>Cost for key management</td>
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<tr>
<td></td>
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</tr>
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<td></td>
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<tr>
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<td><strong>Costs</strong></td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>Implementation of the EPCglobal standards including redesign of databases and software systems &amp; architecture</td>
</tr>
<tr>
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<td><strong>Benefits</strong></td>
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<td>Cost for standard definition</td>
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<td><strong>Benefits</strong></td>
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<tr>
<td></td>
<td>Usage of company-internal syntax and semantics</td>
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<tr>
<td>Flexibility</td>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td></td>
<td>Cost for development and deployment of backend software</td>
</tr>
<tr>
<td></td>
<td>Cost for deploying hardware</td>
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<tr>
<td></td>
<td>Cost for middleware configuration</td>
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<tr>
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<td>Cost for network infrastructure</td>
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<tr>
<td>Factor</td>
<td>Cost &amp; benefits</td>
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<tr>
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<td>Low-cost tags and readers can be used</td>
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<td>Sophisticated middleware solutions allow for an easy configuration of the devices and integration with backend systems</td>
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<tr>
<td></td>
<td>Solution is flexible in a sense that the latest global data can be used to adapt to changes</td>
</tr>
<tr>
<td></td>
<td><strong>Costs</strong></td>
</tr>
<tr>
<td>Major costs &amp; benefits decentralized solution</td>
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<tr>
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<td><strong>Benefits</strong></td>
</tr>
<tr>
<td>Response time</td>
<td>No network infrastructure is required if all necessary data is stored on the tag and functions are performed locally on one item</td>
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<tr>
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<td>Extracting data from backend systems and writing this data onto the tag is a straightforward and low-cost process</td>
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<tr>
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<td>Cost of catastrophic behavior due to low network and database performance</td>
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</tr>
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<td></td>
<td><strong>Benefits</strong></td>
</tr>
<tr>
<td></td>
<td>Avoidance of network and backend system bottlenecks without adapting legacy system and extending infrastructure</td>
</tr>
</tbody>
</table>

**Table 9: Cost-benefit model**

**What recommendations can be given to practitioners?**

Based on the descriptions of both the centralized and decentralized solution as well as the cost-benefit investigations for each identified factor following recommendations can be given to the management (see Table 10).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Management implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronization</td>
<td>Although it is argued that decentralization leads to synchronization issues, this is only the case if the tag data and the same data in the database are manipulated simultaneously.</td>
</tr>
<tr>
<td><strong>Factor</strong></td>
<td><strong>Management implications</strong></td>
</tr>
<tr>
<td>---------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>The decentralized solution can be implemented if locally generated data and data extracted from the backend system is treated as cache.</td>
</tr>
</tbody>
</table>
| External data exchange | Exchanging data via tag may be an option if the GDNS and EPCglobal Network have not yet been implemented, a low number of partners are involved and less critical data are exchanged.  
Although there is a lack of information systems that support reverse logistics processes data for these processes should not be exchanged via tag because of security, standardization and data volume issues. |
| Security            | Fundamentally, security schemes presume a centralized model making a decentralized model less secure or harder to manage.  
Both solutions require a complex key management and challenges arise from assigning fine-grained access rights.                                                       |
| Standardization     | The EPCglobal Network is the most comprehensive set of software and hardware standards for RFID applications and should be used.  
Design a ubiquitous computing system based on existing standards to keep the cost down and to secure the investment.                                                   |
| Flexibility         | Whereas the decentralized solution is able to cope with local uncertainty based on locally available data, the centralized solution is able to cope with both local and global uncertainty based on system-wide data.  
The decentralized solution should be implemented if flexibility is a key performance indicator and the adaptation of legacy systems and network infrastructure is not feasible. |
<table>
<thead>
<tr>
<th>Factor</th>
<th>Management implications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response time</td>
<td>Although it is argued that response time is shorter in a decentralized solution, this is not always the case because the time needed for reading data from the tag increases with the amount of data stored on the tag. Design a ubiquitous computing system based on peak loads and not average loads if response time is critical for a process because response time increases dramatically when a certain threshold is reached. The decentralized solution should be implemented if response time is a key performance indicator and the adaptation of legacy systems and network infrastructure are prohibitively expensive.</td>
</tr>
</tbody>
</table>

*Table 10: Summary management implications*

### V.2 Theoretical implications

The research results offer a supplementary view of the existing research on the centralization versus decentralization dispute in ubiquitous computing, in particular and in information systems in general. Since the question on whether to centralize or decentralize has emerged as an important issue in ubiquitous computing and has not yet been sufficiently addressed in existing literature, the research aimed at closing this research gap.

According to Schneider\(^{307}\) results can be classified as theoretical contributions if three requirements are fulfilled: (1) a problem must exist, (2) all relevant terms and concepts must be defined and (3) examples must be given. In this research, the problem is outlined in chapter I.1 and a detailed overview of the problem is given in chapter II. Additionally, a solution to the problem is developed in chapter IV. For both, the problem and the solution, all relevant terms and concepts are defined. Finally, eleven examples are presented in chapter III. The following list summarizes the theoretical contribution of the research:

---

\(^{307}\) Schneider 1981, p. 41
The thesis gives an overview of the centralization versus decentralization debate in research fields related to ubiquitous computing research. The widespread discussion on this issue has led to considerable ambiguity in the meanings ascribed to the terms centralization and decentralization. By giving a detailed multi-disciplinary overview of the topic, a comprehensive theoretical understanding could be reached.

In this thesis a framework has been developed that describes technological, organizational, operational and economic factors and their impact on the degree of (de)centralization of data and functions in ubiquitous computing applications in the manufacturing domain in particular and information systems in general. This framework extends the long-standing discussion on whether to centralize or decentralize which has flourished for several decades by presenting a detailed analysis based on a case study approach. Whereas the factors security, flexibility and response time have been identified as an influencing factor on the (de)centralization by previous research, the factors synchronization, external data exchange, and standardization have not.

In the introductory chapter it was argued that ubiquitous computing applications can take the form of a complex system and therefore complexity theory and literature on complexity management should give relevant and applicable input on whether to centralize or decentralize in ubiquitous computing applications. However, although applicable, this research stream neither allowed drawing any concrete conclusions on the issue for ubiquitous computing applications, nor were quantitative measures with regard to complexity contributed to. By analyzing the centralized and decentralized solutions, elements could be identified that contributed the complexity of a solution and quantitative measures could be given by analyzing costs and benefits.

V.3 Practical implications

Regardless of the industry and how manufacturing is structured, companies continuously invest to improve efficiency and effectiveness. The ability to obtain and use accurate, timely, granular information based on ubiquitous computing technologies will have a direct impact on the success of these investments. While many manufacturers are adopting RFID by force of mandates in the supply chain, even more of them are seeking ways to use the technology to improve their internal
production processes. A large body of reports, white papers, trade magazines, and vendor leaflets has been published on RFID applications and their benefits. However, those are mainly journalistic and promotional in nature and there is a lack of academic studies that reveal critical success factors and offer lessons learned from real-world applications. Yet, for companies to be able to assess the actual impact of RFID technology on existing production processes and on the information technology architecture, a detailed understanding of the design, development and implementation of such systems is necessary. Manufacturers that gain this understanding of the opportunities and challenges of ubiquitous computing application deployment and then approach it with a sound plan and realistic expectations will be best equipped to meet their internal and external requirements.

Therefore, the thesis aimed at improving the practical understanding for practitioners who are responsible for the application design as well as software vendors in the manufacturing domain:

- The case studies in chapter III represent real-world applications based on ubiquitous computing technologies in the manufacturing domain. Each case description is structured along the elements initial situation and objectives, application description and implications on the decentralization of data and functions. These cases help practitioners understand how ubiquitous computing technologies may be used to overcome certain process issues and what the implications for the information technology infrastructure are.

- The explanatory model in chapter IV is used for interpreting and discussing the results derived from the case studies. This chapter helps practitioners understand what factors or drivers actually cause the (de)centralization of data and functions in manufacturing by investigating both the centralized and decentralized solutions in regard to their theoretical grounding, strengths and weaknesses as well as risk factors and trade-offs. As the alternative solutions are investigated a cost-benefit model has been developed which helps to decide on the best solution for a company.

- Finally, in chapter IV the theoretical insights gained are taken a step further to provide concrete guidance for practitioners. Specifically, a prescriptive model is presented which suggests how ubiquitous computing applications in the manufacturing domain should be designed with particular focus on the
decentralization of data and functions. In addition to that, decision support is
given on the evaluation of the alternative solutions.

V.4 Conclusion and outlook

The aim of this thesis was to improve the understanding of the centralization versus
decentralization debate in ubiquitous computing research by investigating factors
that influence the design decision on whether or not to store data on tag and to
decentralize business logic. By analyzing eleven case studies supplemented with the
participation in an RFID project, factory visits, semi-structured interviews and
literature research, six factors could be revealed that have an influence on
(de)centralization. The identified factors are synchronization, external data
exchange, security, standardization, flexibility and response time. The explanation
of the centralized and decentralized solution in regard to each factor and the
resulting costs, benefits and implications form a model that can support software
providers and managers wishing to implement RFID applications in manufacturing
on how to design the application.

As with any study, this research is not without its limitations. First, it is based on a
relatively small number of case examples, owing to the early stage of technology
adoption in manufacturing. Therefore, the validity of future research would benefit
from insights obtained from quantitative data. In addition, the study is limited by the
fact that it concentrates primarily on cases in which data are stored on the tag and
these cases come from only seven industries. Including additional cases in which
data are not stored on the tag, analyzing other industries and looking beyond the
manufacturing domain could both reveal additional factors and further enhance the
transferability of the results.

For the positive potential of ubiquitous computing technologies to be realized, it is
crucial that they not form a technology island but be tightly integrated into existing
information technology architectures. As these technologies are likely to join the
ranks of those information technologies that are labeled disruptive, their adoption
by companies and subsequent integration into existing information system
architectures will lead to considerable changes of the established architectures and
business processes. The cost of the required reengineering tasks may well exceed
the cost for hardware and software.\textsuperscript{309} These facts make it worthwhile to have a good understanding of the influence ubiquitous computing may have on the information system architecture.

\textsuperscript{309} Günther, Kletti, & Kubach 2008, p. V
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Wessel, R. 2006. "Clothing Manufacturer Invests Its ROI in RFID."


Appendix A: List of conducted interviews

The list of conducted interviews is shown in Table 11.

<table>
<thead>
<tr>
<th>Company</th>
<th>Expert</th>
<th>Function</th>
<th>Place and date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huf Tools</td>
<td>Veit Schröter</td>
<td>Division Manager RFID Systems</td>
<td>Telephone interview,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>July 7(^{th}), 2007</td>
</tr>
<tr>
<td>IBM</td>
<td>Dirk Spannaus</td>
<td>Business Development Representative RFID</td>
<td>Telephone interview,</td>
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<td></td>
<td></td>
<td></td>
<td>June 26(^{th}), 2006</td>
</tr>
<tr>
<td>Inet-logistics</td>
<td>Oswald Werle</td>
<td>CEO</td>
<td>Telephone interview,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>May 11(^{th}), 2006</td>
</tr>
<tr>
<td>Intel</td>
<td>Dr. Dieter Kilian</td>
<td>Senior Project Manager</td>
<td>Telephone interview,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>June 29(^{th}), 2007</td>
</tr>
<tr>
<td>Intellion</td>
<td>Dr. Markus Dierkes</td>
<td>CEO</td>
<td>St. Gallen,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>July 15(^{th}), 2007</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Telephone interview,</td>
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<td></td>
<td></td>
<td></td>
<td>May 3(^{rd}), 2006</td>
</tr>
<tr>
<td>Nofilis</td>
<td>Franz Angerer</td>
<td>CEO</td>
<td>Ismaning,</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>August 10(^{th}), 2007</td>
</tr>
<tr>
<td>OATSystems</td>
<td>Martin Swerdlow</td>
<td>Managing Director</td>
<td>Halifax,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>January 24(^{th}), 2008</td>
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<tr>
<td>SAP</td>
<td>Stephan Haller</td>
<td>Senior Researcher,</td>
<td>Telephone</td>
</tr>
<tr>
<td>Company</td>
<td>Expert</td>
<td>Function</td>
<td>Place and date</td>
</tr>
<tr>
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<td>-------------------</td>
<td>----------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>University of Dortmund</td>
<td>Sergey Libert</td>
<td>Project Manager</td>
<td>interview, May 16\textsuperscript{th}, 2007</td>
</tr>
<tr>
<td>Zetes</td>
<td>Eddy Van Herbruggen</td>
<td>Group Specialist Data Communication &amp; Security RFID</td>
<td>Halifax, January 25\textsuperscript{th}, 2008</td>
</tr>
</tbody>
</table>

*Table 11: List of conducted interviews*
Appendix B: List of factory and lab visits

The list of factory visits is shown in Table 12.

<table>
<thead>
<tr>
<th>Company</th>
<th>Place</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>Hull, UK</td>
<td>November 15\textsuperscript{th}, 2005</td>
</tr>
<tr>
<td>University of Dortmund (Chair of Materials Handling and Warehousing)</td>
<td>Dortmund</td>
<td>May 30\textsuperscript{th}, 2006</td>
</tr>
<tr>
<td>Sony</td>
<td>Barcelona, Spain</td>
<td>January 17\textsuperscript{th}, 2007</td>
</tr>
<tr>
<td>Nestlé UK</td>
<td>York, UK</td>
<td>February 22\textsuperscript{nd}, 2007</td>
</tr>
<tr>
<td>Nestlé UK</td>
<td>Tutbury, UK</td>
<td>March 12\textsuperscript{th}, 2007</td>
</tr>
<tr>
<td>Nestlé UK</td>
<td>Halifax, UK</td>
<td>March 13\textsuperscript{th}, 2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>January 24\textsuperscript{th}, 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>January 25\textsuperscript{th}, 2008</td>
</tr>
<tr>
<td>Nestlé UK</td>
<td>Fawdon, UK</td>
<td>March 19\textsuperscript{th}, 2007</td>
</tr>
<tr>
<td>University of Cambridge (Distributed Information &amp; Automation Laboratory)</td>
<td>Cambridge</td>
<td>April 26\textsuperscript{th}, 2007</td>
</tr>
</tbody>
</table>

*Table 12: List of factory and lab visits*
CURRICULUM VITAE

Chris Kürschner

born on July 7, 1975 in Bad Salzungen

ACADEMIC STUDIES

11/2004-08/2008 PhD student at the University of St. Gallen (HSG), Institute of Technology Management

04/1998-12/2003 Study of Business Administration at the Bayerische Julius-Maximilians-Universität Würzburg

08/2000-05/2001 Exchange student at the University of Texas at Austin

09/1991-06/1994 University-entrance diploma at Herzog-Georg-Gymnasium, Bad Liebenstein

WORK EXPERIENCE

since 10/2008 Consultant at SAP Deutschland AG & Co. KG, Walldorf

09/2006-08/2008 Research associate at SAP Schweiz AG, St. Gallen

01/2004-10/2004 Software developer at the Bayerische Julius-Maximilians-Universität Würzburg

04/2003-02/2004 Software developer at Simplan AG, Maintal

06/2002-09/2003 Student research assistant at the Bayerische Julius-Maximilians-Universität Würzburg

06/2001-12/2001 Software developer at i-te systems GmbH, Würzburg

08/1999-07/2000 Freelancer at IBIS Prof. Thome GmbH, Würzburg

02/1998-05/1998 Employee at Wartburg-Sparkasse, Eisenach

08/1995-01/1998 Apprenticeship at Wartburg-Sparkasse, Eisenach