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Diplomarbeit

Development of a Relation Model to determine the Degree of Implementation for Digitalization of Value-Added Processes

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines

Diplom-Ingenieurs

unter der Leitung von

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Hainburg/D, im Jänner 2019

Philip Geißler

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Diplomarbeit

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Hainburg/D, im Jänner 2019

Philip Geißler

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Abstract

Industrial companies are under increased pressure for change, resulting from increased globalization and therefore competition with companies from around the world. Thus, they are facing the challenge of constantly improving their value creation processes in order to make them more efficient, flexible and economic to remain competitive. One approach to increase process performance results from concepts such as industrial digitalization – currently observed in new manufacturing paradigms such as Industry 4.0.

The positive results from increased digitization are rigorously analyzed and widely accepted. However, the question of "*how digitalization concepts exactly relate to different process components of internal value creation processes*" is still widely uncovered from a scientific point of view – and therefore the core question of this Master Thesis.

To answer this question, a relation model is developed which builds on the requirements of industrial digitalization for internal industrial value creation. More precisely, these requirements are split into physical objects and information elements within value creation processes that are interlinked with existing production factors of industrial companies (dimensions). Through this linkage so-called "matching boxes" are developed which are filled with concrete implementation examples of industrial digitalization from real manufacturing environments. In order to fill the "matching boxes", an encompassing systematic literature review was conducted using more than 1100 search terms and resulting in 8875 results. Out of all results 332 publications were considered further development of the relation model.

In a next step, the implementation examples were then clustered into abstract implementation concepts. By developing these clusters, a more general model results, that contains 10 dimensions in which the progressiveness of the company's digitalization of value creation can be assessed. This model finally transformed into a method to assess the implementation status in manufacturing companies between 1-low implementation and 5-high implementation. Using this approach, the relation model and assessment method was successfully tested in the Industry 4.0 Pilot Factory of the TU Wien.

Transferring the model into a practical assessment tool offers great potential to help companies to identify their implementation level of digitalization in multiple dimensions. Knowing their as-it-is-status moreover enables them to derive strategic steps towards more digitalized, thus more competitive value creation processes.

Kurzfassung

Industrieunternehmen stehen aufgrund zunehmender Globalisierung und dem damit erhöhten Wettbewerb mit Unternehmen aus aller Welt unter erhöhtem Veränderungsdruck. Hieraus ergibt sich die Herausforderung, deren Wertschöpfungsprozesse ständig zu verbessern, um diese effizienter, flexibler und wirtschaftlicher zu gestalten und hierdurch wettbewerbsfähig zu bleiben. Ein Ansatz zur Steigerung der Prozessleistung resultiert aus Konzepten industrieller Digitalisierung, welche aktuell in neuen Produktionsparadigmen wie der Industrie 4.0, zu beobachten sind.

Die positiven Effekte zunehmender Digitalisierung der Wertschöpfung sind bereits umfassend analysiert und weitgehend anerkannt. Die Frage, „Wie sich Digitalisierungskonzepte im Detail auf verschiedene Prozesselemente interner Wertschöpfungsprozesse auswirken“, ist jedoch aus wissenschaftlicher Sicht noch weitgehend ungeklärt und damit die Kernfrage dieser Diplomarbeit.

Um diese Frage zu beantworten, wird ein Relationen-Modell entwickelt, welches auf den Anforderungen der industriellen Digitalisierung für interne industrielle Wertschöpfung aufbaut. Genauer gesagt, werden diese Digitalisierungs-Anforderungen innerhalb der Wertschöpfungsprozesse in physische Objekte und Informationselemente geteilt, und diese mit bestehenden Produktionsfaktoren von Industrieunternehmen (Dimensionen) verknüpft sind. Durch diese Verknüpfung werden sogenannte „Matching-Boxes“ entwickelt, welche mit konkreten Umsetzungsbeispielen der industriellen Digitalisierung aus realen Produktionsumgebungen befüllt werden. Um die „Matching-Boxes“ zu füllen wurde eine umfassende systematische Literaturrecherche mit mehr als 1100 Suchbegriffen durchgeführt, welche zu 8875 Ergebnisse führte. Von diesen Ergebnissen wurden 332 Publikationen für die weitere Entwicklung des Relationen-Modelles berücksichtigt.

In einem nächsten Schritt wurden die konkreten Implementierungsbeispiele zu abstrakten Implementierungskonzepten geclustert. Durch die Entwicklung dieser „Cluster“ entsteht ein allgemeines Modell bestehend aus 10 Dimensionen, in denen die Progressivität der Digitalisierung der Wertschöpfung von Unternehmen bewertet werden kann.

Das Modell wurde anschließend in eine Methode zur Bewertung des Implementierungsstatus in produzierenden Unternehmen zwischen 1-geringe Implementierung und 5-hohe Implementierung überführt. Das Relationen-Modell sowie die Bewertungsmethode wurden in der Industrie 4.0 Pilotfabrik der TU Wien erfolgreich getestet.

Die Überführung des Modells in ein praktisches Bewertungsinstrument bietet großes Potential, Unternehmen dabei zu unterstützen, Ihren Implementierungsgrad der Digitalisierung zu identifizieren. Die Kenntnis des Ist-Zustanden, ermöglicht Unternehmen anschließend strategische Schritte zu erhöhter Digitalisierung, und so wettbewerbsfähigerer Wertschöpfungsprozessen, abzuleiten.

Table of Contents

1 Introduction

1.1 The Challenge of Digitalization – Problem Definition

Due to the pressure for change, resulting of the fourth industrial revolution, companies are faced with the challenge of digitalizing their value-added processes, to remain competitive.

This challenge results in the raise of the question of how digitalization affects the value-added processes of manufacturing companies. To answer this question, a model is developed that links the requirements, more precisely the requirement-fields information and physical object, for a digitalized value-added process with its existing transformation factors. Thus, the meanings of the requirements of a digitalized value-added process for the production transformation factors, can be determined.

Based on these matches, the model is to be transferred into measurable variables in the future to be able to determine the degree of digitalization of a value-added process based on targeted questions.

1.2 Research Question of the Master Thesis

To tackle the issue of uncertainty about how digitalization affects the value-added processes, a model of assessing the relationship between the requirements for a digitalized value-added process (requirement fields) with its transformation factors appeared as the most promising scientific approach.

Based on this relation model approach, this work aims for the development of a relation model that should enable the evaluation of the degree of implementation for digitalized value-added processes.

Based on the outlined problems, the obvious need for a relation model, the research question of this thesis is developed:

How can the requirements for a digitalized value-added process be interlinked with its transformation factors and how can the requirements be implemented for the value-adding-factors?

Details about the approach for developing the relation model as well as included methodologies are presented in the following.

1.3 Work Packages of the Master Thesis

This master thesis is carried out in three work packages (see Figure 1) ranging from theoretically (Work package 1) to practically applied (Work package 3) content.

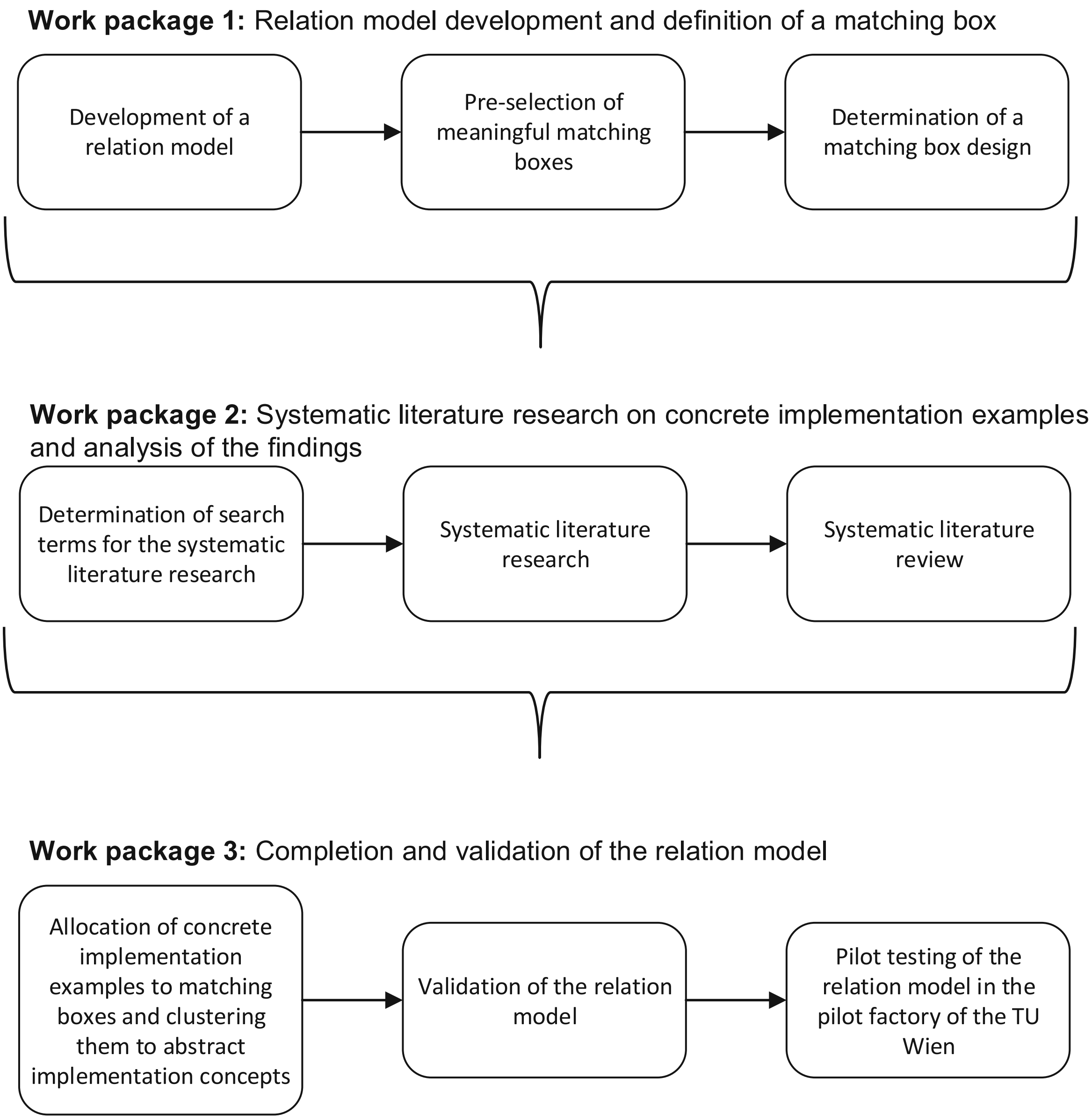

Figure 1: Work packages of the master thesis [1]

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[1] Created with the software Microsoft Visio

- **Work package 1:** Relation model development and definition of a matching box

In a first step, a so-called relation model is developed to illustrate and visualize the relationship between the requirements for a digitalized value-added process and the dimensions of a production and materials flow process. The second step is the pre-selection of meaningful matching boxes, which are boxes where a requirement meets a dimension, before filling them with literature. In a last step, a design for the matching boxes is determined.

- **Work package 2:** Systematic literature research on concrete implementation examples and analysis of the findings

To fill the matching boxes with concrete implementation examples, a systematic literature research is carried out. Search terms are determined to enable the above-mentioned systematic literature research. The findings are then analyzed to collect only relevant implementation examples.

- **Work package 3:** Completion and validation of the relation model

In the last work package, the analyzed findings from the systematic literature research (concrete implementation concepts) are allocated to suitable matching boxes and clustered to abstract implementation concepts. In a final step, the relation model is validated by pilot testing it within the pilot factory of the TU Wien.

1.4 Structure of the Master Thesis

The master thesis focuses on the development of a relation model which is used to link the requirements for a digitalized value-added process with the dimensions of a production and materials flow process to evaluate de degree of implementation for digitalization of value-added processes. The thesis is structured into five main chapters:

Following **Chapter 1** (Introduction), **Chapter 2** (Methodological Approach to develop the Relation Model) presents the scientific background of the methods used in this master thesis to develop the relation model.

In **Chapter 3** (Model-Development and the resulting Relation Model) the development-procedure as well as the resulting relation model are described in detail. The 3.1st chapter (Development of the Relation-Model) explains the structured model development and the design of a matching box. Finally, the resulting relation model is presented in chapter 3.2 (Result: The Relation Model). In order to represent the results, chapter 3.3 explains the so-called implementation report.

Chapter 4 (Pilot-Testing of the Relation Model) presents the models first testing in the pilot factory of the TU Wien. The detailed results are highlighted in chapter 4.1 and chapter 4.2 shows the visualization of the degree of implementation in a radar chart.

Finally, the 5th **Chapter** (Discussion and Outlook) aims for summarizing the results and findings (5.1 Summary of Results and Findings) and explains further development plans (5.2 Further Research Directions).

2 Methodological Approach to develop the Relation Model

2.1 Methodological Approach at a glance - Concept Mapping

Concept mapping is a graphical method for organizing and representing knowledge in so called “concept maps”. In these maps, a concept can be sees as “a perceived regularity in events or objects“. The origin of the method was found in 1972 where researchers were trying to follow and understand changes in children’s knowledge and representing the results in the form of a concept map.[2]

2.1.1 Concept maps development

Concept maps consist of the **concepts** which are certain perceived regularities or patterns which are related to each other and are usually enclosed in boxes of some type. To highlight these relations, so-called **relationship (cross-link)** between the concepts indicated by a connecting line linking two concepts are used. To specify the relationship between two concepts **propositions (linking words** or **linking phrases)** are added to the relationship-line.[3]

Main characteristics of concept maps:[4]

- Graphical tools for organizing and representing knowledge
- Concept maps help to answer “Focus Question(s)”
- Concepts are represented in hierarchical fashion (from general to specific)
- Cross-links are included showing the relationships between the concepts
- Propositions specify the relationship between to concepts by using linking words or linking phrases

The main advantage of concept maps is the easier understanding due to the visualization and summarization of information in a graphical way leading in a faster information processing of the visual impressions of the concept maps.

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[2] (Novak and Canas, 2008, p. 1-2)
[3] (Novak and Canas, 2008, p. 1-3)
[4] (Novak and Canas, 2008, p. 1-5)

2.1.2 Procedure to create the methodological concept map of the thesis

Concept mapping is used for representing the different conceptual relations of the methodological approaches to develop the relation model in the thesis by following a three step-process:[5]

Step 1: Construction of a focus question

Content of Step 1:
To create a context, that will help to determine the hierarchical structure of the concept map, a particular problem or question has to be identified leading in the construction of a focus question that clearly specifies the issue or problem the concept map should help to resolve.

Outcome of Step 1:
Clearly defined focus question

Application of Step 1 on the thesis:
The focus question of the concept map for the thesis is: "What theoretical foundations are included into the thesis to develop a relation model for determining the degree of implementation for digitalization of value-added processes and for what purpose"?

Step 2: Identification of key and sub-concepts

Content of Step 2:
After constructing a defined question or problem in step 1, the next step is to identify the key concepts which are related to the focus question by executing group-works or literature reviews. Key concepts are general patterns that can be found during the group-works or literature review.
The more specific concepts are called sub-concepts which are related to the key-concepts. After listing these concepts, they are ranked in a list from the most general on the top of the list (key-concepts), to the most specific at the bottom of the list (sub-concepts). The next step is to move these concepts into the concept map where they fit in.

Outcome of Step 2:
Preliminary concept map including key and sub-concepts

Application of Step 2 on the thesis:
Concept map - See Figure 2: Concept map - Theoretical Foundations of the thesis

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[5] (Novak and Canas, 2008)

Step 3: Definition of cross-links and finalization of the concept map

Content of Step 3:
In the final step, cross-links are added to the preliminary concept map. Cross-links are linkages between concepts in different segments of knowledge to illustrate how the concepts are related to each other.

Outcome of Step 3:
Final concept map including all concepts (key and sub-concepts) and cross-links

Application of Step 3 on the thesis:
Concept map - See Figure 2: Concept map - Theoretical Foundations of the thesis

2.1.3 Resulting concept map of the master thesis

The resulting concept map can be seen on Figure 2. It visualizes the different theoretical foundations used in this thesis to develop a relation model to determine the degree of implementation for digitalization of value-added processes.

In order to ensure that the concept map is clearly visible, only the main cross-links have been visualized.

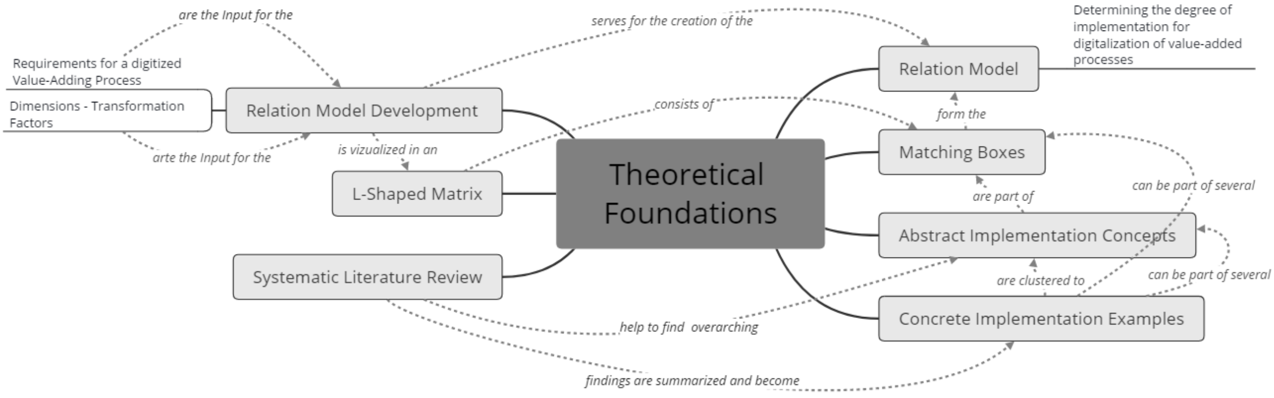

Figure 2: Concept map - Theoretical Foundations of the thesis[6]

In the following chapters, the theoretical content of the resulting methods as well as their application and relevance for the thesis are described in more detail.

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[6] Created with the software Xmind - www.xmind.net

2.2 Systematic Literature Review on the resulting Matching Boxes

In this chapter the systematic literature review, which is required to fill the matching boxes with concrete implementation examples (see Figure 2), is described.

A literature review provides a rigorous overview of scientific articles, books and other sources relevant to a particular issue, area of research, or theory thus providing a description, summary and critical evaluation of that work.[7] The goal of a literature review is to bring the reader up-to-date with current literature, on a topic and to form the basis for the justification for future research in that area.[8]

In contrast to traditional literature reviews, systematic literature reviews, which are used to answer well-focused questions, use a more thorough and well-defined approach to reviewing the literature.[9]

2.2.1 The importance of a systematic literature review and its advantages

Traditional research starts with a literature review in any way by describing and summarizing previous works in the field of research, but they do not describe the specific method by which literature was identified, selected and critically evaluated. Due to the fact, that a literature review is thorough and fair, traditional research as described above is of little scientific value which is the main rational reason for executing systematic literature reviews.[10] Systematic literature reviews use explicit and rigorous criteria to identify, evaluate and synthesize all the literature on a particular topic.[11]

However, the most notable reason to work with systematic literature reviews is the increasing number of publications in all fields of science which makes it impossible to capture the state of the art in a field of research without using a systematic approach.

Main advantages of a systematic literature review:[12]

- Providing information about effects of some phenomenon across a wide range of settings and empirical methods
- Possibility of combining data using meta-analytic techniques
- Ensuring complete acquisition of existing literature in the relevant scientific field
- Possibility to replicate the scientific findings

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[7] (Ramdhani et al., 2014, p. 48)
[8] (Cronin et al., 2008, p. 38)
[9] (Cronin et al., 2008, p. 39)
[10] (Kitchenham, 2004, p. 2)
[11] (Ramdhani et al., 2014, p. 49)
[12] (Kitchenham, 2004, p. 2)

2.2.2 Followed procedure of a systematic literature review in thesis

To find concrete implementation concept examples in literature, a systematic literature review is conducted. Thus, a six-step procedure is developed based on several literature sources to ensure a systematic and implementable process for conducting the literature review:[13] [14] [15] [16]

Step 1: Selection of the review topics

Content of Step 1:

The first step of a systematic literature review is the selection and definition of the review topic for which the relevant literature should be found. To create a manageable number of findings it is advisable to avoid selecting a review title that is all encompassing. The review topics should be clearly defined to focus on the topics.

Outcome of Step 1:

Defined review topics

Application of Step 1 on the thesis:

The main review topic of the systematic literature review is "Concrete Implementation Concepts for the Matching Boxes (Where a requirement meets a value-adding factor)".

Step 2: Definition of the purpose of the systematic literature review

Content of Step 2:

The second step is to define the exact purpose of the systematic literature review and to highlight how the literature review supports answering the research question.

Outcome of Step 2:

Defined purpose of the systematic literature review

Application of Step 2 on the thesis:

The purpose of the systematic literature review is to fill the matching boxes with concrete implementation concepts to give examples of how the requirements can be implemented for the value-adding factors.

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[13] (Cronin et al., 2008, pp. 39–43)
[14] (Ramdhani et al., 2014, pp. 50–53)
[15] (Okoli and Schabram, 2010, pp. 6–9)
[16] (Schumacher, Diplomarbeit, pp. 35-39)

Step 3: Preparation of a documentation protocol

Content of Step 3:
After defining the purpose of the systematic literature review, the next step is the preparation of a documentation protocol to ensure systematic throughout the whole literature search. The following criteria need to be defined:

General criteria:

- Definition of a search strategy
- Definition of database used for searching the literature

1st degree criteria *(applied using the filter-function in the database)*

- Language of publications
- Time range of publications
- Type of literature
- Used search terms
- Science areas to search for publications
- Search area of the "used search term" in the publications

2nd degree criteria *(applied on the 1st degree criteria findings)*

- Relation to the review topic?
- Supports answering the research question?
- Meets the required quality of literature?

Outcome of Step 3:
Defined General criteria, 1st degree criteria and 2nd degree criteria

Application of Step 3 on the thesis:

General criteria:

- **Definition of a search strategy:**
  Web-based search using the online database of a scientific search engine
- **Definition of database used for searching the literature:**
  Database of Science Direct[17]

1st degree criteria *(applied using the filter-function in the database)*

- **Language of publications:**
  English
- **Time range of publications:**
  2000 - 2017/2018 (search extended over the change of the year)

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[17] http://www.sciencedirect.com/

If the results after the 1st degree criteria were too many, the time range was individually changed and documented in the protocol.

- **Type of literature:**
  Journals, books
- **Used search terms:**
  See Table 7: Full Results - Systematic literature review
- **Science areas to search for publications:**
  Computer science, engineering
- **Search area of the "used search term" in the publications:**
  Abstract, title, keywords

2nd degree criteria *(applied on the 1st degree criteria findings)*

- **Relation to the review topic?**
- **Supports answering the research question?**
- **Meets the required quality of literature?**

The above-mentioned questions from the 2nd degree criteria were answered with yes or no during the screening by the researcher.

Step 4: Searching the literature and first screening

Content of Step 4:
Step 4 consists of the execution of the literature search by applying the general, 1st degree and 2nd degree criteria. After applying the general and 1st degree criteria on the search the findings are documented (used search terms, used time-range in case of an adaption and the number of results after general and 1st degree criteria) and a list of findings is created in the database without downloading the publications.

After creating a list of findings, the 2nd degree criteria are applied by screening the title of the results online. A first selection of literature is carried out and the findings are downloaded for screening the abstract and the full text. The number of results of the downloaded literature is also documented in the protocol.

Outcome of Step 4:
Downloaded (locally stored on computer) collection of publications fulfilling the general, 1st and 2nd degree criteria

Application of Step 4 on the thesis:
The results of the search are described in chapter 2.2.3 Results of the systematic literature review and the numbers of results with the used search terms are depicted in Table 7: Full Results - Systematic literature review.

Step 5: Full text screening of the downloaded findings

Content of Step 5:
Finally, in step 5 the remaining findings are reviewed in a more detailed and critical way by screening the full text. The relevant passages are then used for step 6 for answering the research question.

Outcome of Step 5:
Collection of full-texts of the publications

Application of Step 5 on the thesis:
The results of the search are described in chapter 2.2.3 Results of the systematic literature review

Step 6: Analyzing of the final literature

Content of Step 6:
The final step of the systematic literature review is to analyze the final set of literature. Thereby, the most suitable literature for answering the research question is used and analyzed.

Outcome of Step 6:
Answers to the research question

Application of Step 6 on the thesis:
The final set of literature was analyzed in detail to find concrete implementation examples. These concrete implementation examples where then assigned to the suitable matching boxes (see chapter 3.2: Result: The Relation Model).

2.2.3 Results of the systematic literature review

The systematic literature review has been conducted through Science Direct which is a data-based search-engine offered by a private scientific publisher. In the case that findings showed up as results of more than one search term they were only considered once to prevent duplicates. Table 7 summarizes the results of the findings after applying the general, 1st and 2nd degree criteria. The left side of Table 7 lists the exact words and phrases, which amount to a number of 1111 and were entered into the search-engine. The reason why only one search-engine was used was the limited time during the master thesis.

- **Search-results of the data-base “Science Direct”:**

After applying the general and 1st degree criteria in the data-base 8875 findings have been generated (Figure 3) (no duplicates included). The findings are then reduced to 332 relevant findings after applying the 2nd degree criteria. This reduction of findings is a result of a relevance check because reading through all the publications in detail would not have been manageable. Due to this, only the most relevant findings have been screened and downloaded (see chapter 2.2.2.).

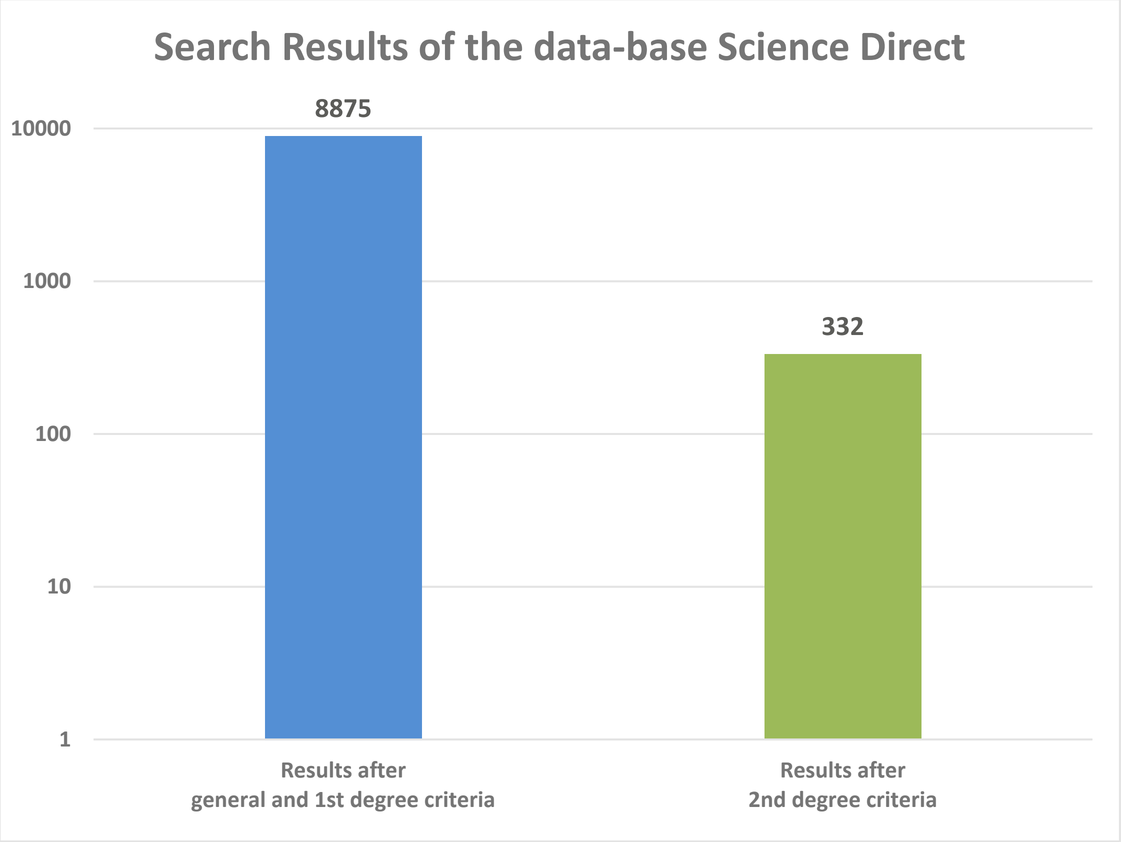

Figure 3: Search results - Science Direct (log-scale)

On the whole, the defined goal of filling the matching boxes with concrete implementation examples resulting of the systematic literature research has been fulfilled.

3 Model-Development and the resulting Relation Model

In this chapter the scientific procedure for the model development as well as the final relation model is presented.

3.1 Development of the Relation-Model

As this master thesis is closely related to a PhD thesis, the definition of digitalization stated in the PhD thesis will be followed, that reads as follows:

"The digitalization of production processes describes the implementation of state-of-the-art technology and process design to transform input of lower value into products and goods in efficient and effective manners. Thereby, digitized information is collected, processed and provided continuously throughout the production process, objects are detected, identified, tracked and handled automatically and human work is carried out in computer-assisted manners."

Due to this definition, requirements for a digitalized value-added process are derived in the two dimensions information and physical objects (see Table 1 and Table 2).

Requirement-field 1: Information	
Continuous and automated collection, processing and provision of digitized information: relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	
Requirement 1.1: (R01)	Information exists solely in digital form (digital information)
Requirement 1.2: (R02)	Information is collected automatically (collected information)
Requirement 1.3: (R03)	Information is processed automatically (processed information)
Requirement 1.4: (R04)	Information is provided automatically (provided information)
Requirement 1.5: (R05)	Information flows continuously (continuous information)

Table 1: Requirement-field Information

Requirement-field 2: Physical Objects	
Automatic detection, identification, tracking and handling of production objects and their condition: information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	
Requirement 2.1: (R06)	Physical objects are detected automatically (object detection)
Requirement 2.2: (R07)	Physical objects are identified automatically (object identification)
Requirement 2.3: (R08)	Physical objects are tracked automatically (object tracking)
Requirement 2.4: (R09)	Physical objects are handled automatically (object handling)
Requirement 2.5: (R10)	The physical object’s condition is detected (condition detected)

Table 2: Requirement-field Physical Objects

In manufacturing environment, a lot of factors can be found that make up the whole production and logistics-system. These traditional transformation factors were systematically summarized and clustered in a bachelor thesis from Okan Bastürk[18] on so-called dimensions (see Table 3), such as production worker and machinery.

In this master thesis these dimensions are also called value-adding factors. This allows the decomposition of each production step and material flow into these dimensions to realize a holistic description.

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[18] (Okan Bastürk, 2017)

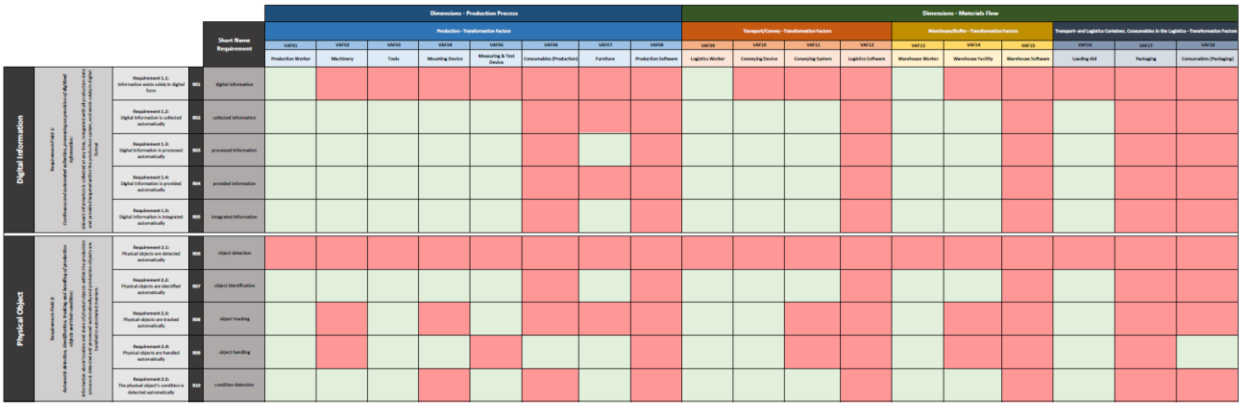
Dimensions - Production Process	**Production - Transformation Factors**	**Value-Adding Factor 1: (VAF01)**	Production Worker
		Value-Adding Factor 2: (VAF02)	Machinery
		Value-Adding Factor 3: (VAF03)	Tools
		Value-Adding Factor 4: (VAF04)	Mounting Device
		Value-Adding Factor 5: (VAF05)	Measuring & Test Device
		Value-Adding Factor 6: (VAF06)	Consumables (Production)
		Value-Adding Factor 7: (VAF07)	Furniture
		Value-Adding Factor 8: (VAF08)	Production Software
Dimensions - Materials Flow	**Transport/Convey - Transformation Factors**	**Value-Adding Factor 9: (VAF09)**	Logistics Worker
		Value-Adding Factor 10: (VAF10)	Conveying Device
		Value-Adding Factor 11: (VAF11)	Conveying System
		Value-Adding Factor 12: (VAF12)	Logistics Software
	Warehouse/Buffer - Transformation Factors	**Value-Adding Factor 13: (VAF13)**	Warehouse Worker
		Value-Adding Factor 14: (VAF14)	Warehouse Facility
		Value-Adding Factor 15: (VAF15)	Warehouse Software
	Transport- and Logistics Container, Consumables in the Logistics - Transformation Factors	**Value-Adding Factor 16: (VAF16)**	Loading Aid
		Value-Adding Factor 17: (VAF17)	Packaging
		Value-Adding Factor 18: (VAF18)	Consumables (Packaging)

Table 3: Dimensions - Production Process and Material Flows

To answer the question how digitalization affects the value-added processes of manufacturing companies the production process and material flows dimensions (see Table 3) are linked with the requirements for a digitalized value-added process (see Table 1 and Table 2) in the developed relation model which is described in the following chapters.

3.1.1 General introduction to the Relation Model

To visualize the relation model (see Figure 4), more precisely to illustrate the relationship between the requirements for a digitalized value-added process and the production process and materials flow dimensions a L-shaped matrix diagram is used. The requirements for a digitalized value-added process are colored in grey representing the first group of the matrix diagram whereas the production process and materials flow dimensions are colored in blue and dark green representing the second group of the matrix diagram.

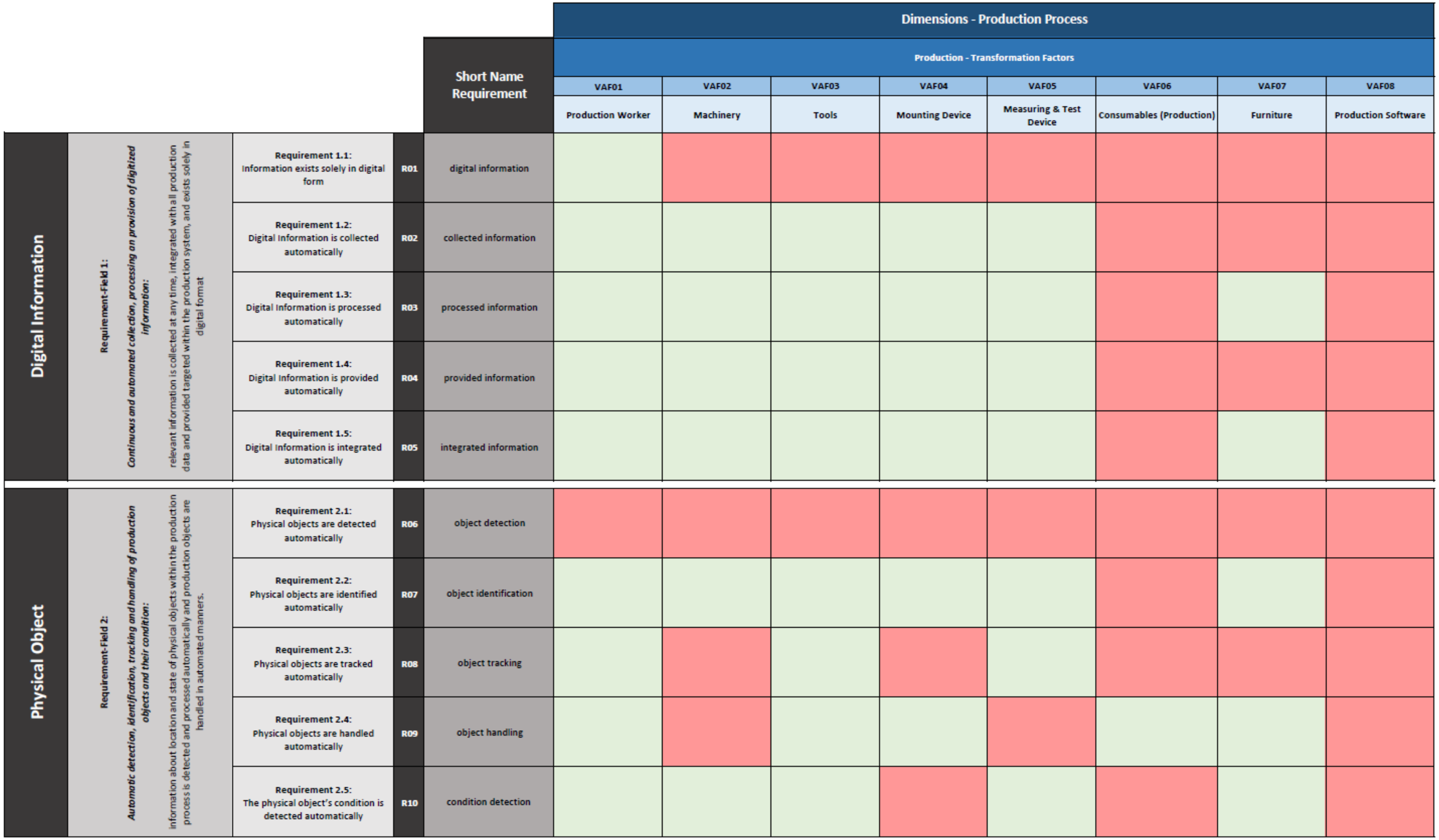


				Dimensions - Production Process								Dimensions - Materials Flow									
				Production - Transformation Factors								Transport/Convey - Transformation Factors				Warehouse/Buffer - Transformation Factors			Transport- and Logistics Container, Consumables in the Logistics - Transformation Factors		
			Short Name Requirement	VAF01	VAF02	VAF03	VAF04	VAF05	VAF06	VAF07	VAF08	VAF09	VAF10	VAF11	VAF12	VAF13	VAF14	VAF15	VAF16	VAF17	VAF18
				Production Worker	Machinery	Tools	Mounting Device	Measuring & Test Device	Consumables (Production)	Furniture	Production Software	Logistics Worker	Conveying Device	Conveying System	Logistics Software	Warehouse Worker	Warehouse Facility	Warehouse Software	Loading Aid	Packaging	Consumables (Packaging)
Digital Information	Requirement 1.1: Information exists solely in digital form	R01	digital information	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥
	Requirement 1.2: Digital information is collected automatically	R02	collected information	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟥
	Requirement 1.3: Digital information is processed automatically	R03	processed information	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟥
	Requirement 1.4: Digital information is provided automatically	R04	provided information	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟥
	Requirement 1.5: Digital information is integrated automatically	R05	integrated information	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟥
Physical Object	Requirement 2.1: Physical objects are detected automatically	R06	object detection	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
	Requirement 2.2: Physical objects are identified automatically	R07	object identification	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟥
	Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	🟩	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟩	🟥	🟥
	Requirement 2.4: Physical objects are handled automatically	R09	object handling	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟩	🟥	🟩
	Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟥	🟩	🟩	🟩	🟥	🟩	🟩	🟥	🟩	🟥	🟥

Figure 4: Relation Model Overall View

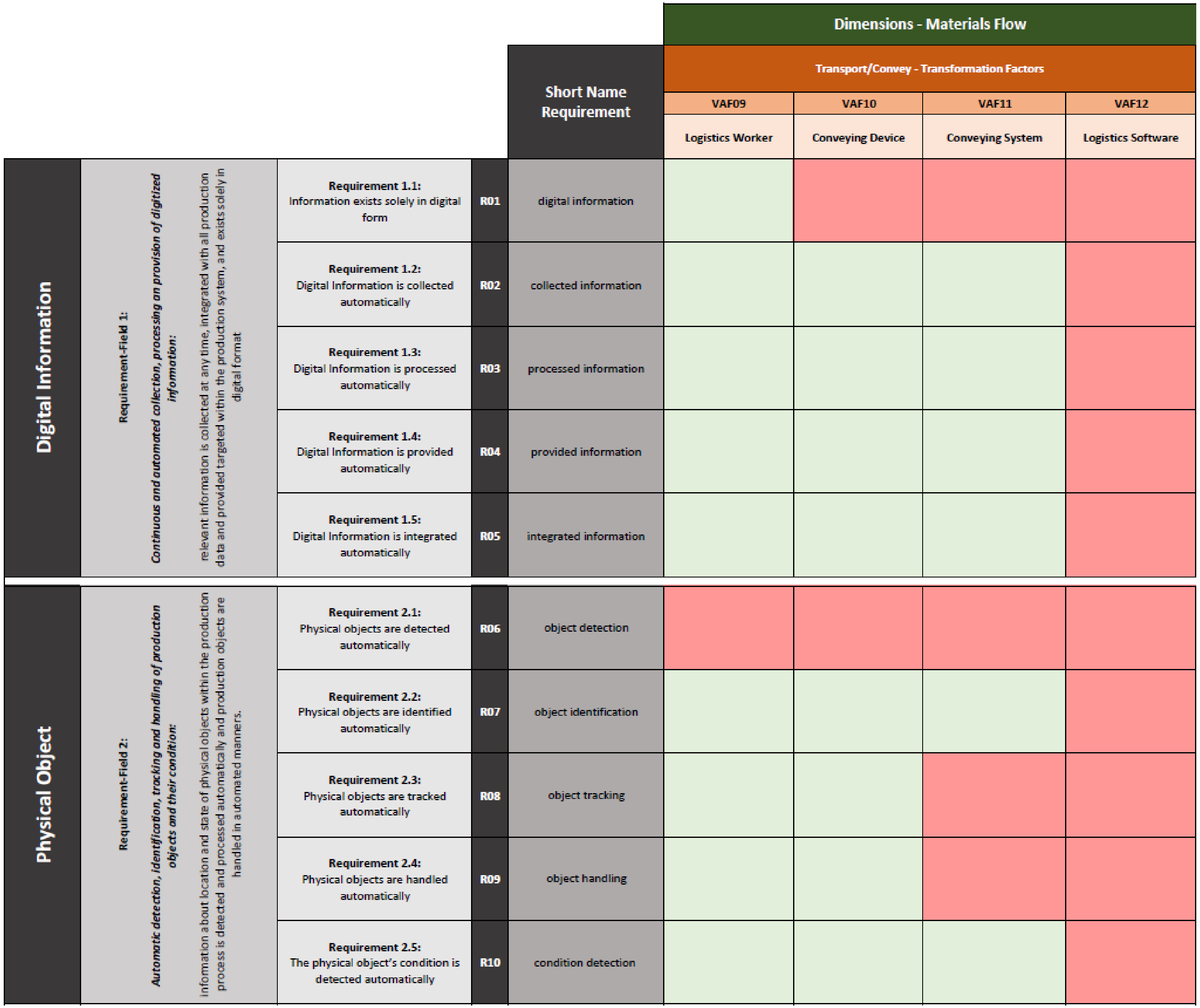
The box where a requirement meets a dimension is called matching box. Due to this matching box the relationship between the requirements and the dimensions can be described by asking the question, *"How can the requirement **X** be implemented for the value-adding-factor **Y**?"*. Each of these matching boxes was then be filled with implementation concepts resulting out of the systematic literature review to answer the question mentioned above.

Due to the fact, that not every matching box makes sense, each box was checked for meaningfulness before filling it with the concrete concepts. The resulting 89 matching boxes which can be seen on Figure 4 to Figure 8, are then visualized with green (matching box is meaningful) and red (matching box is pointless) colored boxes. An example of a pointless matching box would be the box where the requirement 2.3 (R08: Physical objects are tracked automatically) meets the value-adding-factor 2 (VAF02: Machinery) resulting in the question, "*How can the requirement **Physical objects are tracked automatically** be implemented for the value-adding-factor **Machinery**?"*. One of the characteristics of a machine, resulting of the bachelor thesis from Okan Bastürk, is that it is stationary, thus it wouldn't make sense to track it.



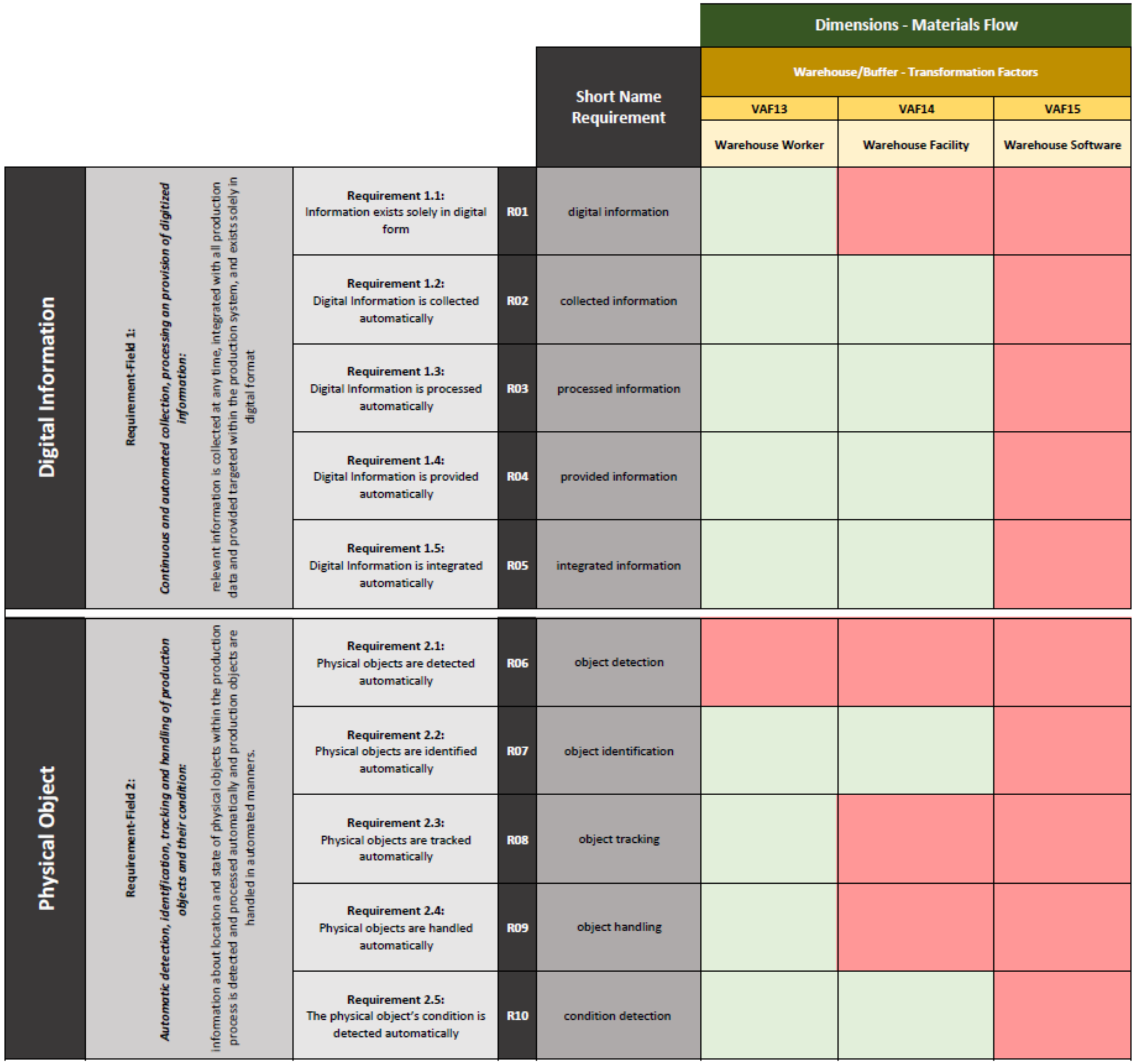
					Dimensions - Production Process							
				Short Name Requirement	Production - Transformation Factors							
					VAF01	VAF02	VAF03	VAF04	VAF05	VAF06	VAF07	VAF08
					Production Worker	Machinery	Tools	Mounting Device	Measuring & Test Device	Consumables (Production)	Furniture	Production Software
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing on provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	**Requirement 1.1:** Information exists solely in digital form	R01	digital information	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	**Requirement 2.1:** Physical objects are detected automatically	R06	object detection	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		Requirement 2.2: Physical objects are identified automatically	R07	object identification	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟥
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	🟩	🟥	🟩	🟥	🟩	🟥	🟥	🟥
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	🟩	🟥	🟩	🟩	🟥	🟩	🟩	🟥
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	🟩	🟩	🟩	🟥	🟩	🟥	🟩	🟥

Figure 5: Relation Model - Dimensions Production Process



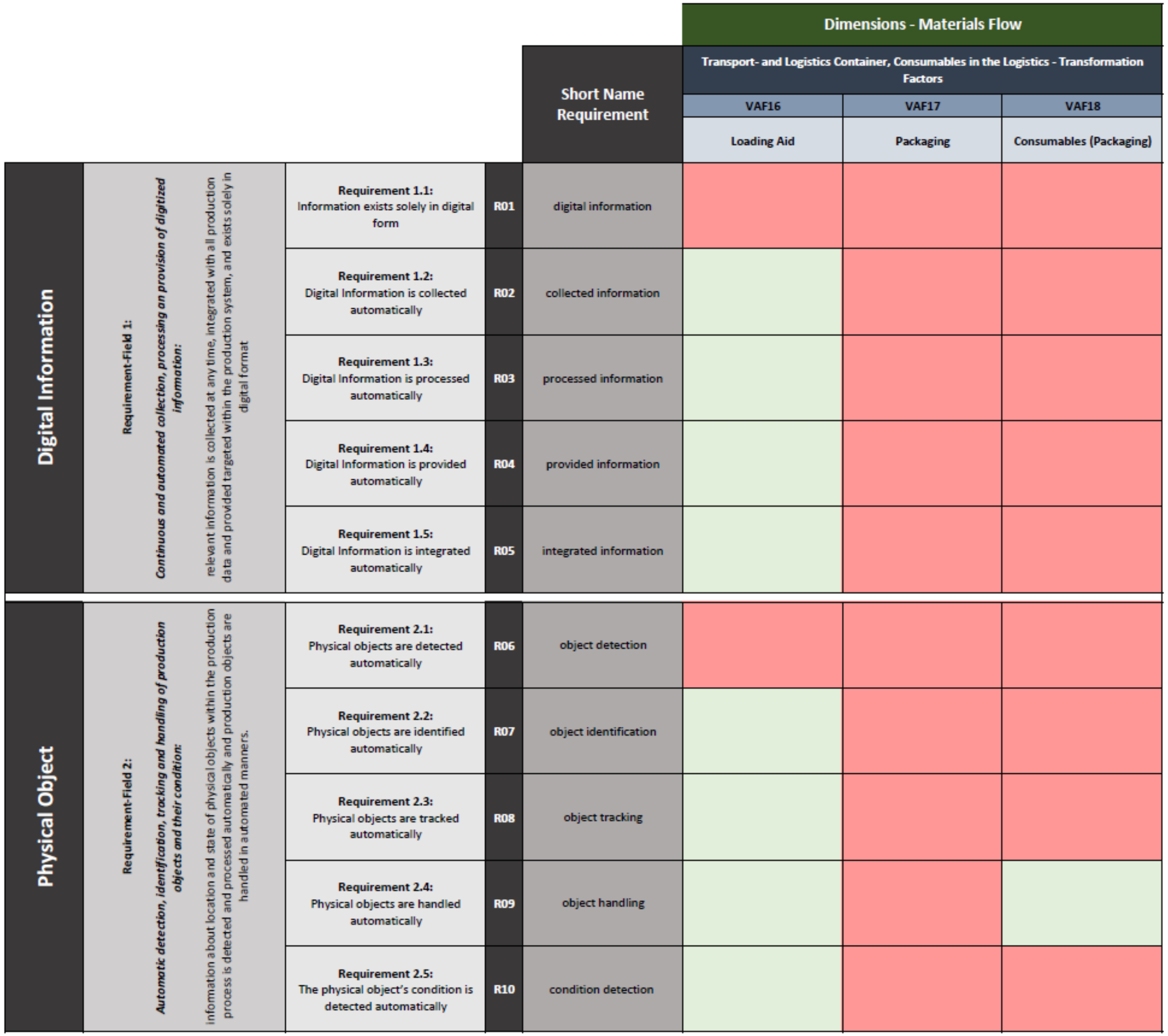
					Dimensions - Materials Flow			
					Transport/Convey - Transformation Factors			
				Short Name Requirement	VAF09	VAF10	VAF11	VAF12
					Logistics Worker	Conveying Device	Conveying System	Logistics Software
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing an provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	**Requirement 1.1:** Information exists solely in digital form	R01	digital information	🟩	🟥	🟥	🟥
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	🟩	🟩	🟩	🟥
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	🟩	🟩	🟩	🟥
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	🟩	🟩	🟩	🟥
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	🟩	🟩	🟩	🟥
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	**Requirement 2.1:** Physical objects are detected automatically	R06	object detection	🟥	🟥	🟥	🟥
		Requirement 2.2: Physical objects are identified automatically	R07	object identification	🟩	🟩	🟩	🟥
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	🟩	🟩	🟥	🟥
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	🟩	🟩	🟥	🟥
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	🟩	🟩	🟩	🟥

Figure 6: Relation Model - Dimensions Materials Flow (Transport/Convey)



					Dimensions - Materials Flow		
					Warehouse/Buffer - Transformation Factors		
				Short Name Requirement	VAF13	VAF14	VAF15
					Warehouse Worker	Warehouse Facility	Warehouse Software
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing on provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	**Requirement 1.1:** Information exists solely in digital form	**R01**	digital information	🟩	🟥	🟥
		Requirement 1.2: Digital Information is collected automatically	**R02**	collected information	🟩	🟩	🟥
		Requirement 1.3: Digital Information is processed automatically	**R03**	processed information	🟩	🟩	🟥
		Requirement 1.4: Digital Information is provided automatically	**R04**	provided information	🟩	🟩	🟥
		Requirement 1.5: Digital Information is integrated automatically	**R05**	integrated information	🟩	🟩	🟥
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	**Requirement 2.1:** Physical objects are detected automatically	**R06**	object detection	🟥	🟥	🟥
		Requirement 2.2: Physical objects are identified automatically	**R07**	object identification	🟩	🟩	🟥
		Requirement 2.3: Physical objects are tracked automatically	**R08**	object tracking	🟩	🟥	🟥
		Requirement 2.4: Physical objects are handled automatically	**R09**	object handling	🟩	🟥	🟥
		Requirement 2.5: The physical object's condition is detected automatically	**R10**	condition detection	🟩	🟩	🟥

Figure 7: Relation Model - Dimensions Materials Flow (Warehouse/Buffer)



					Dimensions - Materials Flow		
					Transport- and Logistics Container, Consumables in the Logistics - Transformation Factors		
				Short Name Requirement	VAF16	VAF17	VAF18
					Loading Aid	Packaging	Consumables (Packaging)
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing an provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	**Requirement 1.1:** Information exists solely in digital form	R01	digital information	🟥	🟥	🟥
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	🟩	🟥	🟥
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	🟩	🟥	🟥
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	🟩	🟥	🟥
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	🟩	🟥	🟥
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	**Requirement 2.1:** Physical objects are detected automatically	R06	object detection	🟥	🟥	🟥
		Requirement 2.2: Physical objects are identified automatically	R07	object identification	🟩	🟥	🟥
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	🟩	🟥	🟥
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	🟩	🟥	🟩
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	🟩	🟥	🟥

Figure 8: Relation Model - Dimensions Materials Flow (Transport- and Logistics Container, Consumables in the Logistics)

3.1.2 Design of a Matching Box of the Relation Model

Table 4 shows the design of a Matching Box. The head of the box, that consists of the **ID**, the **Requirement** and the **Value-Adding Factor**, is used to uniquely identify the box. The rest of the Matching Box consists of the sections **Abstract Implementation Concepts and Concrete Examples** and **Derived from the following Literature**.

- **ID:** The ID is a combination of the number of the requirement (e.g.: R01) with the number of the value-adding-factor (e.g.: VAF01) resulting in a uniquely identification of each matching box. For example, the ID R01VAF01 identifies the box where the requirement R01 meets the value-adding-factor VAF01.
- **Requirement:** Description of the requirement (e.g.: R01, Digital Information - Information exists solely in digital form) that are listed in Table 1 and Table 2.
- **Value-Adding-Factor:** Description of the value-adding-factor (e.g.: VAF01, Production Worker) that are listed in Table 3.

<table>
<tr><th>ID</th><th>Requirement</th><th>Value-Adding-Factor</th></tr>
<tr><td>Matching Box ID</td><td>Description of Requirement (see Table 1 and Table 2)</td><td>Description of the Value-Adding Factor (see Table 3)</td></tr>
<tr><td colspan="3">Abstract Implementation Concepts and Concrete Examples</td></tr>
<tr><td colspan="3">Abstract Implementation Concept 1
• Concrete Example 1.1
• Concrete Example 1.2
• Concrete Example …

Abstract Implementation Concept 2
• Concrete Example 2.1
• Concrete Example 2.2
• Concrete Example …

Abstract Implementation Concept …</td></tr>
<tr><td colspan="3">Derived from the following Literature</td></tr>
<tr><td colspan="3">List of Literature</td></tr>
</table>

Table 4: Matching Box Design

- **Abstract Implementation Concept and Concrete Examples:** Description of the abstract implementation concepts that consists out of concrete examples. The concrete examples are concrete implementation examples based on the systematic literature review that answer the question *"How can the requirement **X** be implemented for the value-adding-factor **Y**?"* and were then clustered to the abstract implementation concepts.
- **Derived from the following Literature:** A list of literature that is used to describe the above-mentioned concrete examples.

3.2 Result: The Relation Model

This chapter shows the detailed result of the matching boxes with their abstract implementation concepts that consist of concrete implementation examples. The contents of the concrete examples of each matching box are based on the referenced literature and were mostly changed only in the formulation and syntax. However, the assignment of the concrete examples to the matching boxes as well as clustering them to abstract implementation concepts was part of this master thesis.

3.2.1 Relation of Digital Information and Value-Adding-Factors

- **Digital Information – Production Worker**

Research Question: How can the requirement “**Information exists solely in digital form**” be implemented for the value-adding-factor “**Production Worker**”? → Information for the Production Worker exists solely in digital form.

<table>
<tr><th>ID</th><th>Requirement</th><th>Value-Adding-Factor</th></tr>
<tr><td>R01VAF01</td><td>Digital Information:
Information exists solely in digital form</td><td>Production Worker</td></tr>
<tr><th colspan="3">Abstract Implementation Concepts and Concrete Examples</th></tr>
<tr><td colspan="3">**1. Computer-based information**
1.1. Replacement of paper-based tasks with a manufacturing system performed by augmented reality tasks.
(Yew et al., 2016)
1.2. Support of computer-related information-transfer with information carrier technologies such as auto-ID systems to reduce verbal and paper-based information exchange. By using sensors, storage media and computing power an increasing number of devices that can receive, use and send data. The gap between the object and information level can be reduced by linking barcode, quick-response code or RFID.
(Müller et al., 2017)</td></tr>
<tr><th colspan="3">Derived from the following Literature</th></tr>
<tr><td colspan="3">[19] (Yew et al., 2016)
[20] (Müller et al., 2017)</td></tr>
</table>

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[19] (Yew et al., 2016, pp. 43–55)
[20] (Müller et al., 2017, pp. 1043–1052)

3.2.2 Relation of Collected Information and Value-Adding-Factors

- **Collected Information – Production Worker**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Production Worker**"? → Digital Information about the Production Worker is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF01	Collected Information: Digital Information is collected automatically	Production Worker

Abstract Implementation Concepts and Concrete Examples

2. Sensor-equipped Wearable Devices

2.1. The bracelet-Microsoft Band is equipped with a huge number of sensors (Heart Rate, Accelerometer, Gyroscope, Ambient light sensor, GPS, Distance, Pedometer, UV, Capacitive Sensor, Microphone, Calories, Barometer, Altimeter). There is also a current sensor on the skin to collect information such as blood pressure, sweat rate and the skin temperature. **Collect information to remind the worker of job fatigue:** By using the collected information from the current sensor of the skin and the heart rate sensor in the band the fatigue degree of the worker can be monitored. **Collect information to supervise the workers work range:** Usage of the GPS sensor in the band to collect information about the workers real-time position.

(Fan et al., 2017)

2.2. See Concrete Implementation Concept Example Number 135.3.

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3. Motion Capture Systems

3.1. Usage of a full-body system for the real-time motion data collection and feedback of ergonomics for manual material handling where all parts of the body are interested during the activities execution.
The system has been applied to the storage area of a warehouse and successively management of typical warehousing activities (picking, packing, etc.), reducing the risk of musculoskeletal disorders and increasing the workers productivity.
The information regarding the full-body movements are collected using an inertial motion capture system developed by Animazoo, called IGS-180i that is composed by 17 Inertial Measurement Units (IMUs) placed on a light full-body suit (see Figure 9).

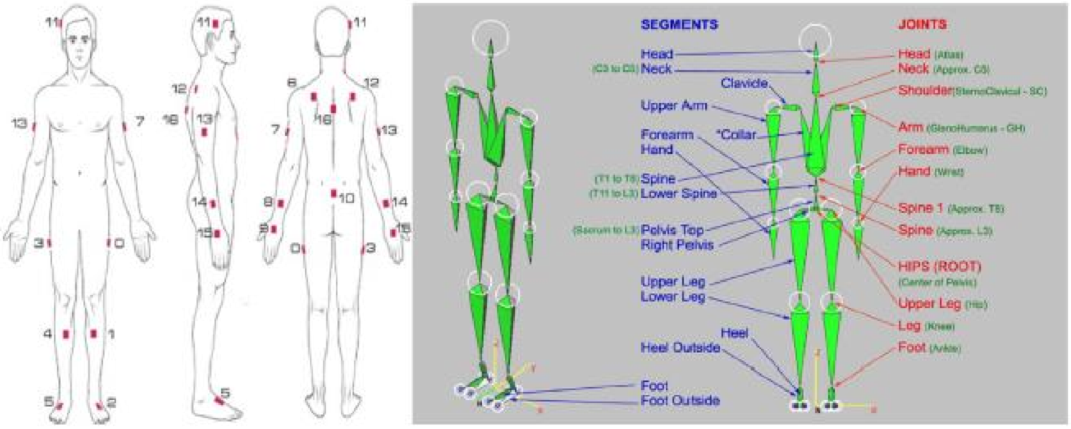
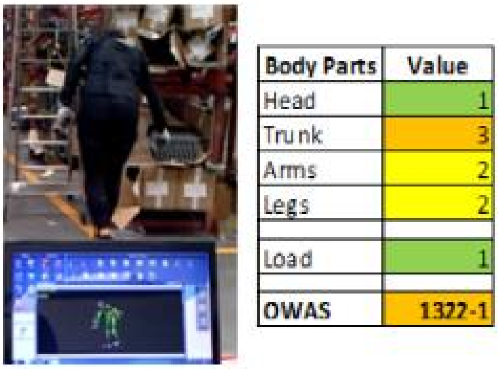


Figure 9: Positions of the IMUs and biomechanical model

The IMUs are linked to a small portable multi-processing unit (MPU) which sends the data to the personal computer for the real-time processing, thanks to a WIFI connection where the Data Collection and Analysis Unit receives the data to perform the ergonomics evaluations. With the help of the Selection Methods Module the worker can then select the best suitable method for his task (see Figure 10).



Body Parts	Value
Head	1
Trunk	3
Arms	2
Legs	2
Load	1
OWAS	1322-1

Figure 10: IGS-180i real-time Processing

(Battini et al., 2014)

3.2. See Concrete Implementation Concept Example Number 64.2.

3.3. See Concrete Implementation Concept Example Number 135.3.

Derived from the following Literature

[21] (Fan et al., 2017)

[22] (Battini et al., 2014)

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[21] (Fan et al., 2017, pp. 425–432)

[22] (Battini et al., 2014, pp. 1–10)

- **Collected Information – Machinery**

Research Question: How can the requirement “**Digital Information is collected automatically**” be implemented for the value-adding-factor “**Machinery**”? → Digital Information about the Machinery is collected automatically.

ID	**Requirement**	**Value-Adding-Factor**
R02VAF02	Collected Information: Digital Information is collected automatically	Machinery

Abstract Implementation Concepts and Concrete Examples

4. Sensor Integration

4.1. Monitoring of machining operations including Tool Condition Monitoring (TCM), unmanned machining, process control, signal processing and sensor fusion based on different sensors (see Figure 11) for various monitoring aspects of the machining and machining environments to enhance productivity, maximize tool life, minimize machine downtime, reduce scrappage and prevent damages.

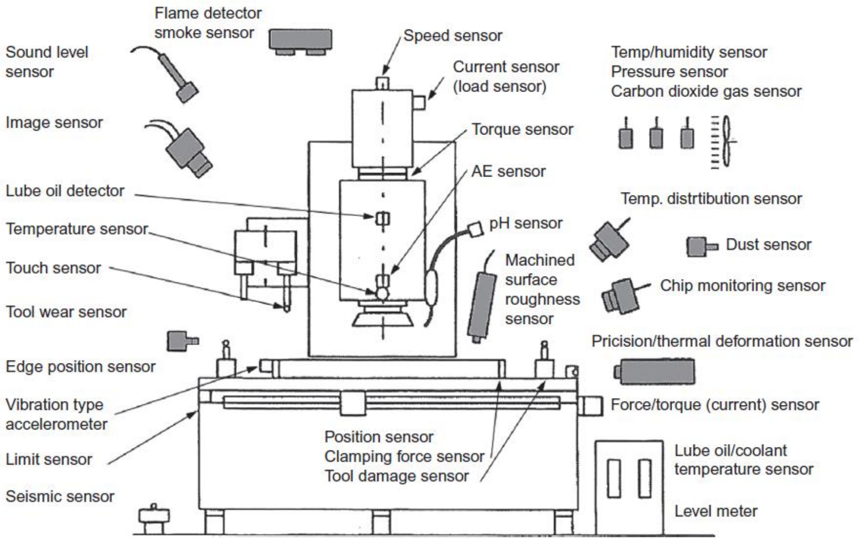

Figure 11: Different sensors used for monitoring machine tool

(Grzesik, 2017a)

4.2. Attaching of piezoelectric strain sensors to specific points on the turret housing of the turning center to produce signals on the cutting action. The signals from the sensors are than evaluated by a monitoring system for tool breakage, tool wear and unpredictable collisions in the working area. **Tool-breakage and tool-wear detection:** The digital breakage-monitoring system continuously monitors the cutting force values. If a tool breakage occurs, the cutting force value rises significantly, followed by a sharp drop (see Figure 12). The system recognizes this deviation and as a result a command is issued to stop the feed motor.

The tool wear monitor system uses the fact of the rising cutting force level that occurs over the lifetime of the cutting edge by checking the rise against a reference cutting edge force and calculates the so called “End of tool life”-limit (see Figure 12). Once this limit is reached the system advises a replacement of the worn tool.

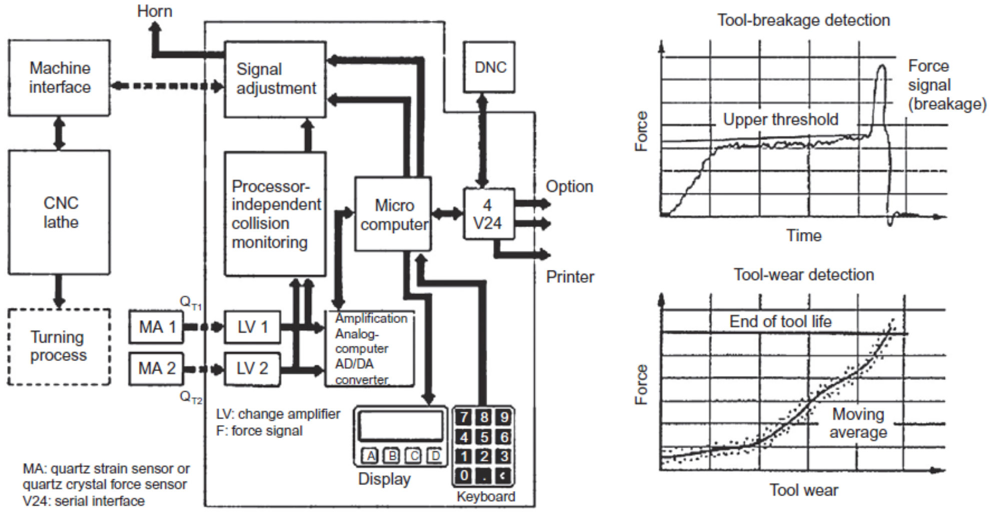

Figure 12: Tool-condition monitoring system for tool-breakage and tool-wear detection

Tool-collision detection: Figure 13 shows the schematic diagram of a tool-collision monitoring system and a graph of the expected force change during a collision. The strain sensor measures the deformation in the turret during machining and compares it with a threshold value. If the measured value reaches the threshold the feed motor stops within milliseconds to avoid damage to the machine.

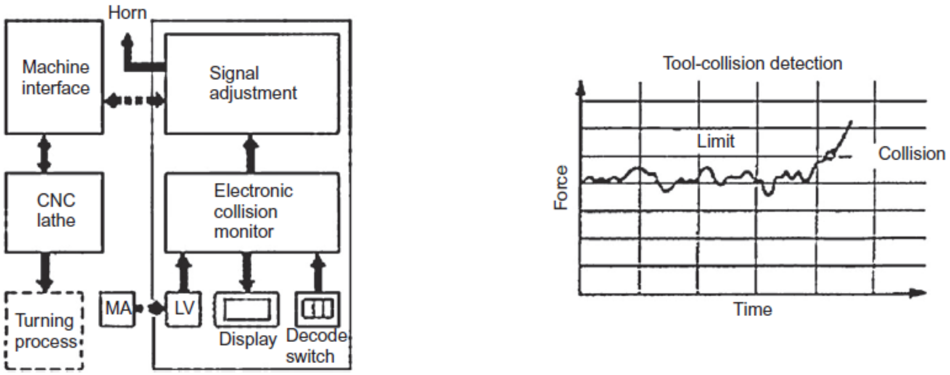

Figure 13: Tool-condition monitoring system for tool-collision monitoring

(Grzesik, 2017a)

4.3. The sensor-based intelligent machining center (see Figure 14) consists of four main functions, namely:

- Detection of deformation
- Calculation of compensation values
- Implementation of compensation
- Counter-measurements

These functions enable the compensation of thermal distortion by thermal actuation, intelligent machining by force/torque control, fail-safe operation by using hydraulic coupling, and external control by workstations connected through the internet.

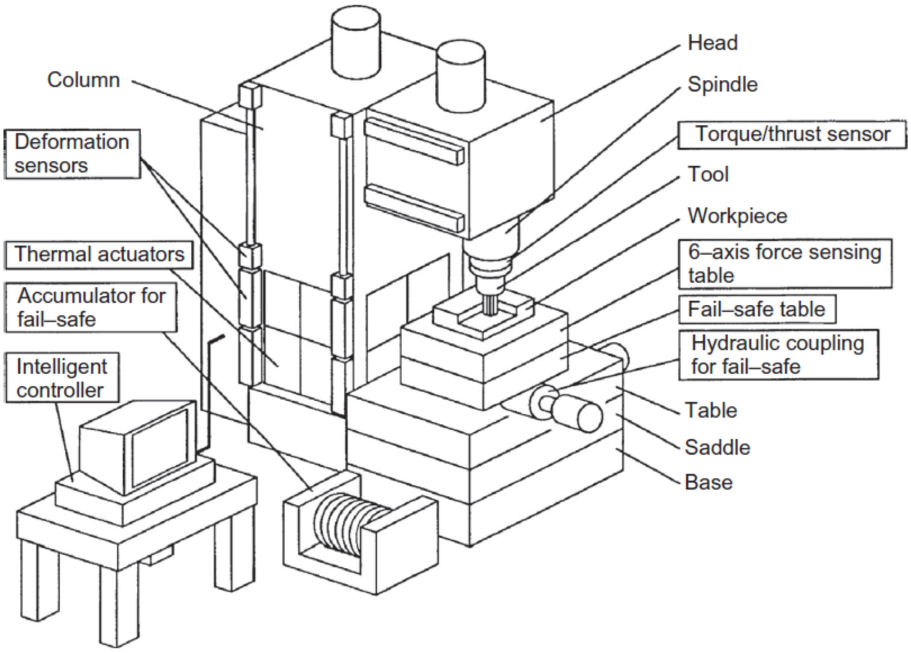

Figure 14: Sensor-based intelligent machining center

The spindle is equipped with sensors to measure the force and torque and fail-safe performance to protect the machine from force and torque overloads.

To protect the head, the table and the saddle against abnormal loads, a one-directional force sensor and a fail-safe element is fitted to them.

The mechanically and thermally induced deformations of the machine tool structure are measured by deformation sensors that are coupled to the surfaces of the column and the head.

Furthermore, temperature sensors are installed onto the surfaces of the machine to detect their local temperatures.

To guarantee the correct geometry the column is constructed as an active structure that is adjusted by commands of the intelligent controller.

(Grzesik, 2017a)

4.4. Implementation of a new sensory z-slide for a 5-axis DMG HSC 55 linear machining center that is equipped with several strain sensors. With these miniature strain sensors, that are applied in the positions P1 to P4, the new slide is able to “feel” the machining process by measuring the process forces and vibrations (see Figure 15).

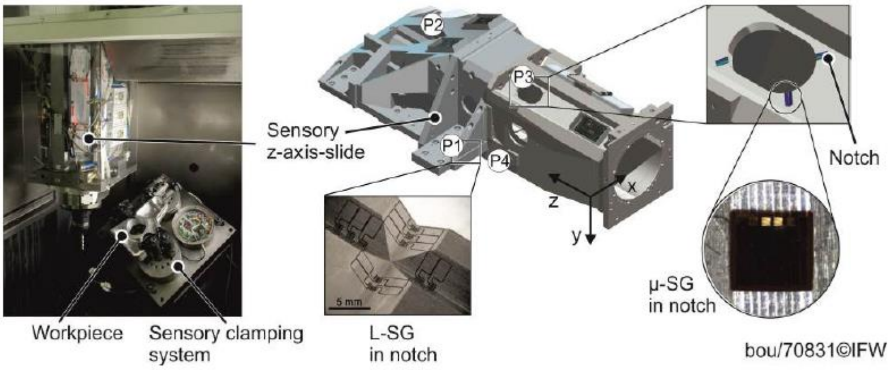

Figure 15: Sensory z-slide for a 5-axis machine center

All the sensors are connected with electronic signal processing devices and communicated to the unit control.

(Denkena et al., 2014b)

4.5. Online capturing of Acousto-optic Emissions (AOE) of tool shank vibrations using a Laser Doppler Vibrometer (LDV) of PolyTech-PVD100 for a A-axis chuck of CNC Vertical Milling center of Jyothi and analyzing the captured data using VibSoft analyzer (see Figure 16).

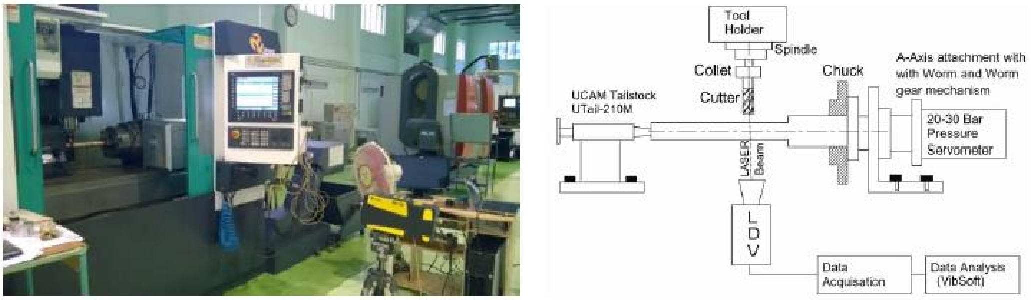

Figure 16: Online capturing of Acousto-optic Emissions - Experimental setup

(Vikram et al., 2016)

4.6. See Concrete Implementation Concept Example Number 35.1.

4.7. See Concrete Implementation Concept Example Number 68.1.

4.8. See Concrete Implementation Concept Example Number 69.1.

4.9. See Concrete Implementation Concept Example Number 70.1.

4.10. See Concrete Implementation Concept Example Number 93.2.

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5. Data Acquisition Card and Sensor Integration

5.1. Sensor installation on a Mazak Quick Turn Nexus 200II (see Figure 17) for real-time collection of acoustic emission, cutting force and vibration information.

Figure 17: Mazak Quick Turn 200 lathe

The analogue signals from the sensors are collected through a data acquisition card (National Instruments PCIe-6351) that is installed in an industrial portable computer and a data logging software developed in LabVIEW. The sensor types as well as the data acquisition scheme are outlined in Figure 18.

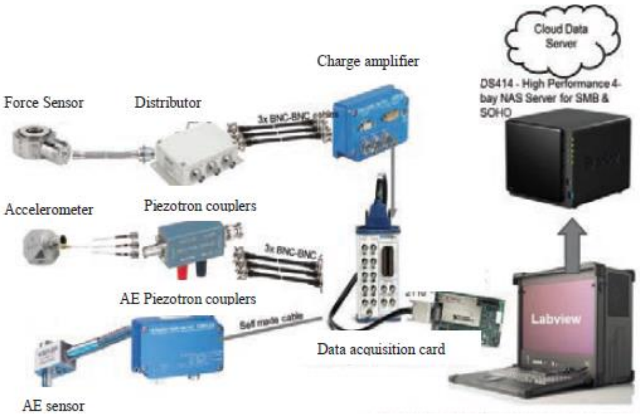

Figure 18: Mazak Quick Turn 200 data acquisition

(Downey et al., 2016)

5.2. See Concrete Implementation Concept Example Number 33.1.

5.3. See Concrete Implementation Concept Example Number 83.1.

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6. Data Acquisition Card, Sensor Integration and CNC/PLC Control System

6.1. Realization of preventive maintenance by mounting sensors for vibration, temperature, electrical power, oil level and pressure on the machine to detect signs of machine break down (see Figure 19).

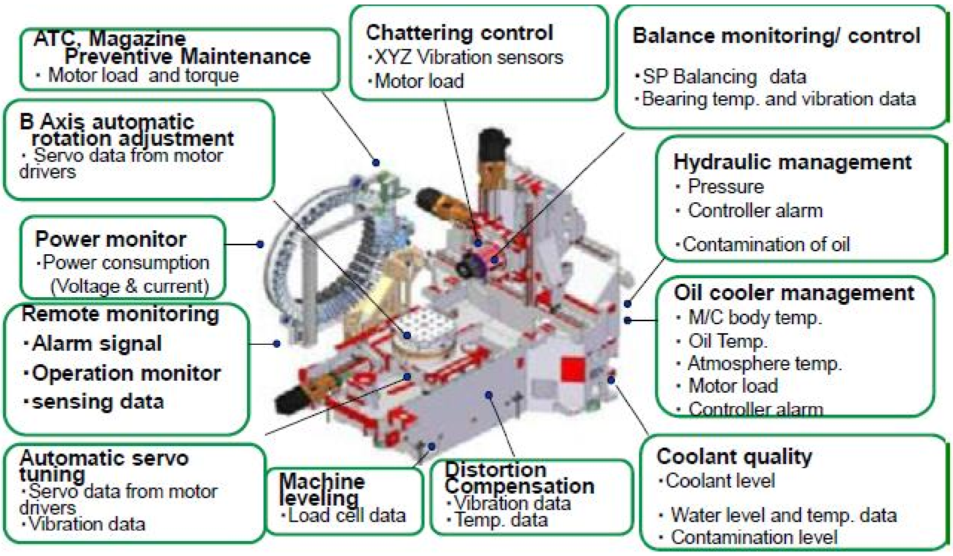

Figure 19: Preventive maintenance sensor application example

The sensors are connected to the 100BASE-TX Ethernet by using four types of interface boards for sensor signal inputs and Ethernet outputs, as shown in Figure 20.

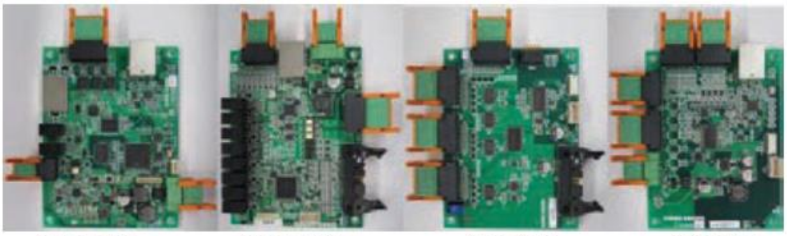
(a) DAQF (b) DAQT (c) DAQL (d) EPM

Figure 20: Interface sensing boards

Data Acquisition FFT Board (DAQF): Three acceleration sensors (each acceleration sensor detects vibration in the X, Y and Z directions) and two temperature sensors can be interfaced with the board that is installed at the spindle unit. The accelerations sensors are used to detect chatter vibration, failure of the spindle bearings and spindle collisions. In addition, the two temperature sensors are installed to compensate the spindle thermal deformation. When the amplitude of the acceleration sensors exceeds a limit, the collision detection signal is output to the PLC high speed I/O.

Data Acquisition Temperature Board (DAQT): This board is a general A/D converter board with a voltage input terminal and a thermistor interface which it is designed to be interfaced with eight temperature sensors.

Electrical Power Monitor Board (EPM): Electrical current sensors and voltage sensors are, which are placed at the power supply, are connected to the EPM-Board that monitors the power consumption and diagnostic data from the oil cooler unit and hydraulic unit via the RS422 interface.

Spindle acceleration sensor application: Two functions, namely MPC (Machine Protection Control) and MVC (Machine Vibration Control), are implemented using the acceleration sensors that are installed at the spindle unit. MPC is an application for preventive maintenance that displays the spindle vibration and load during machining operation and stops the machining operation automatically when an abnormal vibration level is detected (see Figure 20).

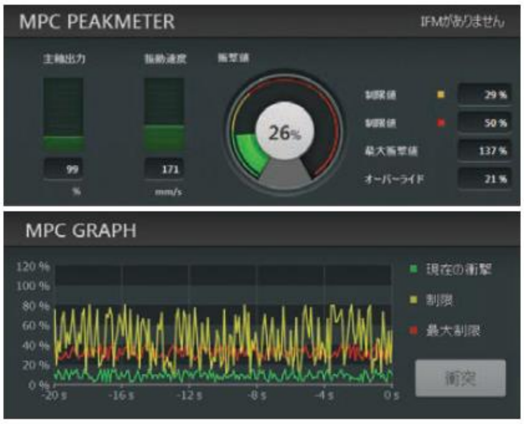

Figure 21: Machine protection control

The machine vibration control is an application that avoids chatter by detecting and analyzing the chatter vibration level and frequency to correct the spindle speed.

(Fujishima et al., 2017)

6.2. Development of a system for automatic acquisition of vibration, force and acoustic emission signals and visual tool condition registration in real-time by implementing a variety of sensors to the turret of a machine measuring acoustic emission, cutting force and vibration, coupled with an image acquisition system monitoring the wear on the tools (see Figure 22).

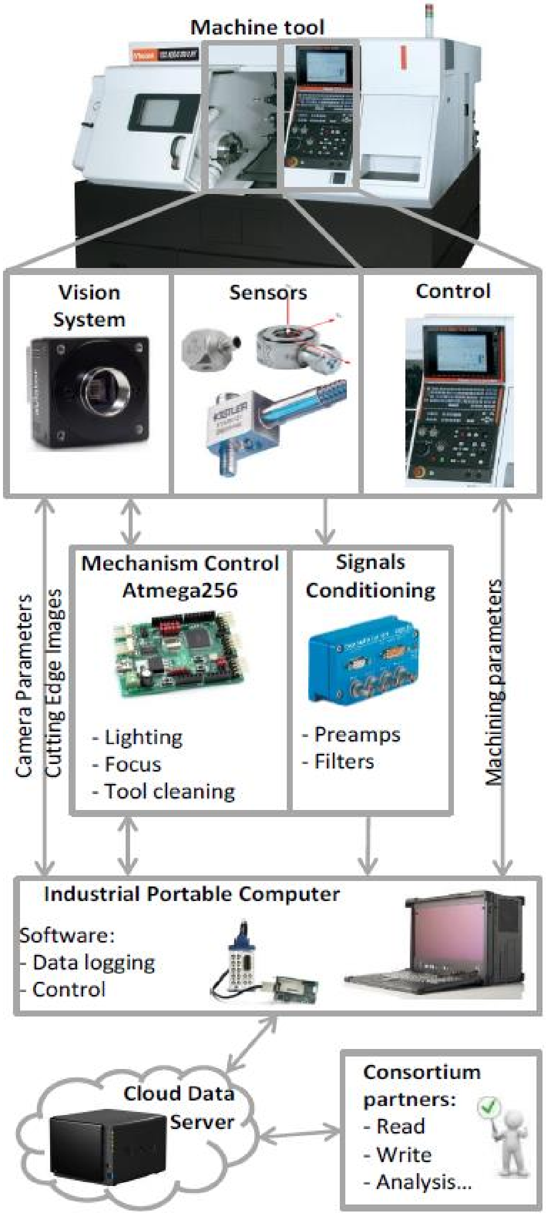

Figure 22: Data acquisition structure

The CNC machine chosen for the deployment of this system is a Mazak Quick Turn Nexus 250-II MS. The sensors (see Figure 23) are mounted in the machining bay (see Table 5) and the vision system is installed inside the work space of the machine tool.

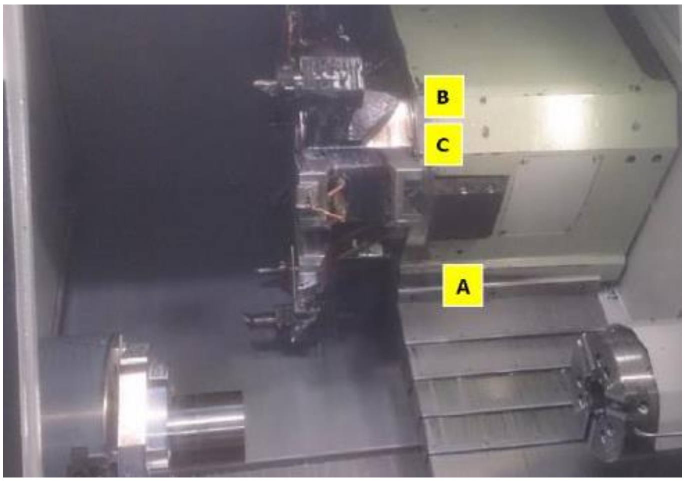

Figure 23: Sensor position in machining bay

Sensor type	Sensor description	Location
Force	KISTLER 9017C with charge amplifier	A
Accelerometer	50g Ceramic Shear Triaxial KISTLER 8763B050AB	B
Acoustic emission	Piezoceramic AE Sensor KISTLER 8152C0050000 - (50-400kHz)	C

Table 5: Sensor types

The photos of the cutting interfaces (flank and rank face of the cutting tool) that come from the vision system are transferred to the industrial portable computer via LAN and saved in the PNG format. The analogue signals from the sensors are collected through a data acquisition card (National Instruments PCIe-6351) that is installed in an industrial portable computer and a data logging software developed in LabVIEW. In addition to above mentioned sensors and data acquisition, there is also other information, such as the spindle speed, program block number, etc. that can be taken from the CNC machine control. In Figure 24 an overview of the communication between the industrial portable computer and the rest of the system is illustrated.

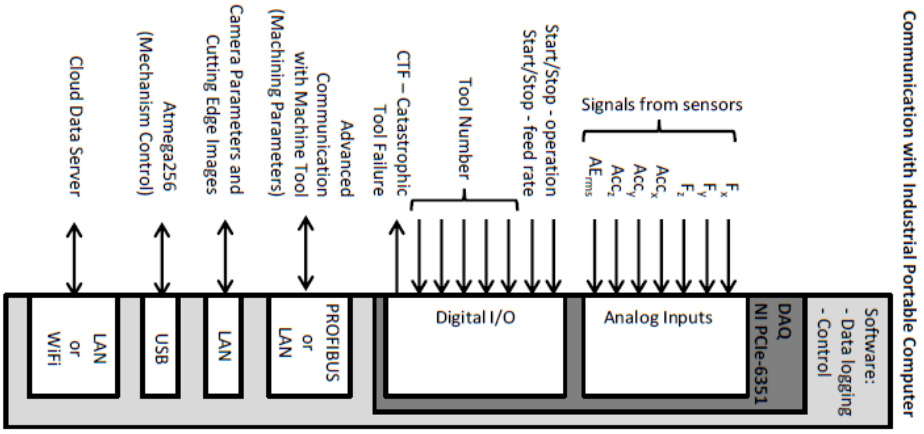

Figure 24: Communication illustration

(Downey et al., 2015)

6.3. Data acquisition and management by using manufacturing data in combination with sensor data from a power and vibration sensor installed in a 3-axis vertical milling machine. The manufacturing data include the main machining parameters describing the manufacturing process, like work piece material and size, spindle speed, feed rate, depth of cut, G-code, cutter location, etc.

In Figure 25 the system architecture for data acquisition and management is schematically shown. The machine that was chosen as the test bed was a Haas VF-2 3-axis CNC vertical milling machine. The manufacturing data are obtained from the machine controller and the sensor data from a data acquisition device. They are merged and organized at a gateway and uploaded to a data base through the internet where users can get access to the data using mobile devices.

Figure 25: System architecture for data acquisition and management

The power sensor is a Hall effect sensor (CR4111S – 100, CR Magnetics Inc.) that was mounted around one of the output cables of the vector drive the CNC machine to capture the change in current consumed by the spindle (see Figure 26).

Figure 26: Hall effect current sensor

The vibration sensor is a ground-isolated 3-axis accelerometer (Type 8762A10, Kistler Instrument Corp.) that is mounted magnetically on the spindle case and is used to capture the induced vibration between the tool and the workpiece during milling operation (see Figure 27).

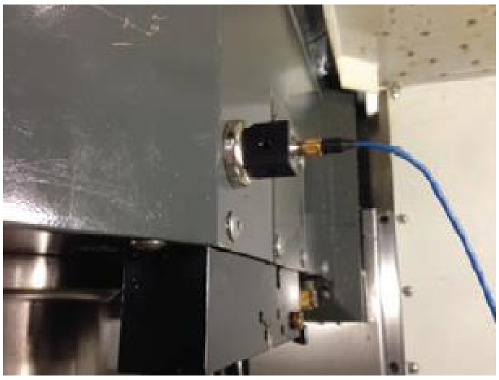

Figure 27: 3-axis accelerometer

The output signal of the Hall effect sensor and the accelerometer are fed into the data acquisition device that consists of an NI 9234 4-channel analogue input module mounted on an NI cDAQ-9184 Ethernet chassis. For the data collection a desktop computer with Windows 7 system using a program compiled with C# and uploaded to an open-source PostgreSQL database on a local PC through the internet using a script in Python is used.

To collect the manufacturing data, an RS232 serial adapter cable connects the DB-25 gateway of the CNC-machine-controller and the USB port of the desktop computer. The manufacturing data are then also stored at a PostgreSQL database on a local PC connected to the internet.

(Cai et al., 2017)

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7. Sensor Integration with CNC and PLC Control System

7.1. The measuring ring (3SA-Ring) shown in Figure 28 is equipped with nine sensors and opens up the opportunity of measuring ten spindle features:

- 3D shaft displacement (SD) with four inductive displacement sensors
- 3D bearing acceleration
- Shaft speed sensor (n)
- Temperature sensor
- Counts time when spindle-on-power
- Counts time when spindle-on-speed

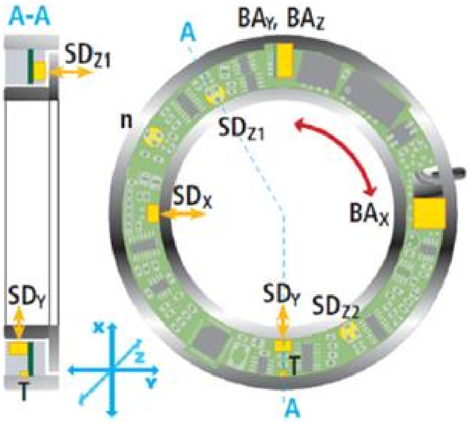

Figure 28: Construction of the three-axis measuring ring

The measuring ring is integrated with the CNC control system (see Figure 29). More precisely the CNC/PLC reads the values and the signals from the measuring ring to correct the spindle-tool position.

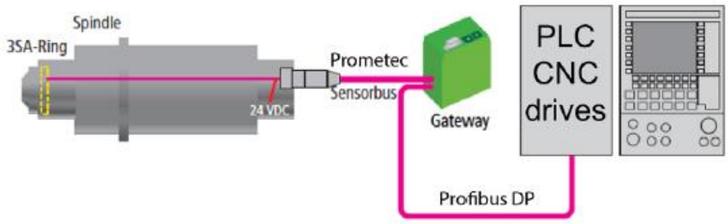

Figure 29: 3SA-Ring connected with CNC control system

To collect all the necessary information the tool monitoring system (TMS) (see Figure 30) monitors machining operations, such as turning, milling, drilling, etc. and offers the functions to detect machine collisions and random tool breakage, prevent tool breakage from overload, wear detection, tool contact/workpiece contact and process visualization and optimization. The TMS consists of four modules:

- Sensors that collect information (loads, etc.) subjected to the tool during machine processing and send signals to the monitor modules
- Monitor modules process the sensor signals, compare them with the set limits and generate information for the machine operator
- Machine interface modules to have an interface between monitor modules and the machine operators

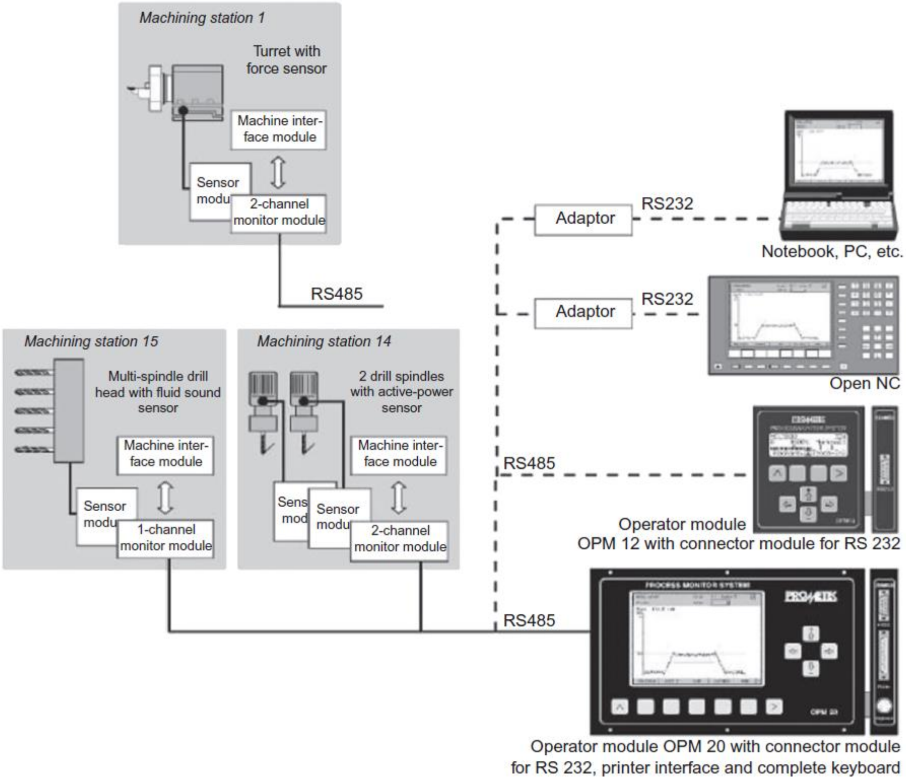

Figure 30: 3SA-Ring tool monitoring system PROMOS 2 from PROMETEC GmbH

(Grzesik, 2017a)

7.2. Installation of an acoustic emission (AE) sensor on the turning-center turret housing to enable tool-condition monitoring performed on a machine center (see Figure 31). During the relevant parts of the CNC program the tool monitor continuously recognizes the current state of the tool and stops the spindle immediately if any tool disturbance is detected.

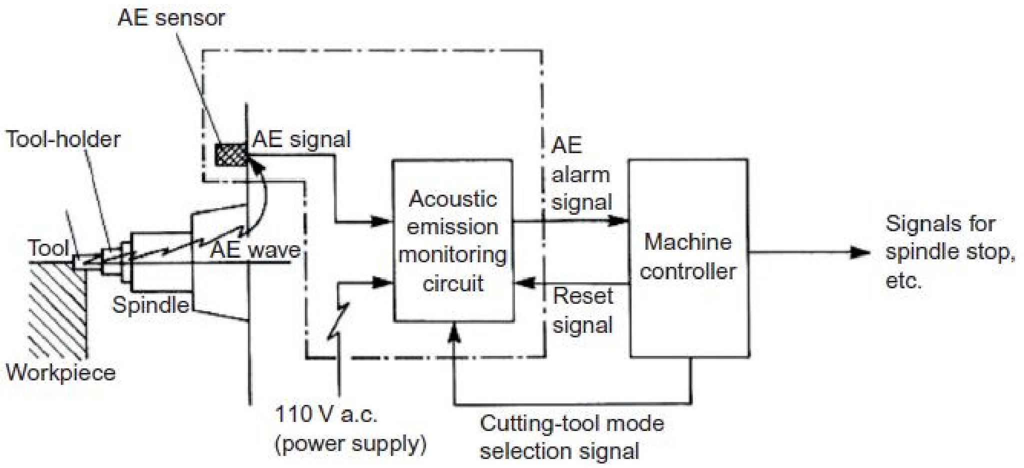

Figure 31: Acoustic emission (AE) principle tool-condition monitoring

Figure 32 shows the measurement circuit for the acquisition of the AE-signals. The AE-sensor generates a low energy signal that is pre-amplified and then filtered correspondingly to the frequency range and the particular monitoring task. After a high-pass, band-pass and low-pass filtering the signal is amplified in the main amplifier and finally the effective value of the sensor signal is formed.

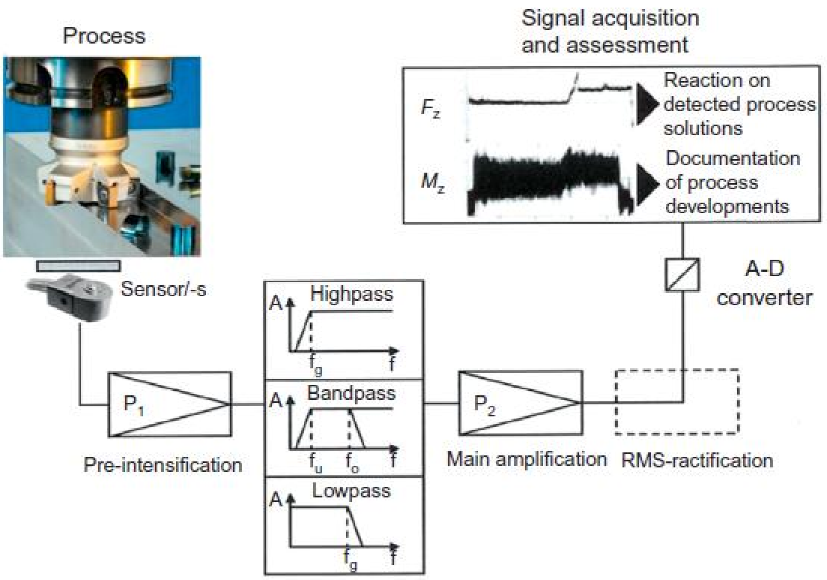

Figure 32: AE-signal acquisition and processing

(Grzesik, 2017a)

7.3. Figure 33 shows an intelligent sensor-assisted machine system for a vertical milling machine. The intelligent controller is used together with the standard CNC controller. This intelligent machining system contains an intelligent machining module (IMM) which runs on commercial CNC systems. In this case the IMM runs on a digital signal processing (DSP) board with multiple A/D and D/A channels that enables simultaneously performance of various intelligent machine tasks, such as adaptive control (AC), tool condition monitoring (TCM) and process control.

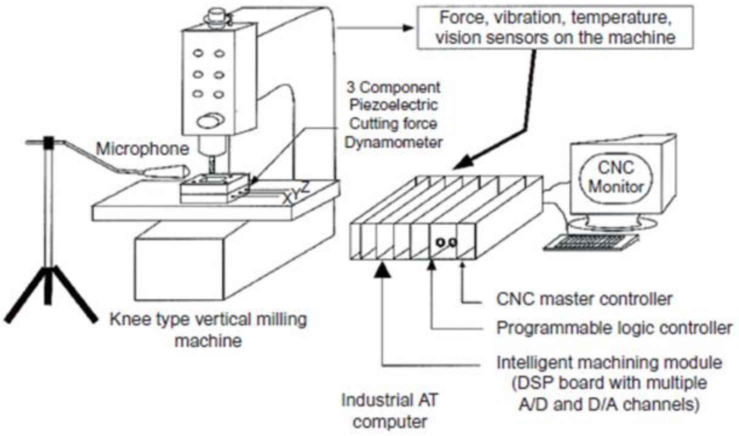

Figure 33: Sensor-assisted intelligent machining system

The IMM communicates with commercial semi-open CNCs through the PC-CNC communication links and software and sends feed and spindle speed change, machine stop, tool change, tool offset and other commands that are accepted by the CNC controller.

Recently, the use of more sensors, also called sensor fusion is extensively developed to create a multi-sensor reconfigurable monitoring system as shown in Figure 34.

Figure 34: Reconfigurable multi-sensor monitoring system concept

(Grzesik, 2017a)

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8. Data Acquisition from CNC and PLC System

8.1. Development of a diagnosis tool for machine spindle (see Figure 36) of a machine tool (see Figure 35) that produces powertrain components.

Figure 35: Machine tool used for experiments

Figure 36: Spindle details

For this reason, an embedded electronic-based cyber-physical system (CPS) has been developed that gathers data from the spindles during the machining process and then analyzes the data to get relevant information. **Spindle data acquisition and pre-processing:** Figure 37 shows the experimental setup where the embedded electronic system is implemented into the machine-tool to gather the required data. The data coming from the Computer Numeric Control/Programmable Logic Controller (CNC/PLC) via ethernet interface is gathered by the CPS. The CPS can communicate with the CNC and request the machine state. When the data has been gathered and a timestamp has been assigned to synchronize the different systems, the data package is sent to the local hard drive device (HDD) where it is stored in a comma separated value format (csv).

Figure 37: Experimental setup for the experiment

The CPS (SOC-e CPPS-gate40 system), developed by Ikergune and SoC-e, is able to establish peer-to-peer communication with the machine tool control system (in this example the PLC and CNC) is shown in Figure 38. It is equipped with different communication ports to gather real-time data from the machine.

Figure 38: CPS hardware for the experiment

The machine tool is controlled by a SIEMENS Sinumerik 840D PLC/CNC that sends data through an Ethernet port to the CPS using the Step7 protocol standard.

The CPS is programmed to gather the following data from the machine´s CNC:

- Power consumption
- Angular speed
- Torque
- Temperature

The data gathered from the CPS are combined with data taken from the PLC for synchronization and pre-processing:

- Timestamp
- Machine and workpiece presence
- Signal when the machining process is running, and the cycle is not empty

(Diaz-Rozo et al., 2017)

8.2. Machine condition monitoring that focusses on sensors, which are already available in the machine. This example focuses on a spindle drive that consists of a servo motor, a gearbox and a mechanical spindle and a three-layer software-based condition monitoring system. The first layer is a so-called data acquisition layer, which is situated on the PLC itself.

The second layer is the data processing loop and the third layer broadcasts the information to the end-user.

The communication procedure, that is based on a TCP/IP based API, is shown in Figure 39. SAP and other ERP systems can access this information to plan production batches ahead of time, consider the condition as well as the failure prediction of each machine.

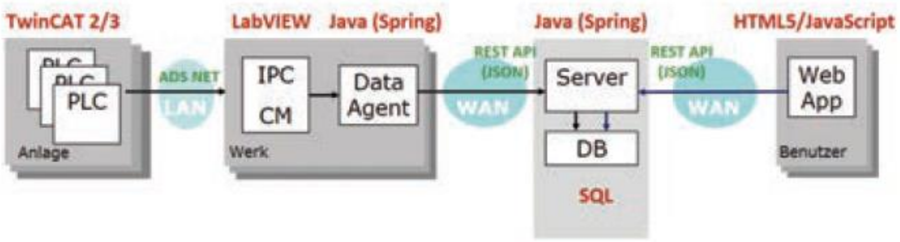

Figure 39: Communication procedure

The interfaces used in this example are open source interfaces based on a JSON that allows an easy encoding.

(Engeler et al., 2017)

8.3. See Concrete Implementation Concept Example Number 36.1.

Derived from the following Literature

[23] (Downey et al., 2016)
[24] (Grzesik, 2017a)
[25] (Diaz-Rozo et al., 2017)
[26] (Cai et al., 2017)
[27] (Denkena et al., 2014b)
[28] (Fujishima et al., 2017)
[29] (Downey et al., 2015)
[30] (Engeler et al., 2017)
[31] (Vikram et al., 2016)

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[23] (Downey et al., 2016, pp. 920–926)
[24] (Grzesik, 2017a, pp. 467–504)
[25] (Diaz-Rozo et al., 2017, pp. 997–1008)
[26] (Cai et al., 2017, pp. 1031–1042)
[27] (Denkena et al., 2014b, pp. 416–423)
[28] (Fujishima et al., 2017, pp. 796–799)
[29] (Downey et al., 2015, pp. 215–220)
[30] (Engeler et al., 2017, pp. 323–328)
[31] (Vikram et al., 2016, pp. 217–224)

- **Collected Information – Tools**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Tools**"? → Digital Information about the Tools is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF03	Collected Information: Digital Information is collected automatically	Tools

Abstract Implementation Concepts and Concrete Examples

9. Sensor Integration

9.1. A transponder mounted screwdriver to calculate the 3D position of the tool. (Fischer et al., 2016)

9.2. Figure 40 shows a sensor-guided boring bar with the ability to correct the cutting-insert location.

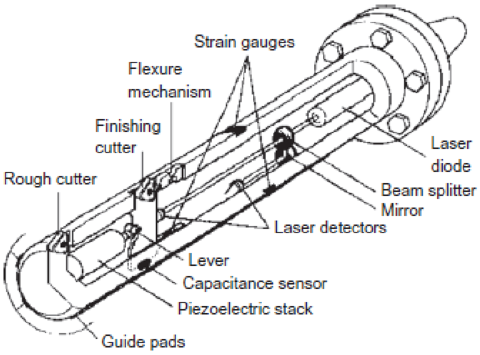

Figure 40: Sensor-guided boring bar

The tool has piezoelectric sensors housed within the tool body, a laser guidance system and a built-in computer. An ultra-precision laser system that measures vibratory displacement and an actuator that corrects the cutting-insert location are inside the tool.
Figure 41 shows the concept of an axial vibration compensation unit. The unit uses piezo-fiber sensors to measure the vibrations which allows the compensation for vibrations in the drive train.

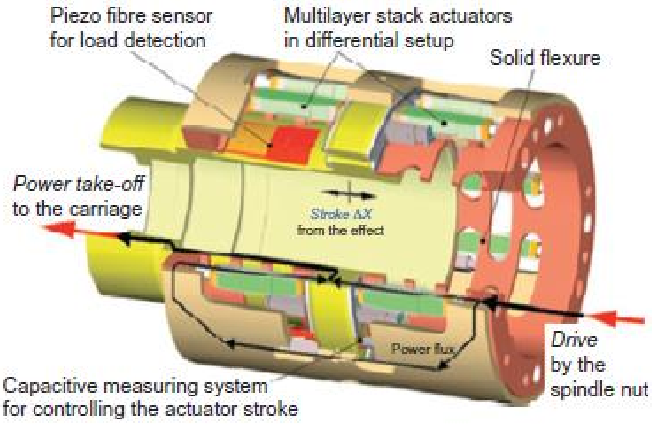

Figure 41: Axial vibration compensation unit

(Grzesik, 2017a)

9.3. Micro-adjustable boring head system, termed KomTronic-Electronic Compensating System by Komet, with measuring system fitted to the adjustment slide, a servomotor and an infrared electronic transmission and receiving system (see Figure 42). The system can perform fully automatic adjustments of micrometer-range in the diameter.

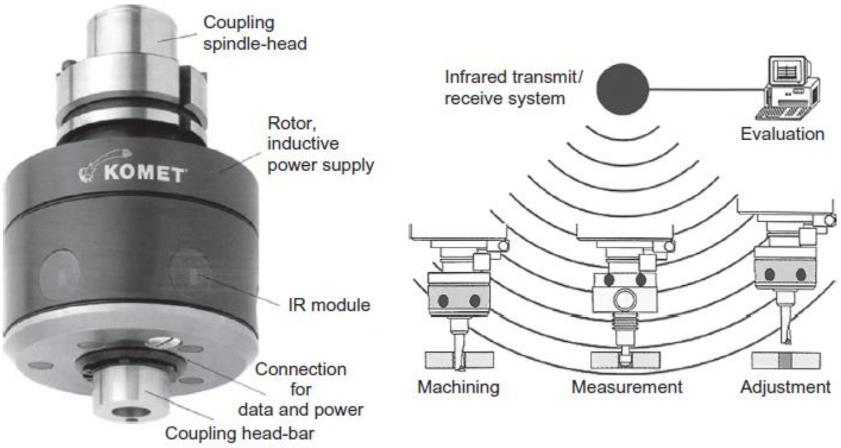

Figure 42: Micro-adjustable boring head (KOMET-M042) and the closed-loop micro-adjustable system from KOMET

(Grzesik, 2017a)

9.4. Monitoring of the cutting tool's temperature based on dielectric ring resonator sensor with a temperature-sensitive resonance frequency. The ring-shaped sensor is fixed to a cylindrical-shaped tool such as a drill. As shown in Figure 43, a reader can obtain the temperature of the sensor by interrogating it with a signal and measuring the frequency from the backscattered signal.

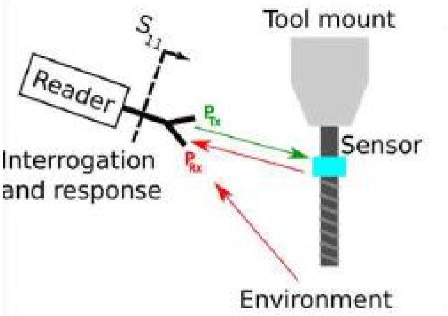

Figure 43: Ring resonator sensor system

(Sáez et al., 2016)

9.5. Real-time acoustic emission indication to predict the product quality of turned parts from a lathe INDEX C200 production turning machine. A “Kistler 8152B1” sensor is attached at the tool holder and connected to the Kistler 5125B1 Piezotron Coupler by cable. The Piezotron Coupler amplifies the electric charge of the piezo sensor which enables the analog/digital conversion by the National Instruments NI USB-6251. The data is than recorded at a laptop using Matlab.

(Albers et al., 2017)

9.6. Development of a modular sensor platform to facilitate incorporation of state-of-the-art sensor technology into an injection molding tool where the core element is an integrated diagnostic unit which provides intelligent data interpretation algorithms and an electronic tool-book for data storage and management (see Figure 44).

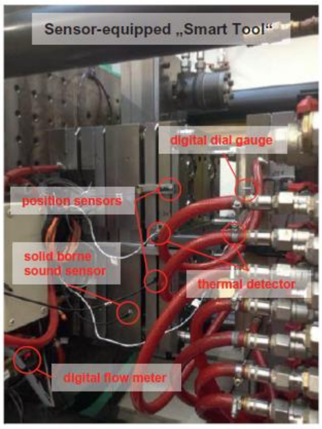

Figure 44: Sensor-equipped Smart Tools

The following sensor concepts have been selected for the modular sensor platform:

- Thermal detector (on the nozzle side and on the extractor side)
- Flow meter (control the cooling circuit)

- Force sensor (detection of extractor force)
- Digital dial gauge (control opening of plates)
- Position sensor (monitor plate and extractor movement)
- Sound sensor (monitor malfunction of the tool)

(Schuh et al., 2014)

9.7. See Concrete Implementation Concept Example Number 4.2.

9.8. See Concrete Implementation Concept Example Number 4.5.

9.9. See Concrete Implementation Concept Example Number 6.2.

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10. Tool Condition Monitoring (TCM) by Sensor Integration and A/D Converter

10.1. Realization of a Tool Condition Monitoring (TCM) System for monitoring turning processes on CNC lathes, and drilling and milling processes on machining centers by mounting a strain gauge sensor in the tool-holder (see Figure 45 - a) to measure torque, and axial and radial forces.

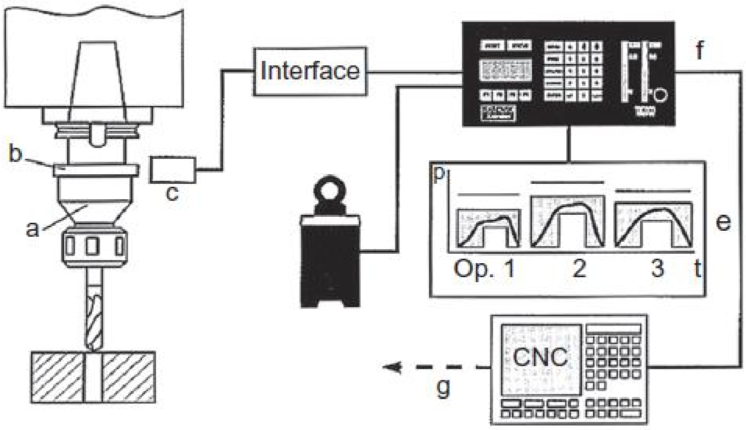

Figure 45: Structure of drilling process monitoring

A preprocessing unit and an A/D converter are embedded into the tool-holder. To transmit the sensor signal to the signal-processing device (see Figure 45 – f) by a wireless signal transmission unit consisting of the ring (b) and the head (c). The signal-processing device can initiate action by the machine controller if the tool is worn, broken or air-cut occurs.

(Grzesik, 2017a)

10.2. Tool Condition Monitoring (TCM), more precisely a tool wear monitoring system, in a turning process on an INDEX CNC GU 600 lathe by using vibration sensors. Vibration signals were registered at the tool shrank by an accelerometer Kistler 8002 that was fixed onto the tool holder to measure acceleration of the occurring vibrations. To sample the sensor-signal an A/D converter NI 625 USB, National Instruments was used. The data was then visualized by an acquisition software (see Figure 46).

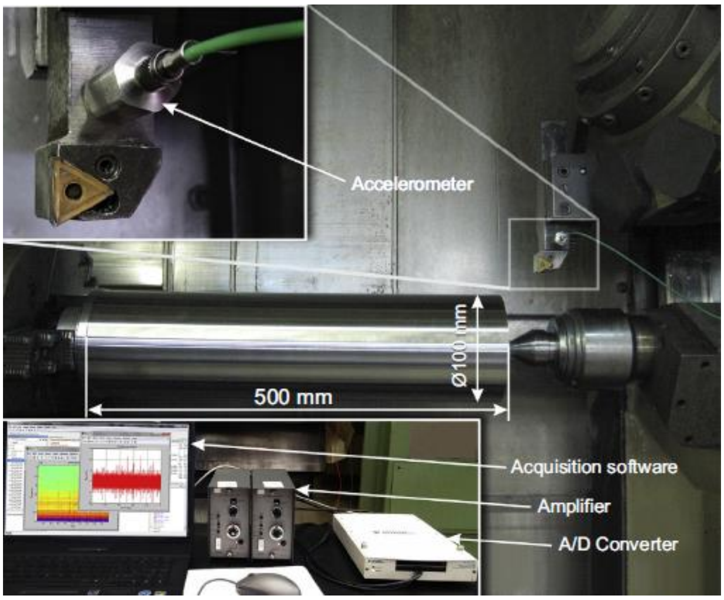

Figure 46: Experimental setup Tool Condition Monitoring

(Antić et al., 2018)

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11. Tool Condition Monitoring (TCM) by Sensor Integration and Data Acquisition Card

11.1. Tool Condition Monitoring (TCM) during a milling process of very thick-very large steel sheets with acoustic emission and vibration signals for monitoring tool wear, tool breakage, chip formation, chip breakage, machine tool vibration, machine vibration, workpiece surface roughness and so on. The milling machine is a TECOI TRF milling machine, using a beveling tool MFB5179173/XKEN2966995 (see Figure 47).

Figure 47: TECOI TRF milling machine and the tool used in the experiment

As shown in Figure 48,the acoustic emission sensor and acceleration sensor were mounted on the enveloped surface of the ram.

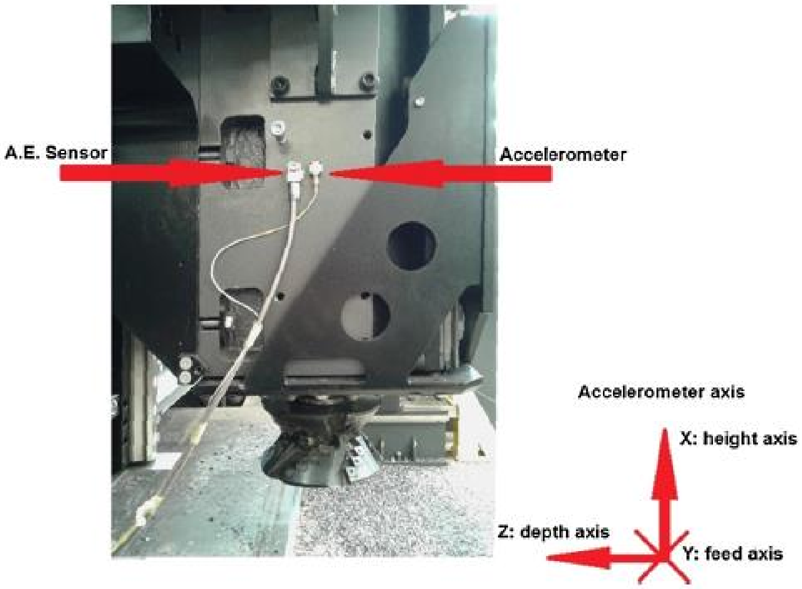

Figure 48: Sensor location and accelerometer axes

Data acquisition system of vibration signals: The used sensor was a piezoelectric accelerometer Kistler K-Shear 8739A which measures the vibrations on three axes (see Figure 49). The sensor requires three Kistler Piezotron 5108A low impedance couplers, which supply the accelerometer with voltage and carry the acquired analogue signals.

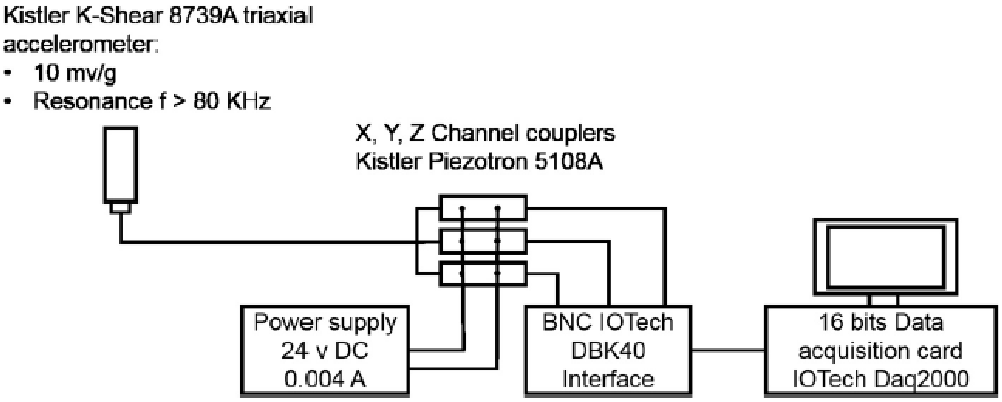

Fig. 3. Acquisition system for vibration signals.

Figure 49: Data acquisition system for vibration signals

The interface for digitizing the acquired signals is a BNC IOTech DBK40 that is connected to an acquisition IOTech Daq2000 (PCI) card through a DB37-P1 plug.

Data acquisition system of acoustic emission (AE) signals: A piezo-ceramic Kistler Piezotron 8152C1 sensor was used that is connected to a Kistler Piezotron 5125C1 coupler, which processes the signals from the sensor and supplies the required voltage (see Figure 50). A NI VirtualBench 8012 was used as signal acquisition and digitization device through the BNC analog channels. The VirtualBench is then connected via USB to a personal computer for storing the acquired data and a LabVIEW software was used for acquiring AE signals.

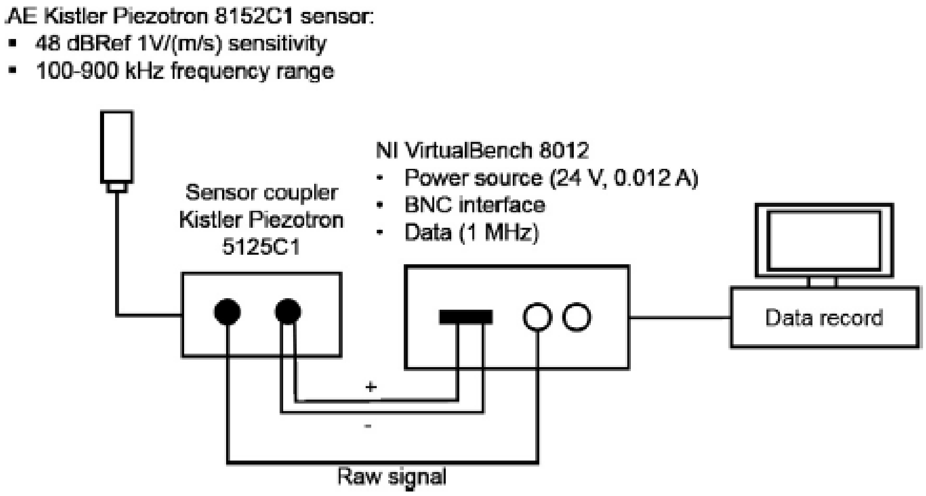

Figure 50: Data acquisition system for acoustic emission signals

(Barreiro et al., 2017)

11.2. Analyzing the deep drilling process vibration-signals to detect the tool wear mechanism on a Haas CNC three axis vertical machining center VF6 based on vibration sensors from a PCB 356A32 miniature tri-axial accelerometer, as illustrated in Figure 51.

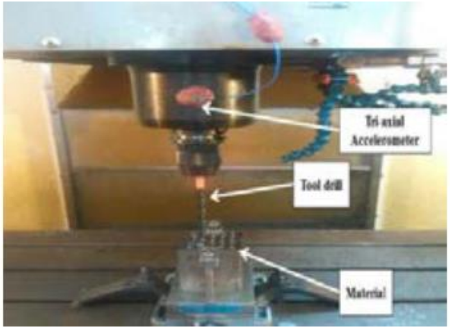

Figure 51: Deep drilling experiment arrangement

To transfer the sensor signal data to a computer a data acquisition module from National Instrument (model 4431) was used and the analyzation was performed in a MatLab software.

(Harun et al., 2016)

11.3. Condition monitoring of face milling tool using universal milling machine 3M (AU) G all feed automatic with an accelerometer and a data acquisition system, as shown in Figure 52. The vibration signals are acquired by a tri-axial IEPE accelerometer (MEAS 7132A), mounted on the spindle housing if the machine. To acquire the acceleration signals from the sensor, a data acquisition system (National Instruments DAQ 9234) is used and these signals are then processed by LabVIEW software on a computer.

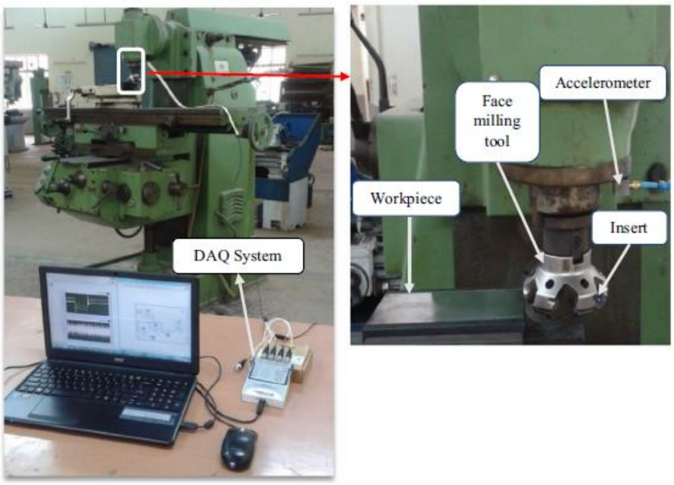

Figure 52: Condition monitoring of face milling tool setup

(Madhusudana et al., 2016)

11.4. Tool wear monitoring in sheet metal stamping with an audio signal analysis. The experimental setup on a semi-industrial sheet metal stamping machine is shown in Figure 53.

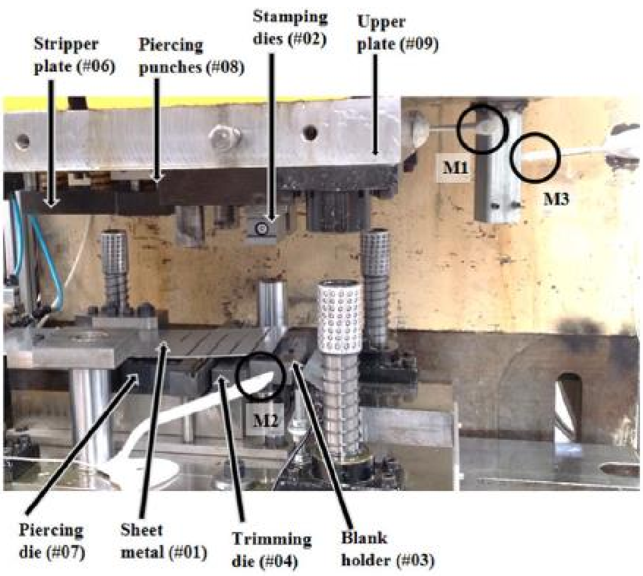

Figure 53: Tool wear monitoring sheet metal stamping

Data acquisition setup: For data acquisition three microphones (see Figure 53, M1-M3) were employed that were mounted on the upper plate (#09), on the stationary bottom (#04) and on the stationary press frame. To record the starting point of each stroke a position sensor was used. The data acquisition system that was used was a National Instrument USB-6009 data acquisition system where the analog channels were used to record the three microphone outputs and the positioning signal. A Thinkpad Lenovo laptop with National Instruments Signal Express software was used to process the signals.

(Ubhayaratna, 2017)

11.5. Virtual tool wear sensing technique based on multisensory data fusion for tool condition monitoring. A multi-sensory data acquisition system is used where the forces and vibrations in three directions are measured and stored on a PC for post processing to detect the tool wear state.

For the experimental setup (see Figure 54) a highspeed CNC milling machine was used and a Kistler quartz 3-component platform dynamometer was mounted between the machine table and the workpiece to measure the cutting forces. To measure the machine tool vibration in x, y, z directions three Kistler Piezo accelerometers were mounted on the workpiece. The measurements were continuously recorded using an DAQ NI PCI1200 and stored in a computer. The offline measurements of the flank wear were performed on a LEICA MZ12 microscope after finishing each surface.

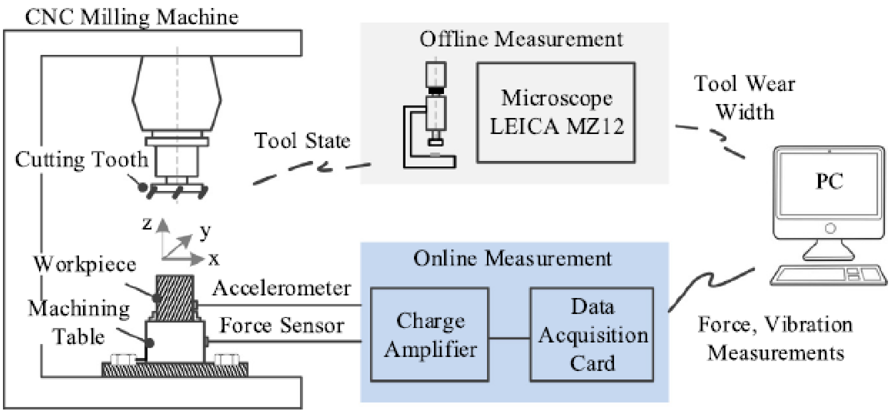

Figure 54: Experimental setup of the virtual tool wear sensing technique

(Wang et al., 2017)

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12. Sensor Integration with CNC and PLC Control System

12.1. See Concrete Implementation Concept Example Number 7.1.

12.2. See Concrete Implementation Concept Example Number 7.2.

12.3. See Concrete Implementation Concept Example Number 7.3.

12.4. See Concrete Implementation Concept Example Number 18.1.

Derived from the following Literature

[32] (Fischer et al., 2016)
[33] (Grzesik, 2017a)
[34] (Barreiro et al., 2017)
[35] (Sáez et al., 2016)
[36] (Albers et al., 2017)
[37] (Antić et al., 2018)
[38] (Harun et al., 2016)
[39] (Madhusudana et al., 2016)
[40] (Ubhayaratne et al., 2017)
[41] (Wang et al., 2017)
[42] (Schuh et al., 2014)

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[32] (Fischer et al., 2016, pp. 242–247)
[33] (Grzesik, 2017a, pp. 467–504)
[34] (Barreiro et al., 2017, pp. 144–157)
[35] (Sáez et al., 2016, pp. 1231–1236)
[36] (Albers et al., 2017, pp. 348–353)
[37] (Antić et al., 2018, pp. 1–15)
[38] (Harun et al., 2016, pp. 508–511)
[39] (Madhusudana et al., 2016, pp. 1543–1551)
[40] (Ubhayaratne et al., 2017, pp. 809–826)
[41] (Wang et al., 2017, pp. 47–58)
[42] (Schuh et al., 2014, pp. 374–379)

- **Collected Information – Mounting Device**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Mounting Device**"? → Digital Information about the Mounting Device is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF04	Collected Information: Digital Information is collected automatically	Mounting Device

Abstract Implementation Concepts and Concrete Examples

13. RFID-Technology

13.1. Using RFID-technology embedded on the jigs to get access or feedback of information.

(Brenner and Hummel, 2016)

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14. Sensor Integration

14.1. MTConnect based monitoring system for data collection and process monitoring for finish machining assembly interfaces of large-scale aircraft vertical tail to overcome the interoperable problems caused by different proprietary interfaces and communication protocols.
There are various types of finish machining equipment on the shop floor of aircraft manufacturing and each of them has its own proprietary interface and communication protocol which leads to a great challenge to the machine monitoring. To overcome these issues the AMT has developed MTConnect which is a set of open, royalty-free standards intending to foster greater interoperability between controls, devices, and software applications by publishing data over networks using the Internet Protocol.
Finish machining system framework: Figure 55 shows the framework where the large component is held and adjusted by the CNC positioners and clamped by the holding device to maintain stability and reduce deformation during machining process that is performed by the machine tool. The laser tracker measures the large component and provides the data for posture evaluation. To handle all the motion controls (aligning, clamping and machining) a CNC (Siemens 840Dsl controller) system is integrated in the framework. To run the process control software which controls the aligning process an IPC is used.

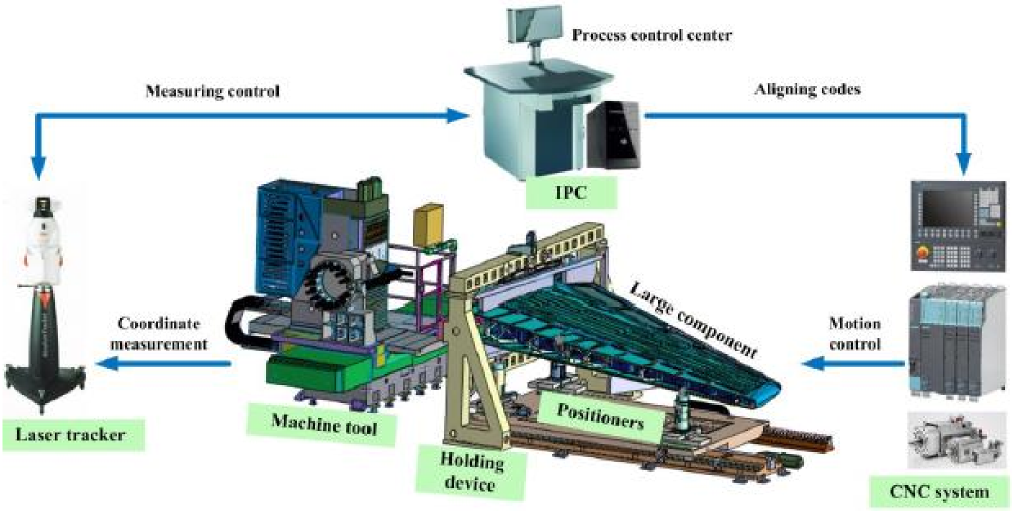

Figure 55: Finish machining system framework

Posture adjustment: The posture adjustment is executed by the CNC positioners, which are connected to the large-scale component by a sphere ring. Each positioner is equipped with a force sensor to monitor the holding force, as shown in Figure 56. During the adjustment process, the holding force would decrease when the large-scale component is going to fall off. The motion parameters of the positioners such as position, velocity and acceleration are also monitored.

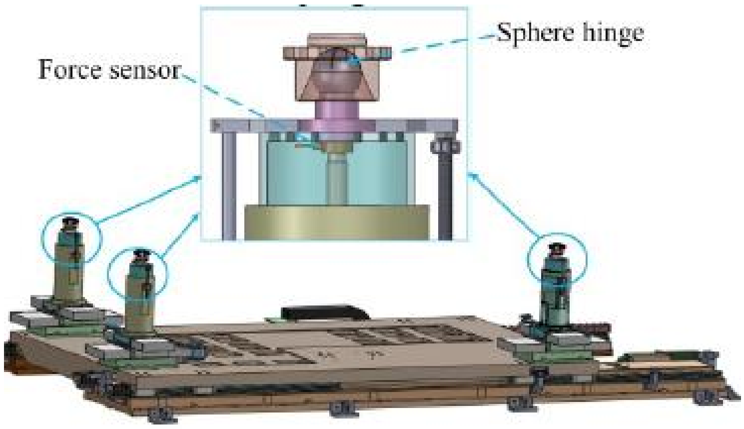

Figure 56: Positioners with force sensors

Clamping and machining: The holding device, as shown in Figure 57, consists of different clamping components which are all equipped with a force sensor mounted on the clamping head and servomotors are adopted to control the clamping forces. The clamping force is monitored to avoid deformation caused by overlarge clamping force.

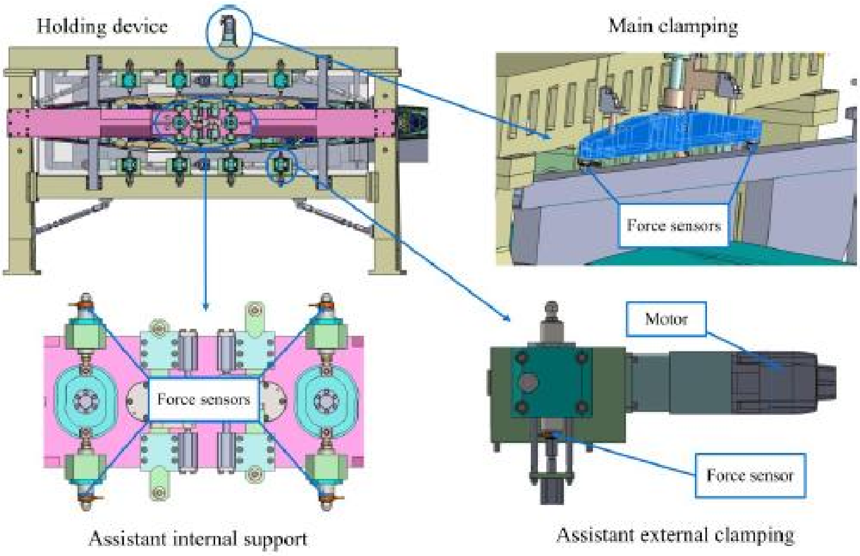

Figure 57: Holding device with force sensors

MTConnect architecture: The MTConnect model of the finish machining system is an XML data mode where the agent software is built with integration of an adapter to collect process data and transform the data. The agent software sends the data in a standard format to the client (IPC). (Lei et al., 2016)

14.2. See Concrete Implementation Concept Example Number 69.1.

14.3. See Concrete Implementation Concept Example Number 73.1.

14.4. See Concrete Implementation Concept Example Number 119.1.

14.5. See Concrete Implementation Concept Example Number 119.2.

14.6. See Concrete Implementation Concept Example Number 151.1.

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15. Sensor Integration and A/D Converter

15.1. Integration of sensors in a hydraulic clamping system for multi-axis machining of cast casing covers typically used in series production. The used sensors were strain gauges for indirect measurement of oil pressure in the hydraulic clamping element as well as piezo-electrical force sensors for direct measurement of the clamping force. Figure 58-a shows the simplified representation of the system structure and Figure 58-b shows the hydraulic clamping fixture which consists of a fixture plate, three hydraulic swing clamps with appropriate supports and one hydraulic work support.

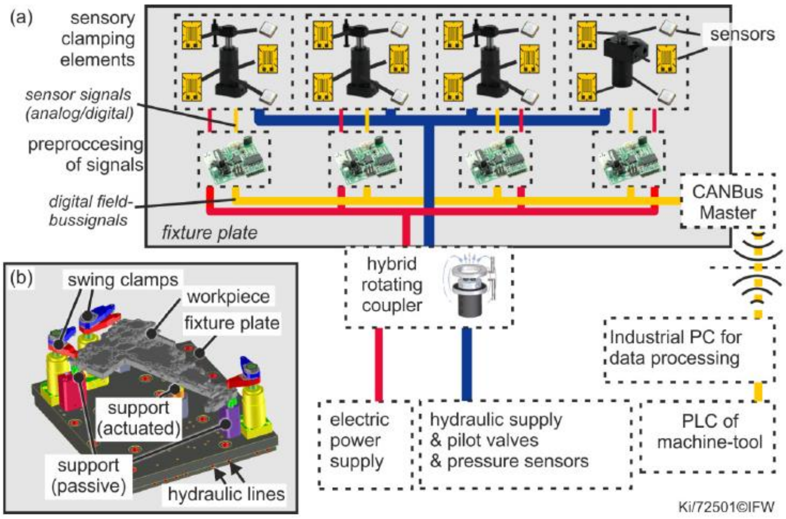

Figure 58: Sensor integrated hydraulic clamping system

The sensors are integrated into the hydraulic clamping elements and the intended quantities for measuring are strains, acceleration and temperatures. For pre-processing the sensor signals every sensory clamping element is equipped with an embedded micro-controller to digitalize the analogue sensor-signals. To enable communication abilities the micro-controller is connected to a common fieldbus which makes it possible to transfer the sensor information to an industrial PC for data processing. The industrial PC is provided with a PROFIBUS-interface for communication with the PLC of the machine-tool to send status information.

(Denkena et al., 2014a)

15.2. Condition and process monitoring system based on sensing hydraulic clamping elements with integrated sensors, decentral electronics for signal processing, bus communication and a central process unit to measure hydraulic pressure, the clamping stroke and the process forces by the clamping elements (swing clamps) themselves during milling operations.

Figure 59-a shows the exemplary hydraulic clamping fixture that consists of a base plate with integrated hydraulic lines, three hydraulic swing clamps with appropriate supports and one hydraulic work support.

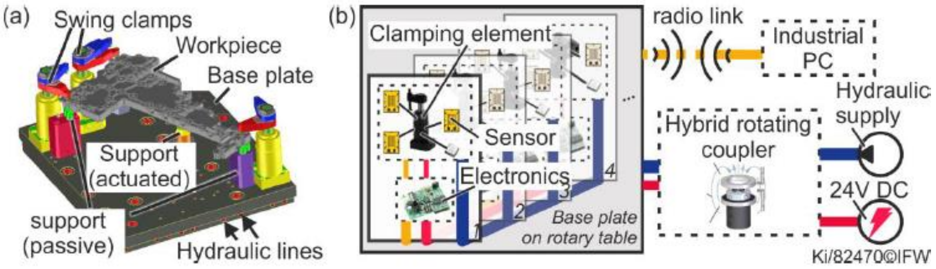

Figure 59: (a) Hydraulic clamping fixture (b) Concept for the sensory clamping system

The concept of the sensory clamping system is shown in Figure 59-b. Strain gauges and Pt100 temperature sensors are applied to the clamping elements to provide the clamping fixture with sensing abilities. The sensors are connected to electronic preprocessing micro-controller that are integrated into the base plate to digitalize the analogue sensor-signals and offer the beneficial use of CAN-bus (controller area network) and radio-link communication to an industrial PC for data processing.

(Denkena et al., 2016)

Derived from the following Literature

[43] (Brenner and Hummel, 2016)
[44] (Denkena et al., 2014a)
[45] (Denkena et al., 2016a)
[46] (Lei et al., 2016)

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[43] (Brenner and Hummel, 2016, pp. 227–232)
[44] (Denkena et al., 2014a, pp. 465–473)
[45] (Denkena et al., 2016a, pp. 235–244)
[46] (Lei et al., 2016, pp. 378–383)

- **Collected Information – Measuring & Test Device**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Measuring & Test Device**"? → Digital Information about the Measuring & Test Device is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF05	Collected Information: Digital Information is collected automatically	Measuring & Test Device

Abstract Implementation Concepts and Concrete Examples

16. On-Machine 3D Touch Probing and CNC Control System

16.1. Application of probing systems, more precisely on-machine inspection probing performing on CNC machine tools and incorporating high-speed CNC CMMs (Coordinate Measuring System) by coupling directly CNC measuring machines (e.g. MACH CMM series by Mitutoyo) with CNC machine tools for concurrent inspection of machining operations to provide pre-/post-machining feedback to machine tools for machining adjustments.

On-machine probing systems include setup, measuring and inspection tasks for both workpiece and tool, usually by programmed probing routines during machining (see Figure 60), which allows fast setups and automated machining of complex parts, identification of the type and size of parts, and checking tools, verification of setups and adjusting offsets.

Figure 60: On-machine probing: Workpiece measuring between machining cycles and tool presetting

(Grzesik, 2017a)

16.2. Installation of 3D touch probes with wire and wireless signal transmission on milling machines and machining centers (see Figure 61 and Figure 62).

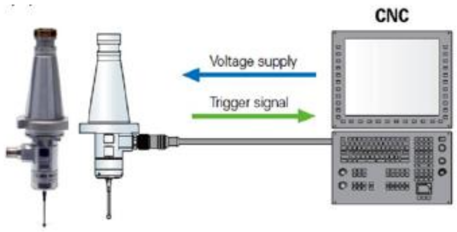

Figure 61: Cable (hard-wired) signal transmission 3D touch probes for machine tools. ***From Heidenhain***

The 3D touch probe is mounted in the machine spindle of CNC-controlled machine tools with manual or automatic tool changer to perform datum setting, workpiece alignment, workpiece measurement and digitizing 3D surfaces.

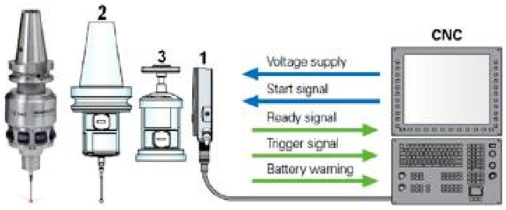

Figure 62: Wireless signal transmission 3D touch probes for machine tools: 1-transmitter/receiver unit, 2-workpiece touch probe, 3-tool touch probe. ***From Heidenhain***

(Grzesik, 2017a)

16.3. Development of a radio transmission system (see Figure 63) that provides long distance communication (up to 15m) between a probe and the controller of the machine.

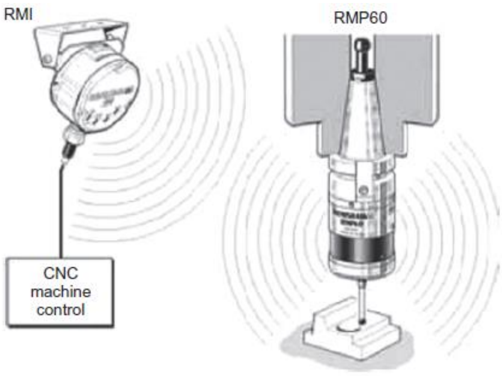

Figure 63: Radio transmission system. ***From Renishaw***

The radio transmission probe transmits the probe status signals to the CNC controller in “operating modes” by using the radio machine interface (RMI) which converts the signals into a form compatible with the CNC programs. The probe also receives signals from the machine control.

The operating modes include workpiece measurement and setup on medium to large vertical, gantry and horizontal machining centers, five-axis and twin-spindle machines.

(Grzesik, 2017a)

16.4. Development of an inductive transmission system (see Figure 64) that works by passing power and probe signals across a small air gap that is located between two induction modules - inductive probe module and machine tool module (IMM). To convert the probe signal into a form accepted by the CNC controller a machine interface unit (M15) is used. Such inspection systems can be installed on machining centers and lathes.

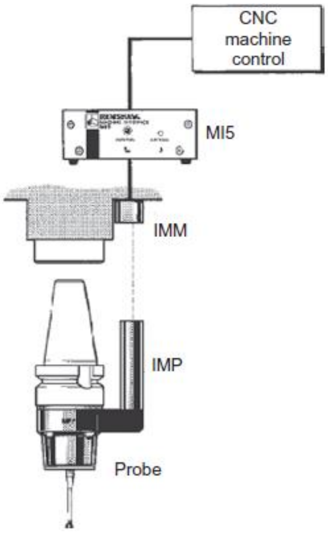

Figure 64: Inductive Transmission systems

(Grzesik, 2017a)

16.5. 3D touch probes with optical (infrared) transmission signal that transmit the signal over an infrared light beam using a transmitter/receiver unit specially designed for high-speed machine tools in horizontal machine centers with automatic tool changers (see Figure 65).

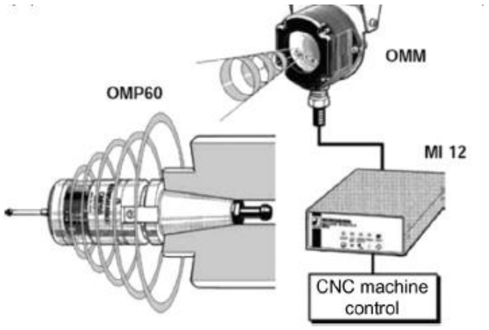

Figure 65: Signal transmission for touch probes using infrared transmission on a horizontal machining center

Multicolor LED indicators on the transmitter/receiver continuously display the condition of the infrared transmission and the touch probe. Signals from the touch probe are transmitted to the optical machine module (OMM) which is hard-wired to a machine interface (MI) to convert the signal for the CNC machine control.

(Grzesik, 2017a)

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17. Tool Setting Arm Probing and CNC Control System

17.1. High-precision pull-down arm (HPPA) and high-precision removable arm (HPRA) are tool setting probing systems for CNC lathes as shown in Figure 66 and Figure 67. The HPPA is a manually operated and permanently located system where the operator has to “pull-down” and “push-up” the system for tool setting operations within the horizontal turning center.

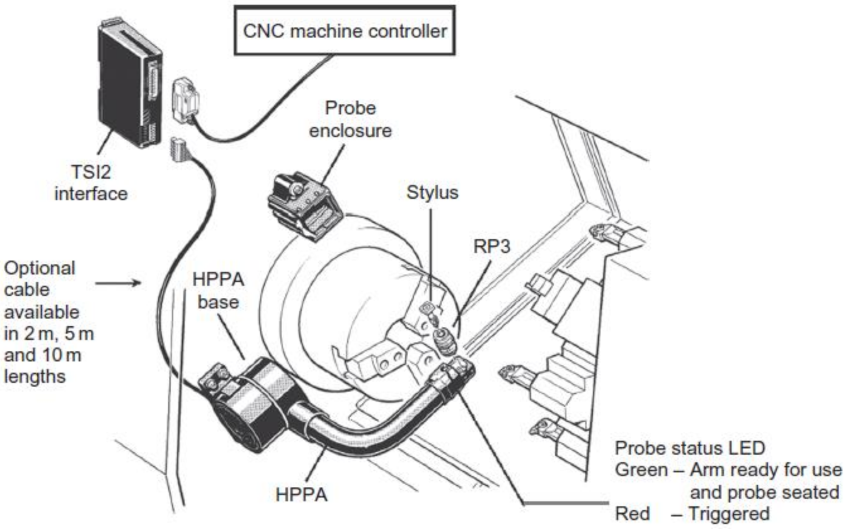

Figure 66: HPPA pull-down arm on a horizontal lathe. ***From Renishaw.***

Figure 67 shows the “plug-in” arm HPRA in a horizontal lathe that is manually located inside the machine for tool setting and removed once it is completed.

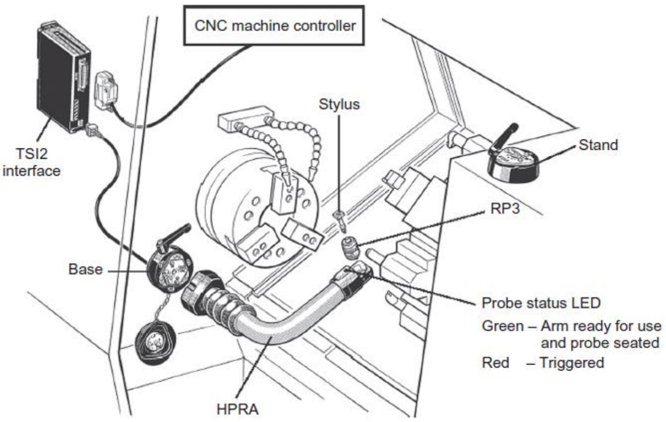

Figure 67: HPRA removable arm on a horizontal lathe. ***From Renishaw.***

(Grzesik, 2017a)

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18. Laser-based Sensor Integration

18.1. Figure 68 shows a non-contact laser control, in-process tool management system that monitors tools in real time within the machining environment. The system certifies that the correct tool is intact within the specific tool-holder and verifies the tools diameter, length, roundness and run-out.

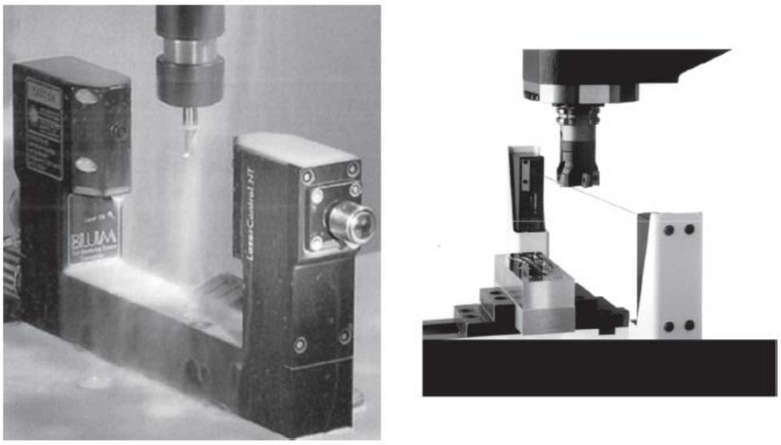

Figure 68: Laser control system for monitoring tool breakage and optical presetting of a cutting tool. ***From Blum LMT and Renishaw.***

Moreover, the measurement system determines the real tool length, tool wear and flight circle deviation, as well as thermal drift of the machine CNC axis and tool and compensates these deviations by an automatically correction that is programmed into the CNC control. The system does not involve setup time or downtime or require the spindle to slow down and stop for tool measurements.

(Grzesik, 2017a)

18.2. Non-contact measuring technology implemented in manufacturing like a laser-based inspection/measurement system (see Figure 69) that uses Z500 laser-based sensors, a pinpoint beam and a 2D vision CCD element with high precision that monitors the profile of the reflected light.

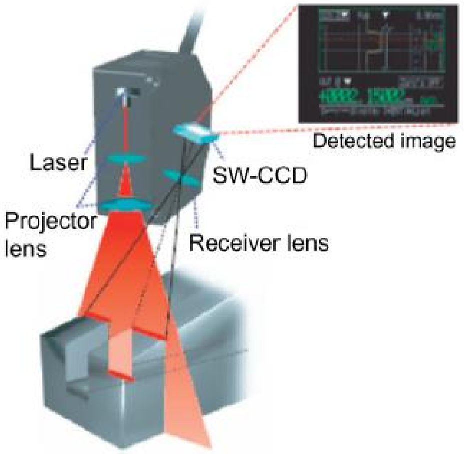

Figure 69: In-line inspection by vision sensors

(Grzesik, 2017a)

18.3. See Concrete Implementation Concept Example Number 14.1.

18.4. See Concrete Implementation Concept Example Number 151.1.

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19. Scanning Probes

19.1. Fast measurement data acquisition with scanning probes for form measurement. An example of such a high-speed scanning probe is shown in Figure 70. The SP25M probe performs the optical measurement via two mirrors on the scan module with a resolution of 0,1µm and is often used for measurements of cylinder and cylinder head bores.

Figure 70: Renishaw´s SP25M high-speed scanning probe for measurements of cylinder and cylinder head bores. ***From Renishaw.***

(Grzesik, 2017a)

Derived from the following Literature

[47] (Grzesik, 2017a)

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[47] (Grzesik, 2017a, pp. 467–504)

- **Collected Information – Logistics Worker**

Research Question: How can the requirement “**Digital Information is collected automatically**” be implemented for the value-adding-factor “**Logistics Worker**”? → Digital Information about the Logistics Worker is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF09	Collected Information: Digital Information is collected automatically	Logistics Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor “Logistics Worker” can be found in the matching model box with the **ID R02VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Collected Information – Conveying Device**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Conveying Device**"? → Digital Information about the Conveying Device is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF10	Collected Information: Digital Information is collected automatically	Conveying Device

Abstract Implementation Concepts and Concrete Examples

20. Sensor Integration and Optical Measurement

20.1. The modified KUKA youBot mobile robot consists of a platform with four Mecanum wheels with commutated DC motors integrated into the joints and wheels and a five-degrees-of-freedom manipulator with a gripper attached at the end of the manipulator (see Figure 71).

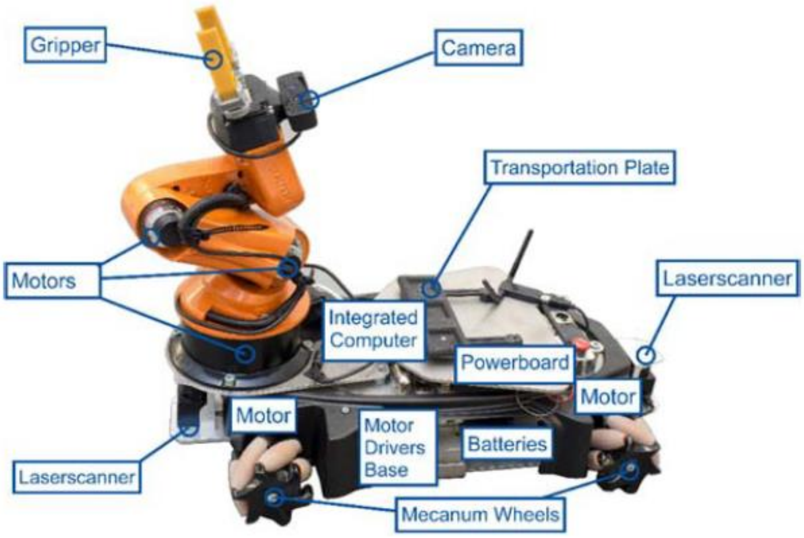

Figure 71: Modified KUKA youBot for mobile manipulation tasks

Furthermore, two commercial laser range finders (Hokuyo URG-04LX-UG01) are equipped at the platform's front and back and an RGB-D camera is mounted on the wrist of the manipulator. The internal computer of the youBot has been replaced by a faster system and the robot is equipped with an emergency stop system.

A watchdog is used for condition monitoring of the components of the modified KUKA youBot. For instance, the force feedback of the gripper is used to validate the grasping level of the grips by estimate the electrical current of the gripper servo. The manipulator is equipped with a lot of sensors that can be used to monitor the condition of the manipulator like actual position, velocity and electrical current of each servo drive.

To validate the robot's motion, the current of each servo drive is used for navigation improvement and then compared to the estimated position from the Adaptive Monte Carlo Localization (AMCL) based localization.

To face the different mobile robotic systems, the device is equipped with a mainboard that distributes the signals from the central microcontroller to up to five measurement boards. Each measurement board can observe up to four electric components.

The measurement device can also be remote controlled by transmitting the measurement results to a connected factory hub via Bluetooth.

The live data is represented by a developed Matlab application using the Matlab Robotic System Toolbox.

(Carstensen et al., 2016)

20.2. See Concrete Implementation Concept Example Number 142.1.

20.3. See Concrete Implementation Concept Example Number 152.1.

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21. Optical Measurement System

21.1. Integration of a control system for a mobile system for manufacturing task by synchronize an automated guided vehicle (AGV) to a moving object like a car on a continuous conveyor. To realize the synchronization between the AGV and the moving objects the speed of the AGV is regulated by controlling the two drive wheels that are in the front of the AGV.

Six devices are set up for an experimental scenario (see Figure 72):

- KUKA robot KR 16 to simulate the continuous conveyor
- AGV KATE
- Optical measurement system Nikon K600 for position measurements of the AGV and the moving object
- Central computer to process the position data and control the AGV
- LabVIEW software for the control program and for the data collection
- Wireless network device to realize the communication among the central computer, the AGV and the Nikon K600

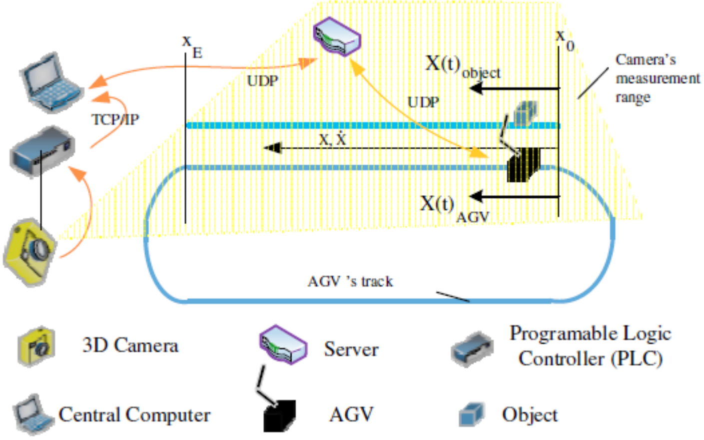

Figure 72: Devices for the Control System for a mobile system experimental setup

A User Datagram Protocol (UDP) is used to realize the communication between the AGV and the central computer as shown in Figure 72. To generate the motion commands regulated values are send from the central computer to the server.

Figure 73 shows the optical measurement system K600 that uses the triangulation method. With three integrated cameras the system can measure in 6 dimensions to get the positions of the AGV and the moving object. The captured data from the measurement system are then sent to the central computer via Transmission Control Protocol/Internet Protocol (TCP/IP) protocol (see Figure 73).

Figure 73: Optical Measurement System – Nikon K600

The control system for the experimental setup executes the following tasks. The first task is to capture the position data from the AGV and the moving object using the optical measurement system. The second task is the analyzation of the position data and the calculation of the deviations. The third task is to process and generate motion commands and send them to the AGV via the wireless network.

The data is analyzed by a LabVIEW program that was created in the central computer and sends the calculated data values to the server. In the server a Java-script program reads the data from the central computer and sends the responding motion commands to the AGV to control the motion of the AGV. Figure 74 shows the experimental setup of the control system.

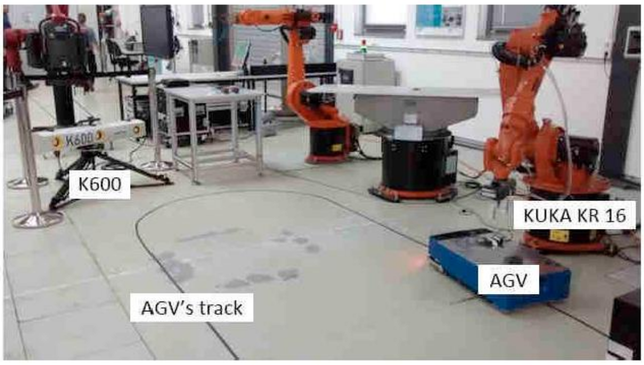

Figure 74: Experimental Setup for the Control System

(Zou et al., 2016)

21.2. Comparison of the 3D range sensor Swiss Ranger SR-4000, Fotonic B70, LRF sensor and Microsoft Kinect (see Figure 75). that are mounted on a mobile platform (see), for indoor mobile robotics and automated logistics scenario of container unloading.

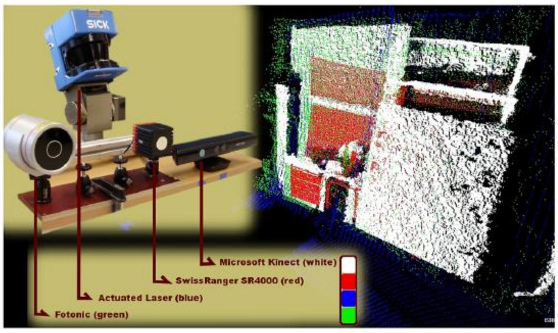

Figure 75: 3D range sensor setup

The sensors are mounted on a mobile platform, for indoor mobile robotics and automated logistics scenario of container unloading (see Figure 76). The experimental setup concentrates on box-, cylinder-, and sack-packed goods inside a mock-up container to collect measurement data.

Figure 76: Sensors mounted on a mobile platform

For the evaluation of the sensors three distinct setups were placed inside a container. The three scenarios with the rendered 3D models and the result of the sensors are pictured as a sample point cloud data are shown in Figure 77.

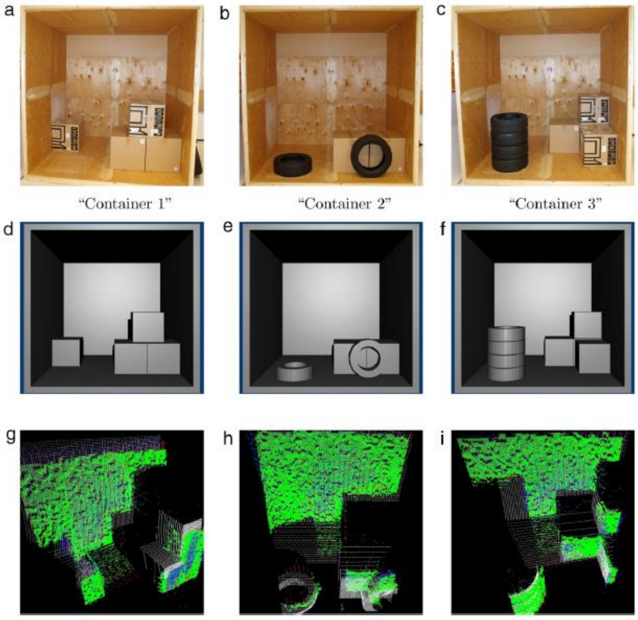

Figure 77: Sample clouds of three setups of different goods

(Stoyanov et al., 2013)

21.3. See Concrete Implementation Concept Example Number 93.1.

21.4. See Concrete Implementation Concept Example Number 140.1.

21.5. See Concrete Implementation Concept Example Number 140.2.

21.6. See Concrete Implementation Concept Example Number 140.3.

21.7. See Concrete Implementation Concept Example Number 140.4.

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22. Sensor Integration

22.1. Microcontroller-based mobile robot navigation system built in a mobile robot operating in a warehouse for robot positioning and obstacle avoidance focusing on the sensory system.

The robot is equipped with 24 ultrasonic sensors arranged around the vehicle (Devantech SRF04 Ranger Compact High-Performance Ultrasonic Ranger) to avoid obstacles that is shown in Figure 78.

Figure 78: Ultrasonic sensor - Devantech SRF04

Figure 79 shows the configuration of the mobile robot. The driving system consists of 4 wheels where each of them are equipped with a separate electric motor. The mobile robot is also equipped with a simple arm and a gripper that is used for loading and unloading of components. The most important device is the control unit which is installed in the front of the robot.

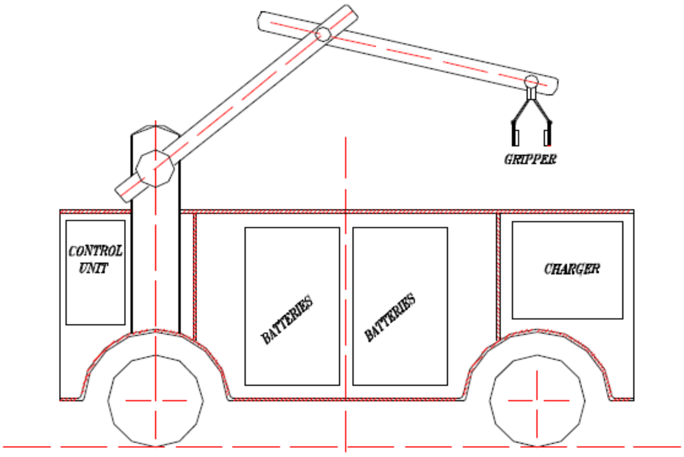

Figure 79: Configuration of the mobile robot

The method used for the localization of the robot is the relative method called odometry. It uses encoders to measure wheel rotation and/or steering orientation and calculates the position out of this information. The HEDS5540, 3 channels high performance optical incremental encoders are used. The control unit that is used is the motion control IC, HCTL-1100 that provides position and velocity control for the electric motors.

(Zaki et al., 2014)

Derived from the following Literature
[48] (Carstensen et al., 2016) [49] (Zou et al., 2016) [50] (Zaki et al., 2014) [51] (Stoyanov et al., 2013)

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[48] (Carstensen et al., 2016, pp. 560–569)
[49] (Zou et al., 2016, pp. 162–167)
[50] (Zaki et al., 2014, pp. 58–71)
[51] (Stoyanov et al., 2013, pp. 1094–1105)

- **Collected Information – Conveying System**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Conveying System**"? → Digital Information about the Conveying System is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF11	Collected Information: Digital Information is collected automatically	Conveying System

Abstract Implementation Concepts and Concrete Examples

23. Sensor Integration and RFID-Technology

23.1. Determine the condition of intralogistics systems using a holistic concept of mobile and stationary sensor units. The mobile units travel along with the containers on a conveying system (continuous roller and belt conveyors) and additional data is collected by stationary units. Each unit pre-evaluates the data and transmits only necessary data to a central evaluation unit. The mobile unit sensor system is handled on the conveyor systems like other containers, but it is equipped with different sensors to collect data at arbitrary spots. In addition, classic stationary sensors are utilized to complete the concept. These sensors can be sensors that are usually installed at the conveyor belts, like light beams or proximity switches or additional sensors integrated in the system.

The transmission of the pre-evaluated data to a central evaluation unit is realized by standardized transmission techniques and transmission protocols. In this experiment the ethernet technique, based on TCP/IP, is used because wired (for longer distances) and wireless techniques (for mobile units and short distances) can be used together in one network.

Mobile measuring unit: The main component of the mobile measuring unit is a regular load container with several acceleration sensors integrated to measure the acceleration in horizontal, vertical and cross direction. The mobile unit is placed on the conveyor and travels along with the other regular material containers to collect data permanently (see Figure 80).

Figure 80: Mobile Measurement Unit

To get information about the position of the mobile unit it is equipped with internal sensors which can detect signals from external sensors installed at defined positions on the conveyor system. Examples of external sensors are barcode scanners, RFID systems and photoelectric barriers. The mobile unit is also equipped with a computer to pre-evaluate the collected data (like data considering shocks and vibrations) and transmits the pre-evaluated data to the central evaluation unit via wireless LAN to identify certain potential failure locations. The central evaluation unit simultaneously collects all data from the mobile and stationary units.

Stationary measurement unit: Roller conveyors offer several possibilities for stationary sensor applications. For example, a measurement roller (see Figure 81) to detect vertical and horizontal dynamic forces by piezo-electric load cells on the roller caused by the handled containers. The data can be used for maintenance purposes or to detect overloads.

Figure 81: Roller Conveyor - Measurement Roller

(Künne and Eggert, 2010)

Derived from the following Literature

[52] (Künne and Eggert, 2010)

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[52] (Künne and Eggert, 2010, pp. 114–119)

- **Collected Information – Warehouse Worker**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Warehouse Worker**"? → Digital Information about the Warehouse Worker is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF13	Collected Information: Digital Information is collected automatically	Warehouse Worker

Abstract Implementation Concepts and Concrete Examples
The abstract implementation concepts and concrete examples of the value-adding-factor "Warehouse Worker" can be found in the matching model box with the **ID R02VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.

Derived from the following Literature

- **Collected Information – Warehouse Facility**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Warehouse Facility**"? → Digital Information about the Warehouse Facility is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF14	Collected Information: Digital Information is collected automatically	Warehouse Facility

Abstract Implementation Concepts and Concrete Examples

24. Sensor Integration

24.1. Sensor implication into storages or cold storages to ensure the freshness of perishables (e.g., fruits, vegetables, frozen food) by monitoring continuously temperature and humidity.

(Borgia, 2014)

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25. RFID-Technology

25.1. Development of a model where the blood bags "products" are identified by RFID technology to create a "intelligent shelf" inside the blood bags refrigerator and share information between supply chain stakeholders (see Figure 82).

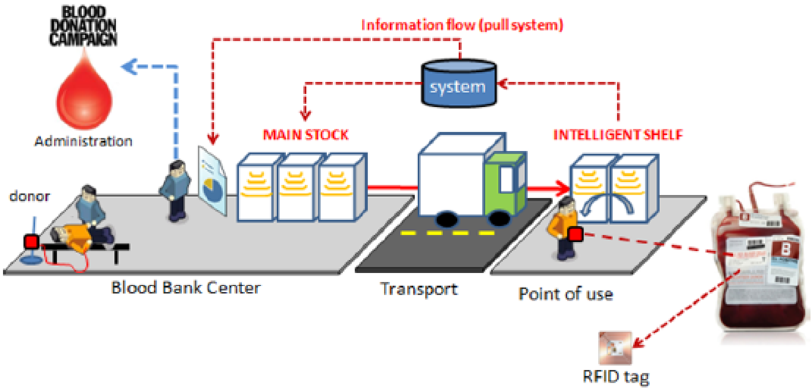

Figure 82: Replenishment Model for Blood Bags

The equipment oriented "intelligent shelf" in the hospital can be resupplied of blood bags from the blood bank center directly by using RFID technology.
Figure 83 shows the reception of the electromagnetic waves emitted by the reader in the RFID tag attached to the blood bag that causes a

response by sending the same information about the blood bag to the system.

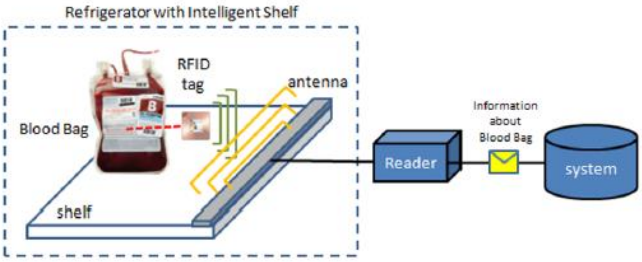

Figure 83: RFID System for the "intelligent shelf"

The information from the RFID tag is then identified by the system and used for various internal processes.

(da Silva and Correia, 2013)

25.2. See Concrete Implementation Concept Example Number 127.1.

25.3. See Concrete Implementation Concept Example Number 128.1.

25.4. See Concrete Implementation Concept Example Number 130.1.

Derived from the following Literature

[53] (Borgia, 2014)
[54] (da Silva and Correia, 2013)

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[53] (Borgia, 2014, pp. 1–31)
[54] (da Silva and Correia, 2013, pp. 21–24)

- **Collected Information – Loading Aid**

Research Question: How can the requirement "**Digital Information is collected automatically**" be implemented for the value-adding-factor "**Loading Aid**"? → Digital Information about the Loading Aid is collected automatically.

ID	Requirement	Value-Adding-Factor
R02VAF16	Collected Information: Digital Information is collected automatically	Loading Aid

Abstract Implementation Concepts and Concrete Examples

26. RFID-Technology

26.1. RFID-equipped loading aids in combination with smart shelves for tracking the loading aids in real time to help reduce material waste.

(Borgia, 2014)

26.2. Development of knowledge-based logistics operations planning system (named K-LOPS) with automatic data capturing technologies i.e. the bar-code system and the Radio Frequency Identification (RFID) system to increase the visibility of the warehouse operations. A RFID tag is attached to the warehouse components to record its identity and exchange data with the RFID reader with antennas that is attached to the warehouse facility, such as entrance and storage racks, to transmit and receive the radio signals. The received data is then decoded into useful information and stored in a centralized database.
Experimental Setup: The experiment was realized in a global third-party logistics service provider called KY Logistics Ltd. in Hong Kong by implementing RFID equipment into the warehouse. Passive RFID tags are stuck onto each carton when they arrive at the warehouse. The tags are also attached to the handling equipment like forklifts to identify them and their working location. The passive RFID tags on the cartons and on the forklift is shown on Figure 84.

Figure 84: Passive RFID tags stuck onto cartons and forklift

The RFID readers are mounted in defined passage ways to keep track of the movement of the cartons and the material handling equipment (see Figure 85).

Figure 85: Passive RFID reader mounted on dock door and warehouse entrance

With these reader at the warehouse entrance the in-and-out movements of the forklifts can be recorded. The reader on the dock door entrance records the carton loading to ensure that the pallet is packed and loaded according to the guidelines given.

(Lam et al., 2015)

26.3. Tracking of the data of food products starting from the stage of raw products farming, through food processing, transport, warehousing, to retailing and reaching the end consumer by recording the data on the product package in the form of a quick response two-dimensional barcodes (QR codes) and RFID technology.
The fruit is delivered to the factory as fresh fruit in smart returnable plastic packaging that is equipped with an RFID tag (see Figure 86).

Figure 86: Plastic packaging for food transportation with an RFID tag

The RFID tag stores data about the fruit origin and the conditions during transport by automatically writing this information in the RFID tag during picking via RFID readers implemented in the fruit transporters. The data about the fruit origin contains the following information:

- GPS coordinates of the location where the fruit was picked
- Date and time of picking
- Weather conditions (min/max temperature during the day)

When the fruits arrive at the factory, the data from the RFID tag are automatically read and written to the database.

(Tarjan et al., 2014)

26.4. Usage of RFID technology for real-time tracking merchandise and inventory on assets such as pallets, cases or bins in combination with intelligent shelves to enhance asset visibility.

(Vlachos, 2014)

26.5. See Concrete Implementation Concept Example Number 113.1.

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27. Sensor Integration and RFID-Technology

27.1. Design of a system for assessing the status of the content of a sealed food container without opening it by employing the RFID technology in conjunction with integrated sensors as well as tracking and monitoring the containers.

Figure 87: Integration of RFID technology and sensors

Figure 87 shows the main elements of the proposed system. Each container is equipped with an integrated circuit (IC) comprising the RFID tag and transmitter with a set of sensors for monitoring specific and general parameters. Such sensors can be simple temperature sensors to measure the temperature of the container, pressure sensors to flag the apparition of gas-generating biological process or more complex sensors that can monitor the apparition/concentration of chemical and biological agents.

These data from the sensors will be stored and recorded by the RFID tag and be available for inspection through integrated radio transceiver.

(Todorovic et al., 2014)

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28. **Barcode-based Inventory Management System**

28.1. Development of an inventory management system with a barcode-based two-bin system to decrease the inventory turnover, waiting times and the overall distances.

(Wanitwattanakosol et al., 2015)

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29. **Sensor Integration**

29.1. See Concrete Implementation Concept Example Number 110.1.

Derived from the following Literature

[55] (Borgia, 2014)
[56] (Lam et al., 2015)
[57] (Tarjan et al., 2014)
[58] (Vlachos, 2014)
[59] (Todorovic et al., 2014)
[60] (Wanitwattanakosol et al., 2015)

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[55] (Borgia, 2014, pp. 1–31)
[56] (Lam et al., 2015, pp. 763–779)
[57] (Tarjan et al., 2014, pp. 1–11)
[58] (Vlachos, 2014, pp. 5–15)
[59] (Todorovic et al., 2014, pp. 1345–1349)
[60] (Wanitwattanakosol et al., 2015, pp. 113–117)

3.2.3 Relation of Processed Information and Value-Adding-Factors

- **Processed Information – Production Worker**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Production Worker**"? → Digital Information is processed automatically by the Production Worker.

ID	Requirement	Value-Adding-Factor
R03VAF01	Processed Information: Digital Information is processed automatically	Production Worker

Abstract Implementation Concepts and Concrete Examples

30. Digital Competence

30.1. Required competences for students and professionals are customization of workflows by Industrie4.0 principles, the enhancement of products with new personalized intelligent parts, electrical and electronic self-programmed components and the control of access of product memory information, to plan in a digital engineering environment and set up of the physical factory to produce customer orders.

(Brenner and Hummel, 2016)

30.2. The next generations must have the idea and digital native know how to hardly differentiate between the virtual and real world.

(Brenner and Hummel, 2016)

30.3. Employees working in office room zones with digital tools, networked worldwide, handling the data on cloud systems, using agile project management methods, creating smart individual products and flexible intelligent factories and designing and implementing in the digital world before transferring it into the physical environment to speed up the customer delivery process.

(Brenner and Hummel, 2016)

30.4. New factories need a technically experienced, economically active IT-architecture team with a maximum overview.

(Brenner and Hummel, 2017a)

30.5. Increase of personalized products leads to changing requirements on the qualification of the workforce in production. New areas of competence must be created to face the digital age. The so-called Digital Taylorism that is a further development of the classical Taylorism is characterized by extreme standardization to reach a very high precision of processes and monitoring of workers. The workers must be given more decision-making competence to deal with the high level of standardization and rules have to be established to what degree a worker may realize changes to the product or even to the production facilities.

(Groß et al., 2017)

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31. Training Systems to improve Digital Competence

31.1. Training employees by using an immersive virtual reality (VR) hardware, the Oculus Rift video-based head mounted display for creating a realistic user experience.

(Gorecky, 2013)

31.2. Using the Microsoft VR holodesk setup in combination with real tools directly at the workspace for the assembly-training of employees to enable gesture-based interaction with an optical see through display that creates the illusion of interacting with virtual objects.

(Gorecky, 2013)

31.3. Development of a systematic knowledge platform for a training system that contains the relevant training content for employees such as geometry of parts and tools, process description, workplace information, user information and feedback data to test different assembly processes.

(Gorecky, 2013)

Derived from the following Literature

[61] (Brenner and Hummel, 2016)
[62] (Brenner and Hummel, 2017)
[63] (Gorecky et al., 2013)
[64] (Groß et al., 2017)

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[61] (Brenner and Hummel, 2016, pp. 227–232)
[62] (Brenner and Hummel, 2017, pp. 198–205)
[63] (Gorecky et al., 2013, pp. 90–97)
[64] (Groß et al., 2017, pp. 291–298)

- **Processed Information – Machinery**

Research Question: How can the requirement “**Digital Information is processed automatically**” be implemented for the value-adding-factor “**Machinery**”? → Digital Information is processed automatically by the Machinery.

ID	Requirement	Value-Adding-Factor
R03VAF02	Processed Information: Digital Information is processed automatically	Machinery

Abstract Implementation Concepts and Concrete Examples

32. Smart Device Applications

32.1. Figure 88 shows a smartphone-based system architecture to acquire, process and control the data from an industrial manipulator by a smart device for remote maintenance services that consists of the following components:

- Industrial manipulator machine with on-board electronics
- Gateway that routes the information from the machine to the smart device and vice versa
- Smart device to acquire the information from the gateway and all the other sensors on board, to process the data, to transfer the information from the “field” to a global network and to set-up and control the machine
- Service manager that collects all the information from the devices and executes the corrective actions

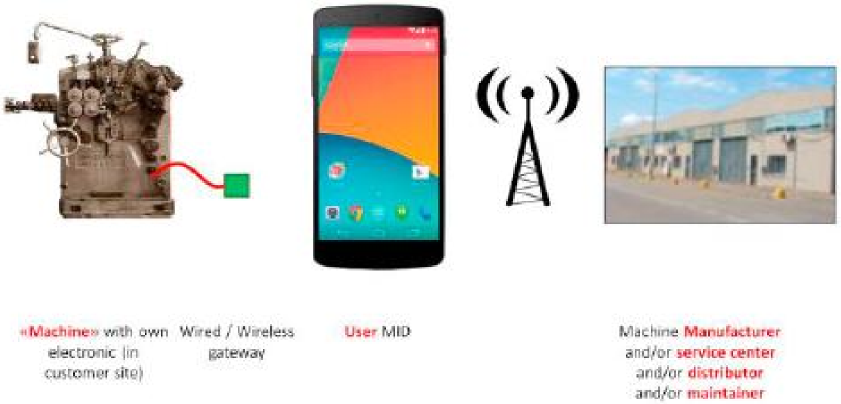

Figure 88: System architecture for an industrial manipulator

The electronic architecture of the machine consists of a power supply board, a motor control board and a command board that exchange data information through a CAN backbone. The communication gateway is realized by a microcontroller that manages the CAN communication by a

CAN bus interface to get the entire data stream from the machine. The gateway also interacts with a semi-autonomous radio module, based on the communication standard IEEE 802.11b/g by using a Wi-Fi protocol for the connection with the smartphone.

The firmware for the gateway is made for setting up, managing the different communication interfaces and linking the smartphone with the operating data. The smart device application is android-based and written in Java. The user makes a video of the machine problem and the remote transmits the video and operational data from the machine via e-mail with a log attached.

(Cologni et al., 2015)

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33. Internet-based Prognostics and Operations Systems

33.1. Condition-based maintenance (CBM) through data acquisition (DAQ) unit that can be installed on the machine equipment to acquire historical machine data, data from the embedded sensors and data about the working condition.

The data is then sent to the reconfigurable prognostics platform (RPP) that integrates hardware and software and uses information technology, communications and data analysis to evaluate and predict the performance of the equipment through a toolbox called Watchdog Agent® (see Figure 89). The toolbox Watchdog Agent® converts the machine data in health functions in real-time and compares them with historical ones, evaluates data and information of machine health and defines the optimization plans.

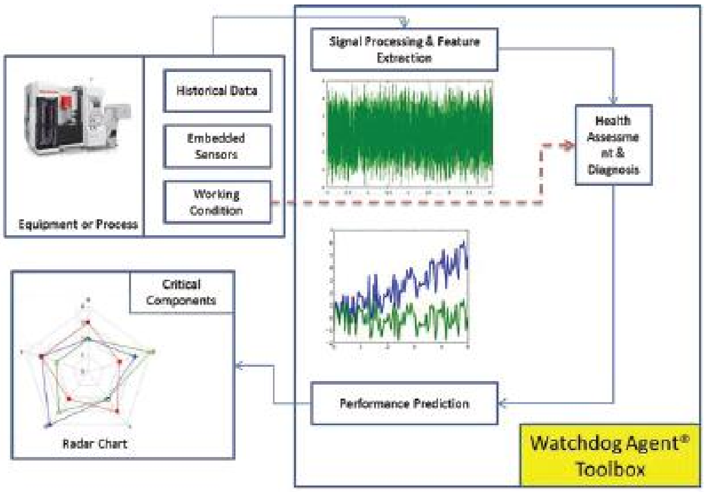

Figure 89: Flowchart of the Watchdog Agent®

(Tedeschi, 2015)

33.2. Implementation of remote diagnostics where the service communicates with the machine control over modem, ISDN or Internet, analyses the control system and repairs it immediately to reduce machine downtime. Such a system called TeleService and TNCdiag PC-based software to perform quick and simple remote diagnosis including the CNC control system, the inverter system and the driving motors is offered by Heidenhain.

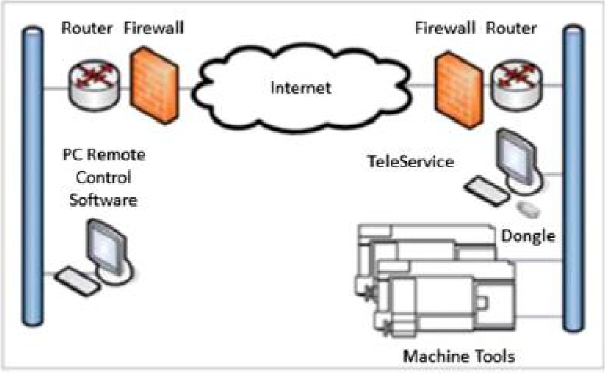

Figure 90: Connection of TeleService with the remote-control software. *From Heidenhain.*

Figure 90 shows the connection of the TeleService software with the remote-control PC that enables remote monitoring and operation of a CNC control system that is connected to the network.

There is also the possibility to implement the Visual Setup Control shown in Figure 91 that allows the monitoring of the current setup or machining situation during CNC program run by conducting of an optical comparison of the actual with the desired condition. If there is a deviation the control system reacts.

Figure 91: Camera-based monitoring system. *From Heidenhain.*

(Grzesik, 2017b)

33.3. Development of remote maintenance (see Figure 92) and machining operation monitoring (see Figure 93) services by machine builder DMG Mori where the communication systems are based on LAN network and Internet. If an error occurs an e-mail describing the details of the alarm will be sent to the Service Center from Mori Advanced Programming Production System where the service personnel remotely diagnoses the cause and quickly provide a solution for machine recovery, deliver replacement parts or service personnel.

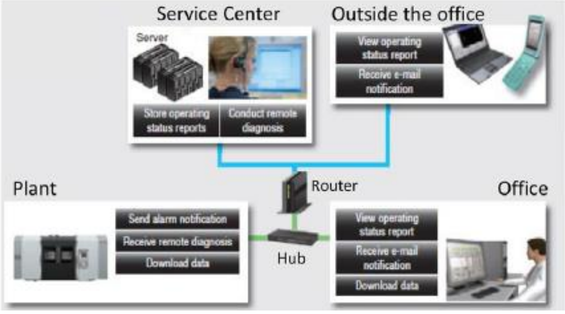

Figure 92: Remote maintenance system by Mori

As shown in Figure 93, using the Machine Operational Monitoring System, the operating status of all machine tools can be centrally managed via LAN network in real-time.

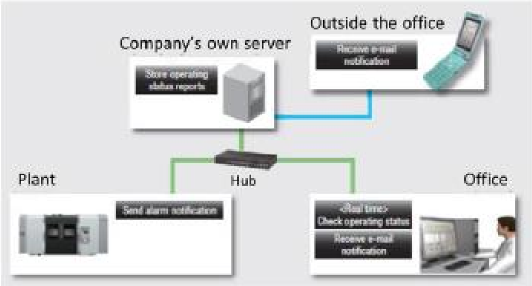

Figure 93: Machine operation monitoring system by Mori

To enable remote access to industrial equipment via Internet a server provider (SP), a service receiver (SR) and the Internet as a communication medium (CM) between the SP and the SR is required as shown in Figure 94.

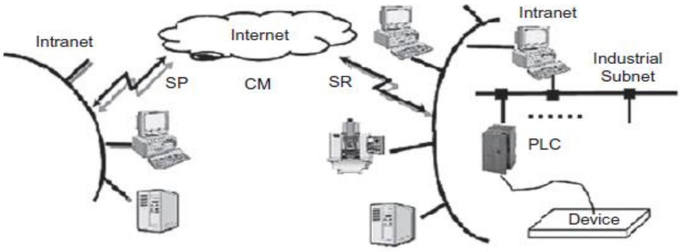

Figure 94: Internet-based remote teleservice

To insure system security and speed, a hierarchical communication network is built to involve enterprise intranet and various industrial subnets into the communication medium system in the local SP and SR sides. The result is a trial communication network system integrated into the global Internet, existing intranet and the to-be-built industrial subnet was designed.

(Grzesik, 2017b)

33.4. Intelligent manufacturing system (IMS) (see Figure 95) in which an artificial satellite-based global communication network is used to connect the office with a CAD/CAM design center, intelligent production cell and intelligent production management system represented by the autonomous distributed manufacturing system via host computer. The IMS also involves other activities such as product distribution and interactive communication with outside subcontractors.

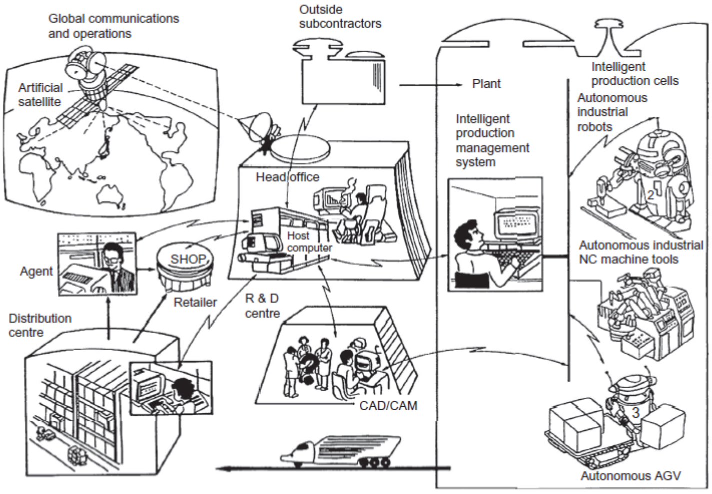

Figure 95: Intelligent manufacturing system

(Grzesik, 2017b)

33.5. Development more modular and flexible control and operations systems that enable seamless data communication and even can combine earlier separated business models. A future control architecture from ExxonMobil is shown in Figure 96. Their future control system should be built of distributed control nodes (DCN) that are dedicated single-channel I/O modules with control capability connected to a real-time data service bus. The devices can be everything that the control system is connected to, such as measurement devices e.g. sensors and analyzers as well as actuating devices.

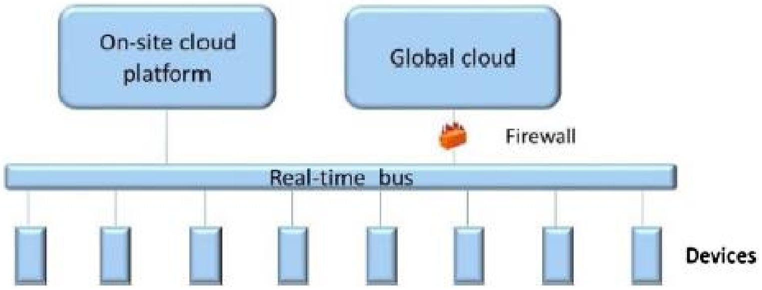

Figure 96: ExxonMobil control architecture

(Isaksson et al., 2017)

33.6. Development of a system to enable a self-optimizing cutting process using learning process models to determine the optimal process parameters with a numerical optimization.

A Sauer Ultrasonic 10 5-axis machine tool is connected to a computer, which runs a Virtual Planner via Ethernet. The Virtual Planner is responsible for storing the process data, making it available for the analyses and selecting the cutting parameters based in the knowledge that can be extract from previous processes. The used target value is the geometric deviation that is measured with an integrated machine tool probe DMG PP-400 and then transferred to the Virtual Planner using an NC-based communication routine realized with variables (R-parameters) on the machine control, which can be read and written by the NC-program as well as by applications running on the machine tool. To get access to the machine data a DDE interface is used. The continuously changing information like the axis values are streamed using TCP sockets and the static variables as the geometric deviation are transferred with HTTP requests. During the machining the simultaneous material removal simulation CutS is deployed to determine effective cutting conditions, such as depth of cut, width of cut and material removal rate. The streamed axis values are directly assigned to the virtual machine tool to mirror the real process and the original tool trajectory. Because of this, the simulation adds further information to the data stream and dynamic processes with changing process conditions can be applied to the learning algorithms.

As shown in Figure 97, all the data is centralized and aggregated by the Virtual Planner that stores the received process data using the high throughput, write speed optimized database Cassandra.

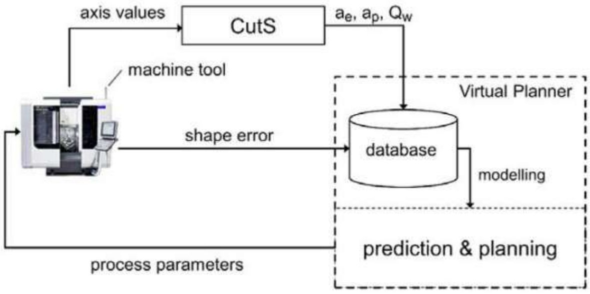

Figure 97: System architecture including the Virtual Planner

The system for the connection between the machine tool and the Virtual Planner can also be used for a large number of machine tools in a large-scale production to realize a complete automation of data capturing, data storing, modeling, optimizing and machining.

(Denkena et al., 2016b)

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34. Machine-embedded Hardware

34.1. Figure 98 shows the multitask machining center by Mazak equipped with the Mazatrol Matrix CNC and an internet information terminal called e-tower. The e-tower plays the role of an information center for setup support, maintenance support, manuals and work scheduling.

Figure 98: Multitask machining center Integrex e-type equipped with an internet information terminal (e-tower)

To make the machining center a cyber production module, which can be used independently or integrated into an advanced cyber factory developed by Mazak, the information terminal (e-tower) features a comprehensive range of IT (see Figure 99):

- Management functions: Information of the machine, such as current machine operation status or job status can be monitored in an office or off-site and the machine operator has a large amount of information.

- Work scheduling: The jobs that have to be performed can be transferred to the machine from an office-PC to inform the machine operator.
- Mobile messenger: The machine status can be monitored by using a smartphone.
- Setup support: The monitor screen can display cutting test of a workpiece feature that is hard to see as well as machine manuals.
- Image transmission: The display shows pictures of machining performance or the status of machine units, such as the tool changer.
- Fingerprint identification system: To ensure that only authorized operators can operate the machine.

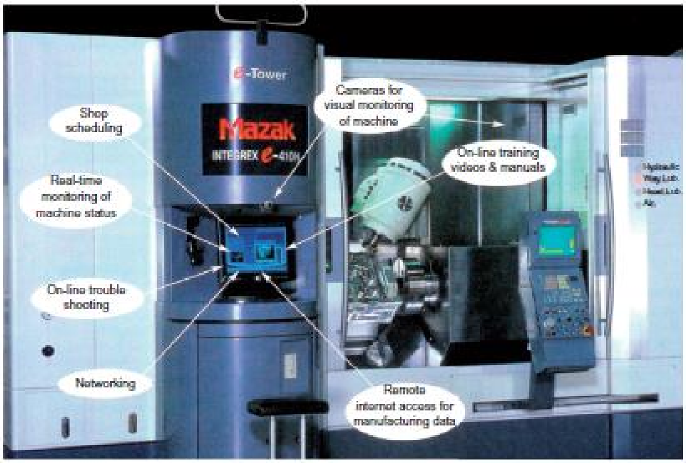

Figure 99: Functions if information of the e-tower

(Grzesik, 2017b)

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35. Computer Hardware Integration and Cloud Data Management

35.1. Concept for decentralized data analytics in the production environment where the basic elements are the single-board computers such as Raspberry Pi, MEMS (Micro Electro Mechanical System) vibration sensors and IoT communication technologies.

A smart sensor network, that contains a number of nodes and is based on single-board computers and low-cost MEMS vibration sensors, is installed in production systems to realize this concept. A MEMS vibration sensor is mounted at each critical machine component such as a ball screw for data acquisition that are processed using a single-board Computer Raspberry Pi. The data acquisition and processing run at the sensor node level and only the results calculated at the sensor node are submitted to a data management system of a cloud server wirelessly, where the information from each node is combined to provide the condition of the production system including each component. Different services that are based on the data analysis in the cloud can be provided for various stakeholders involved in the production such as maintenance operators via smart mobile devices.

*) Source of the Machine Tool:
Schaudt Mikrosa GmbH
CMMS: Computerized Maintenance Management Systems

Figure 100: Decentralized data analysis using smart sensor network

Figure 100 shows a solution for decentralized data analysis in the production environment based on the above described system to analyze acquired sensor data close to the components to be monitored in a production system. The system can act as a sensor network and can be used for condition monitoring application at machines in the production to enable predictive maintenance. The ZigBee protocol is used for communication that enables the data exchange between each sensor node and the gateway.

Communication architecture: Figure 101 shows the communication architecture of the centralized data analysis in the production environment. MEMS vibration sensors and a single-board Raspberry Pi Zero represent a sensor node of the implemented sensor network and are used to realize the data acquisition.

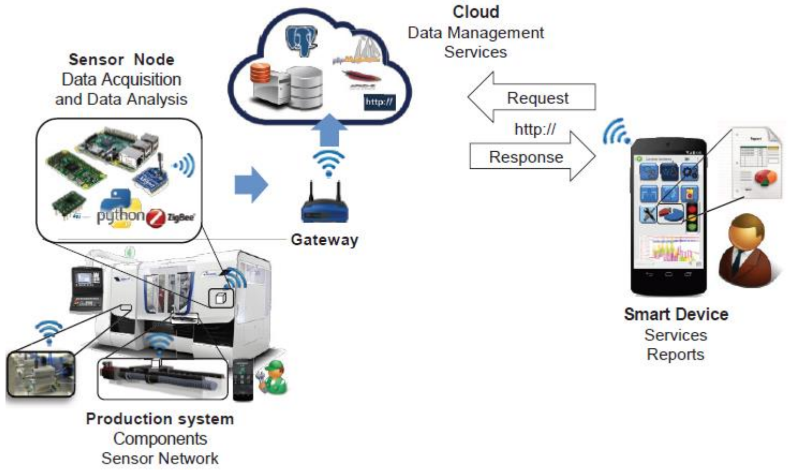

Figure 101: Communication architecture of the centralized data analysis

After the data acquisition several steps of data analysis are performed on the sensor node level and the results are then transmitted to the cloud server, where a PostSQL data base system for data management is implemented. The communication between each sensor node and the cloud server is realized using a ZigBee protocol which is a Machine-to-Machine (M2M) communication protocol based on IEEE 802.15.4 standard that offers mechanisms for encryption and authentication of the transmitted data. To realize the communication between mobile devices and the cloud server a HTTP (Hypertext Transfer Protocol) is used which allows data visualization and reporting on the smart devices from different providers.

Experimental setup: The experimental setup was performed on an axis test rig that is part of a centerless grinding machine to generate vibration data of different failure conditions on the ball screw using a MEME sensor LIS3DH (see Figure 102).

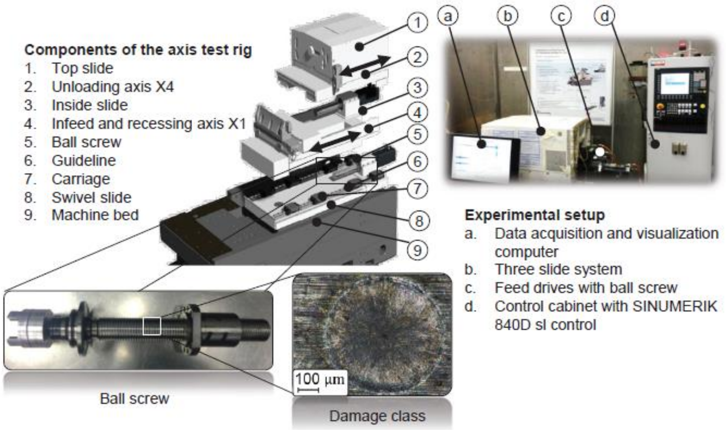

Figure 102: Experimental setup of the centralized data analysis

(Uhlmann et al., 2017)

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36. Computer Hardware Integration

36.1. Real-time monitoring for drilling bolt-holes on a 5-axes machining center MIKRON UCP1050 that is equipped with a SIEMENS Sinumerik 840D controller. The process data origination from the NC of the Sinumerik 840D is collected by an OPC-Server (Object linking and embedding for process control) is processed in an experimental setup. Comparing OPC data logging and fieldbus data logging with respect to the data quality was performed.

OPC data logging: The process data representing effective spindle power, torque of the spindle, the effective power of the feed drive and the NC-sequences were collected by an OPC server installed on the machine-tool controller SIEMENS Sinumerik 840D under the shell of WinXP-SP2. The data was then transmitted to a client-PC for further processing via LAN. OPC provides a universal mean for the exchange of data between different hardware without the need to know the exact internal design of each device. The test configuration for OPC data logging is shown in Figure 103 by providing a common bi-directional abstraction level.

Figure 103: Test configuration OPC data logging

Fieldbus data logging: Fieldbus systems are used to connect different devices on different command levels (e.g. actors, sensors and controllers) with numerical controllers and workstations on the so-called master level with one serial connection. A logging client is installed on to the topology of the profibus in the machine tool for configuration of the machine tool for the fieldbus data logging. To realize data storage and transmission a small embedded PC was installed. The test configuration is shown in Figure 104.

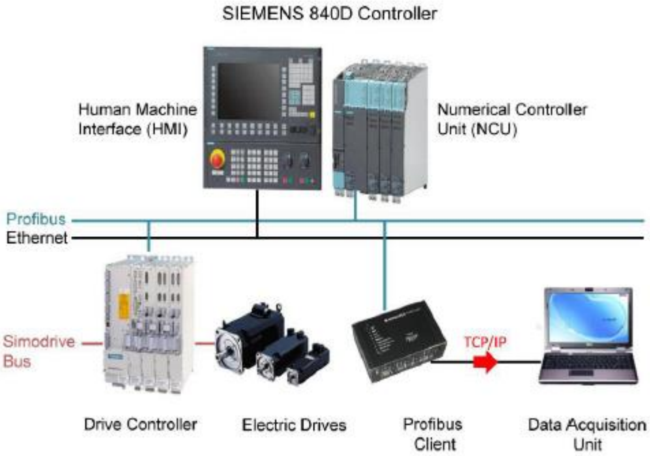

Figure 104: Test configuration fieldbus data logging

(Eckstein et al., 2015)

36.2. Development of industrial big data analytics for maintenance and service innovations for sawing machine tool to process and analyses machine data, evaluate the health condition of critical components and predict upcoming failures. In the connection level (see Figure 105), data is acquired from machines through both add-on sensors and controller signals. In addition, acoustic emission, temperature and current sensors, 20 control variables such as blade speed have been pulled out of the PLC controller and the data is processed in the industrial computer connected to each machine.

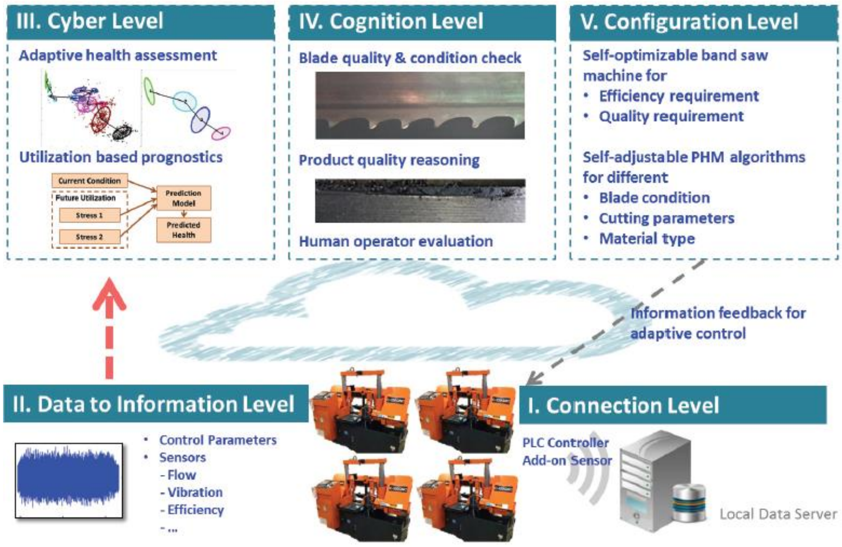

Figure 105: Cyber Physical System setup for band saw machines

In the conversion level, the computer performs feature extraction and data preparation that consists of extracting conventional time-domain and frequency domain features. These calculated features along with other machine state data is being sent through Ethernet or Wi-Fi network to the cloud server.

In the cyber level, the adaptive clustering method is performed on the cloud server to segment the blade performance history (from when a new blade was installed to now).

In the cognition level, the health stages can be further utilized and in the configuration level for optimization purposes. To help decision-making processes, Web and iOS-based user interfaces have been developed so that the health information of each connected machine tool can be accessed in real-time by computers or mobile devices (see Figure 106).

Figure 106: User interface for machine health information

(Lee et al., 2015)

36.3. See Concrete Implementation Concept Example Number 4.3.

36.4. See Concrete Implementation Concept Example Number 5.1.

36.5. See Concrete Implementation Concept Example Number 6.2.

36.6. See Concrete Implementation Concept Example Number 83.1.

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37. Processor Monitoring Systems

37.1. See Concrete Implementation Concept Example Number 4.2.

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38. Prognostics Software Systems

38.1. See Concrete Implementation Concept Example Number 6.1.

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39. **CNC and PLC Control System Integration**

39.1. See Concrete Implementation Concept Example Number 7.1.

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40. **Embedded Cyber-Physical System**

40.1. See Concrete Implementation Concept Example Number 8.1.

40.2. See Concrete Implementation Concept Example Number 68.1.

Derived from the following Literature

65 (Tedeschi et al., 2015)
66 (Grzesik, 2017b)
67 (Isaksson et al., 2017)
68 (Uhlmann et al., 2017)
69 (Denkena et al., 2016b)
70 (Eckstein et al., 2015)
71 (Lee et al., 2015)
72 (Cologni et al., 2015)

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[65] (Tedeschi et al., 2015, pp. 47–52)
[66] (Grzesik, 2017b, pp. 505–531)
[67] (Isaksson et al., 2017)
[68] (Uhlmann et al., 2017, pp. 1120–1126)
[69] (Denkena et al., 2016b, pp. 221–226)
[70] (Eckstein et al., 2015, pp. 227–232)
[71] (Lee et al., 2015, pp. 3–7)
[72] (Cologni et al., 2015, pp. 822–827)

- **Processed Information – Tools**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Tools**"? → Digital Information is processed automatically by the Tools.

ID	Requirement	Value-Adding-Factor
R03VAF03	Processed Information: Digital Information is processed automatically	Tools
Abstract Implementation Concepts and Concrete Examples		

41. Processor Monitoring System

41.1. See Concrete Implementation Concept Example Number 4.2.

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42. CNC and PLC Control System Integration

42.1. See Concrete Implementation Concept Example Number 7.2.

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43. Built-in Micro Computer Hardware

43.1. See Concrete Implementation Concept Example Number 9.2.

43.2. See Concrete Implementation Concept Example Number 9.6.

43.3. See Concrete Implementation Concept Example Number 10.1.

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44. Personal Computer Hardware Integration

44.1. See Concrete Implementation Concept Example Number 11.3.

44.2. See Concrete Implementation Concept Example Number 11.4.

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45. Network Platform

45.1. See Concrete Implementation Concept Example Number 115.2.

Derived from the following Literature

- **Processed Information – Mounting Device**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Mounting Device**"? → Digital Information is processed automatically by the Mounting Device.

ID	Requirement	Value-Adding-Factor
R03VAF04	Processed Information: Digital Information is processed automatically	Mounting Device
Abstract Implementation Concepts and Concrete Examples		
46. **Built-in Micro Computer Hardware** **46.1.** See Concrete Implementation Concept Example Number 15.1. **46.2.** See Concrete Implementation Concept Example Number 15.2. ------------ **47.** **Personal Computer Hardware Integration** **47.1.** See Concrete Implementation Concept Example Number 15.2.		
Derived from the following Literature		

- **Processed Information – Measuring & Test Device**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Measuring & Test Device**"? → Digital Information is processed automatically by the Measuring & Test Device.

ID	Requirement	Value-Adding-Factor
R03VAF05	Processed Information: Digital Information is processed automatically	Measuring & Test Device

Abstract Implementation Concepts and Concrete Examples

48. Web-enabled Operation Systems

48.1. Web-enabled, real-time quality assurance for machining production systems based on the integration of two manufacturing open specifications, namely MTConnect and Quality Measurement Results (QMResults).

Figure 107 shows the system architecture of the MTConnect standard where an "MTConnect Device" is a component that provides data. The main part of MTConnect is the "Agent", which is a process that acts as a bridge between a "MTConnect Device" and a "Client Application". The "MTConnect Agent" receives data from the "MTConnect Device" and transports standardized XML data to the "MTConnect Client" that is linked with the Internet.

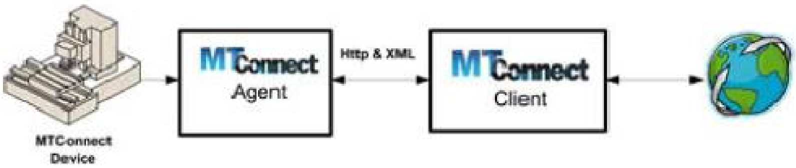

Figure 107: Overview MTConnect

The system architecture of the components that were used to realize the web-enabled, real-time quality feedback is shown in Figure 108. The system uses a machine tool located in the CNC machine shop that also has a multi-directional touch-trigger probe to perform the part inspections. After the probing the CNC outputs the measured featured value and the dimensional differences.

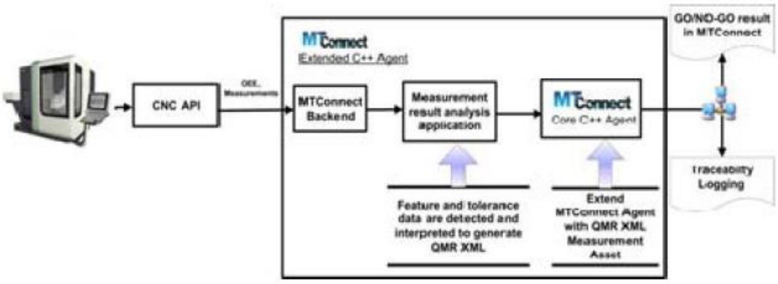

Figure 108: System architecture of the quality feedback system

To enable the real-time feedback the CNC was connected to the Internet via MTConnect, as already mentioned. To integrate the various software components the so called MTConnect Institute was used that provides an opensource C++ Agent implementation. Within the Agent an MTConnect Back-end adapter was embedded to communicate with the CNC using the open-architecture communication technology OPC to retrieve measurement results.

(Michaloski et al., 2013)

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49. Computer Hardware Integration and CNC Control System

49.1. See Concrete Implementation Concept Example Number 14.1.

49.2. See Concrete Implementation Concept Example Number 18.1.

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50. On-Machine 3D Touch Probing and CNC Control System

50.1. See Concrete Implementation Concept Example Number 16.1.

50.2. See Concrete Implementation Concept Example Number 16.2.

50.3. See Concrete Implementation Concept Example Number 16.3.

50.4. See Concrete Implementation Concept Example Number 16.4.

50.5. See Concrete Implementation Concept Example Number 16.5.

Derived from the following Literature

[73] (Michaloski et al., 2013)

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[73] (Michaloski et al., 2013, pp. 332–339)

- **Processed Information – Furniture**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Furniture**"? → Digital Information is processed automatically by the Furniture.

ID	Requirement	Value-Adding-Factor
R03VAF07	Processed Information: Digital Information is processed automatically	Furniture
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Processed Information – Logistics Worker**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Logistics Worker**"? → Digital Information is processed automatically by the Logistics Worker.

ID	Requirement	Value-Adding-Factor
R03VAF09	Processed Information: Digital Information is processed automatically	Logistics Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Logistics Worker" can be found in the matching model box with the **ID R03VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Processed Information – Conveying Device**

Research Question: How can the requirement “**Digital Information is processed automatically**” be implemented for the value-adding-factor “**Conveying Device**”? → Digital Information is processed automatically by the Conveying Device.

ID	Requirement	Value-Adding-Factor
R03VAF10	Processed Information: Digital Information is processed automatically	Conveying Device

Abstract Implementation Concepts and Concrete Examples

51. Built-in Micro Computer Hardware

51.1. See Concrete Implementation Concept Example Number 20.1.

51.2. See Concrete Implementation Concept Example Number 21.1.

51.3. See Concrete Implementation Concept Example Number 22.1.

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52. Computer Hardware Integration

52.1. See Concrete Implementation Concept Example Number 140.4.

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53. PLC Control System Integration

53.1. See Concrete Implementation Concept Example Number 142.1.

Derived from the following Literature

- **Processed Information – Conveying System**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Conveying System**"? → Digital Information is processed automatically by the Conveying System.

ID	Requirement	Value-Adding-Factor
R03VAF11	Processed Information: Digital Information is processed automatically	Conveying System
Abstract Implementation Concepts and Concrete Examples		
54. Computer Hardware Integration **54.1.** See Concrete Implementation Concept Example Number 23.1. ------------ **55. Programmable Logic Controllers (PLC)** **55.1.** See Concrete Implementation Concept Example Number 113.1.		
Derived from the following Literature		

- **Processed Information – Warehouse Worker**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Warehouse Worker**"? → Digital Information is processed automatically by the Warehouse Worker.

ID	**Requirement**	**Value-Adding-Factor**
R03VAF13	Processed Information: Digital Information is processed automatically	Warehouse Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Warehouse Worker" can be found in the matching model box with the **ID R03VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Processed Information – Warehouse Facility**

Research Question: How can the requirement “**Digital Information is processed automatically**” be implemented for the value-adding-factor “**Warehouse Facility**”? → Digital Information is processed automatically by the Warehouse Facility.

ID	Requirement	Value-Adding-Factor
R03VAF14	Processed Information: Digital Information is processed automatically	Warehouse Facility
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Processed Information – Loading Aid**

Research Question: How can the requirement "**Digital Information is processed automatically**" be implemented for the value-adding-factor "**Loading Aid**"? → Digital Information is processed automatically by the Loading Aid.

ID	Requirement	Value-Adding-Factor
R03VAF16	Processed Information: Digital Information is processed automatically	Loading Aid
Abstract Implementation Concepts and Concrete Examples		
56. Micro-Processor **56.1.** See Concrete Implementation Concept Example Number 110.1.		
Derived from the following Literature		

3.2.4 Relation of Provided Information and Value-Adding-Factors

- **Provided Information – Production Worker**

Research Question: How can the requirement “**Digital Information is provided automatically**” be implemented for the value-adding-factor “**Production Worker**”? → Digital Information is provided automatically to the Production Worker.

ID	Requirement	Value-Adding-Factor
R04VAF01	Provided Information: Digital Information is provided automatically	Production Worker

Abstract Implementation Concepts and Concrete Examples

57. Mobile Devices – Screen

57.1. Generating multimedia-based work instructions, for production workers at the assembly stations by means of film sequences and their screenshots with marking in the work instructions App, visualized on mobile tablet-pc`s.

(Brenner and Hummel, 2016)

57.2. Situation-dependent variable visualization of key figures based on past, forecast and real-time data for digital decentralized shop floor meetings via the interactive free moving Microsoft Surface Hub 84”.

(Brenner and Hummel, 2017a)

57.3. Visualization of maintenance instructions on smartphones at the ESB Logistics Learning Factory at Reutlingen University.

(Brenner and Hummel, 2017a)

57.4. Visualization of disruption and quality information on the workplace tablet at the ESB Logistics Learning Factory at Reutlingen University.

(Brenner and Hummel, 2017a)

57.5. Reuse of relevant data from virtual validation to implement a web-based worker information system (WIS) that enables a 3D-visualization of manual assembly steps and standard information to safely assemble a power electronic unit.

(Fischer et al., 2015)

57.6. Hypermedia information system for assisting shop floor workers in performing machine maintenance. An application called MyAID aims the user to identify the fault and solve the fault once it has been detected. MyAID runs on a tablet or a panel PC and on a smartwatch allowing the worker to control the troubleshooting application via a hands-free gesture-based interaction.

(Villani et al., 2016b)

57.7. See Concrete Implementation Concept Example Number 32.1.

57.8. See Concrete Implementation Concept Example Number 34.1.

57.9. See Concrete Implementation Concept Example Number 35.1.

57.10. See Concrete Implementation Concept Example Number 36.2.

57.11. See Concrete Implementation Concept Example Number 84.1.

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58. Augmented Reality – See-trough Display

58.1. Augmented Reality in aircraft manufacturing to overlay diagrams on real-world objects during aircraft manufacturing operations with a see-through head-mounted display device.

(Yew et al., 2016)

58.2. Augmented Reality for augmenting an exoskeleton wearing teleoperator`s vision, which is restricted by the exoskeleton, with a view of the remote environment.

(Yew et al., 2016)

58.3. Provided information and visual output as text or 3D graphics provided by an augmented reality interface for production workers with a head-mounted display that allows the machinist to inspect the design features of a product or part individually by interacting directly with the 3D model and allows the user to hide and show specific parameters of the product and the machine, such as dimensions, tolerances, machine information, etc. (see Figure 109).

Figure 109: Augmented reality interactive 3D model

(Yew et al., 2016)

58.4. Visualized real-time sensor data and animated graphical maintenance instructions of smart machining objects for the maintenance personnel with a head-mounted display that are imposed directly on the actual machine parts to provide easy to understand guidance (see Figure 110).

Figure 110: Augmented Reality user interface machining context (left) and maintenance context (right)

(Yew et al., 2016)

58.5. Using AR glasses (Vuzix star 1200 XL) and handheld devices (Apple iPod) for truck assembly where the operator can be guided through a 3D content by the AR glasses and additionally with the handheld device to navigate through the process steps and provide feedback during the process (see Figure 111).

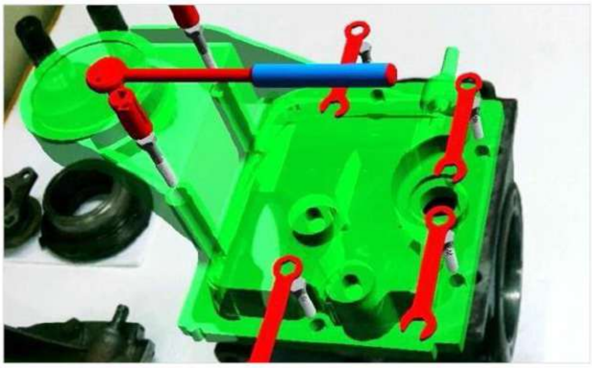

Figure 111: AR glasses assistance system

(Pintzos et al., 2014)

58.6. See Concrete Implementation Concept Example Number 136.2.

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59. Wearable Devices – Screen

59.1. The bracelet-Microsoft Band is equipped with a huge number of sensors (Heart Rate, Accelerometer, Gyroscope, Ambient light sensor, GPS, Distance, Pedometer, UV, Capacitive Sensor, Microphone, Calories, Barometer, Altimeter). There is also a current sensor on the skin to collect information such as blood pressure, sweat rate and the skin temperature. To provide the worker with information the bracelet has a display (see Figure 112) and can vibrate in nine different ways.

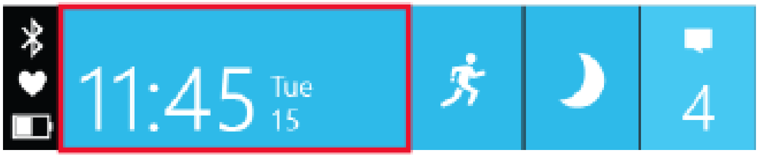

Figure 112: Display of the Microsoft Band

<u>**Provide information to remind the worker of job fatigue:**</u> By using the collected information from the current sensor of the skin and the heart rate sensor in the band the fatigue degree of the worker can be monitored. If the pulse pressure is out of scope the band reminds the worker to stop work immediately by sending a message on the bands display and by vibration to avoid fatigue. When the heart rate is beyond the normal value the band reminds the worker to continue his work in the same way.
<u>**Provide information to supervise the workers work range:**</u> Usage of the GPS sensor in the band to collect information about the workers real-time position. If the worker leaves work area the band will send a vibration alert as well as a message that the worker must go back to work as soon as possible.

(Fan et al., 2017)

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60. Visual Assistance Systems –Screen

60.1. Web-based worker information system (WIS) for a manual assembly workstation to graphically present necessary data like two 3D models of a tool that represent target and actual position on a monitor (see Figure 113).

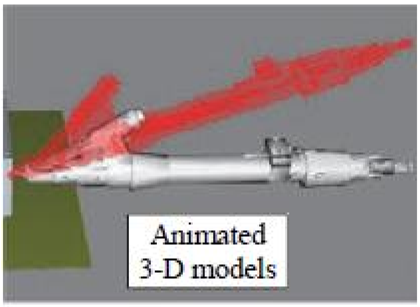

Figure 113: Visualization of target (red) and actual (grey) comparison for localization of a screwdriver embedded into WIS

(Fischer, 2016)

60.2. Assistance system with a user interface is implemented via an HTML5-based GUI in order to display as many contents as possible regardless of the particular device and operating system. The devices that can be used are tablets, but smart watches can also be used. The assistance system offers different kinds of information for the user like information on the process (e.g. instruction with text, videos, photos, augmented reality overlay) which is only displayed if the performance of the task is required. On the other hand, the assistance system offers information about the process and sensor values and operating numbers concerning the process.

(Prinz et al., 2017)

60.3. See Concrete Implementation Concept Example Number 34.1.

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61. Visual Assistance System – Light Guidance

61.1. Light-guided worker information system, more precisely pick-by-light that uses signal lights to inform about positions for removal or storing of components and provide the necessary worker information via these light signals.

(Lušić et al., 2016)

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62. Audio Assistance System – Voice Guidance

62.1. Usage of an acoustic WIS like Pick-by-Voice to inform about positions for removal or storing of components via voice signals.

(Lušić et al., 2016)

62.2. Realization of a worker information system with audio and vibration feedback. If there is an error or a special event on the assembly line the user could be notified by a special audio or vibration signal of the smartphone or the tablet PC to react faster to the event. After this signal he can look on the display of the smartphone or the tablet to analyze the problem.

(Kollatsch et al., 2014)

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63. Augmented Reality – Screen

63.1. Realization of worker support by using a display on which a live RGB video stream is shown. The different states of the support function that is using a display attached to the assembly work station are depicted in Figure 114 and Figure 115. By using the two-dimensional video stream of the camera, the current situation of the assembly steps is displayed in real-time.

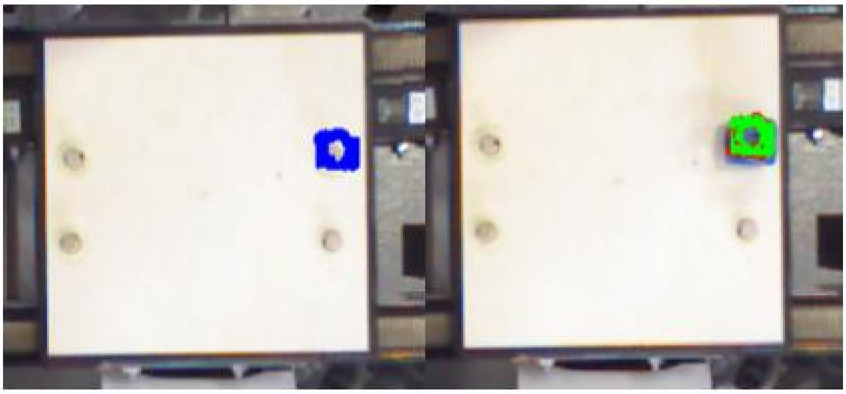

Figure 114: Worker support system - awaiting assembly part (left) and correct assembly (right)

The video is processed by a software to create and show different colored overlays to fill the video with information about the current assembly step. The position on which a part is expected in the current assembly step is colored blue. Due to this information the worker can easily see, where he needs to assemble the part. When the worker assembled the correct part in the correct orientation and position the overlay changes its color to green and if failures are made the color changes to red.

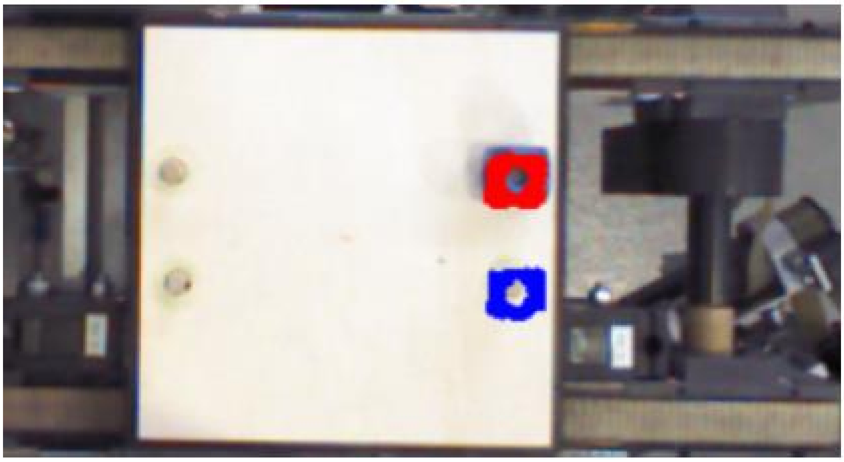

Figure 115: Worker support system - failure in assembly recognized

This worker support system helps the worker to deal with an increased number of variants and in addition he is able to recognize assembly failures at an early stage.

(Kaczmarek et al., 2015)

63.2. See Concrete Implementation Concept Example Number 118.1.

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64. Virtual Assistance System – Projection Mapping

64.1. Mixed reality assistance system, also called projection mapping technology, that provides virtual assistance to the operator by projecting instructions onto the workstation environment. The set-up consists of a projector mounted in a fixed position over the assembly workstation for manual assembly of business card holders. The projector pictures the next assembly step and the position of the parts directly onto the workstation (see Figure 116).

Figure 116: Projection mapping technology - virtual assistance system

(Rodriguez et al., 2015)

64.2. Equipment of a manual business card holder assembly workstation with an assistance system and a recognition system (see Figure 117).

Figure 117: Assistance system and recognition system of a manual assembly workstation

The assistance system provides real-time instructions streaming on a screen in front of the operator and it was also extended with the projection mapping solution so that the instructions can now be visualized directly on the workplace and the operator be assisted in a natural way. The workflow recognition system determines the actual work context during operations, e.g. If the operation has been finished, the recognition system automatically displays the next assembly step. To make the projection mapping instructions realistic a beamer was used and positioned over the assembly area so that it can cover the required projection mapping area (workstation, part and tool) and the image perspective view was adjusted according to the operator's angle/point of view. Autodesk 3DS MAX The 3D software was used for the 3D modelling and rendering. The used communication protocol to allow the interaction among computers and other multimedia devices, optimized for networking technology was the Open Sound Control (OSC) protocol.

The recognition system consists of a Microsoft Kinect that gathers the information about the environment and movements and integrates this information to the assistance system. The running Java code determines when the operator finished an assembly step and the assistance system sends a command for projecting the next step to the

(Rodriguez et al., 2015)

64.3. Worker information system that uses projections directly onto the workplace and a tablet that shows step-by-step assembly instructions (see Figure 118) as well as a smartwatch (Figure 119) to request an expert by touching the appropriate icon on the watch for high variances in assembly of battery modules is shown in.

Figure 118: Worker information system for battery module assembly

Figure 119: Worker information system smartwatch

(Vernim and Reinhart, 2016)

64.4. Development of a system that consists of a standard assembly workbench equipped with a projector placed above the worker and foot pedals to enable switching to the next task step. The projection highlights the boxes with task relevant parts and shows the assembly instruction steps (see Figure 120). For tracking the hands movements, a Polhemus system was used, which generates a magnetic field and delivers marker positions with respect to the magnetic transmitter position.

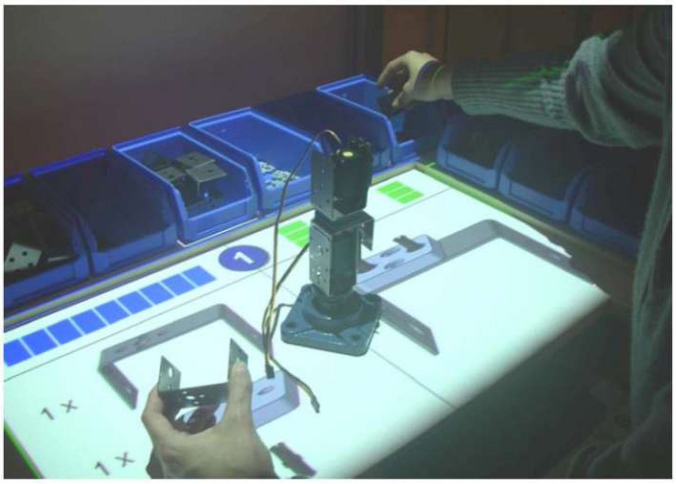

Figure 120: Projector-based assembly station

(Stork and Schubö, 2010)

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65. Mobile Devices – Augmented Reality

65.1. Usage of mobile devices such as an iPad, iPhone and PC tablet and a head-mounted display (HMD) as the platform to enable augmented reality. **BIM (Building Information Modelling) + AR Context-aware Mobile System:** Development of a set of functionalities that can dynamically trigger the augmented models into mobile devices by tracking the barcode and QR (see Figure 121). By scanning a barcode attached to each component, the system can demonstrate the menu on top, which can be customized by the users to show them as much information (e.g. information of component location, fabrication, design, attribute list of the component and so on). The users can view the attributes of any objects such as pipe, screw, connector, or reducer and at the same time they can see the AR components. By clicking these AR components, the conjoint components will pop up, so that the users know what should be assembled then. The users can also report a problem and organize a meeting to figure out solutions.

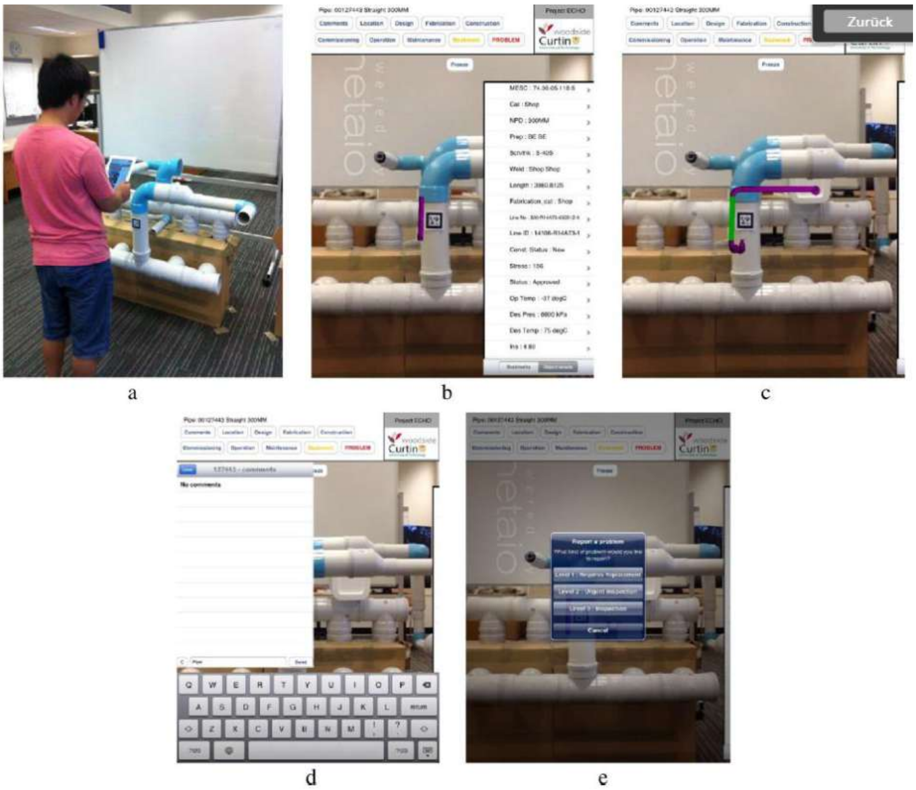

Figure 121: BIM + AR context aware mobile systems

BIM + AR for Onsite Assembly: Simulating the installation sequences visually in the real scale and right in the real context using AR-based animation. Figure 122 shows the step by-step installation sequence of a piping skid in a real scale through augmented reality. The system is created based in the AR toolkit where the hardware includes HD7200 Logitech Camera and Vuzix1200 Head Mounted Display (including C910 HD Logitech Camera) and 60 Inch TV.

Figure 122: BIM + AR Onsite Assembly

BIM + AR for Way-finding: Indoor BIM-based navigation technology that is integrated with AR which helps construction workers to easily find out where the exact component is located in a warehouse by the use of the mobile devices GPS. As an example, a scenario of finding a valve is shown here. A box containing a valve with an RFID tag on has arrived at the warehouse and the material coordinator doesn't know where it is because all the boxes at the warehouse look the same. He inputs the valve number into the iPad interface ant then scans a reference marker at the entrance of the warehouse (see Figure 123 left) and then follows a green arrow (see Figure 123 right) shown on the iPad screen with the valve ID and the estimated distance from the entrance to the location of the box.

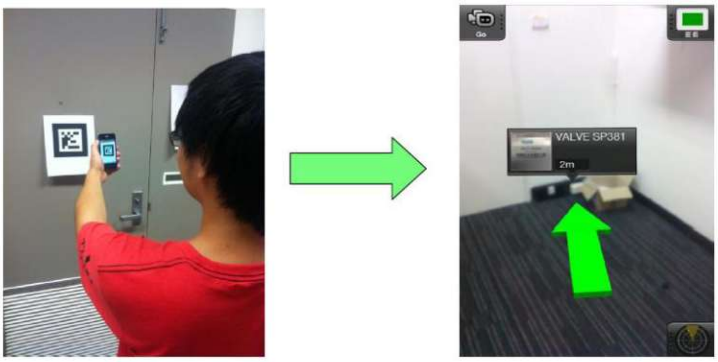

Figure 123: AR-based way finding

(Wang et al., 2014)

65.2. 2D Graphical User Interface (GUI) elements on a tablet PC that gives a clear view of the process data to the user is shown in Figure 124.

Figure 124: Process data visualization on a tablet PC

The visualization shows the single process steps in a sorted sequence of information fields with text and figures and warnings and erroneous elements.

(Kollatsch et al., 2014)

65.3. See Concrete Implementation Concept Example Number 154.1.

Derived from the following Literature

[74] (Brenner and Hummel, 2016)
[75] (Brenner and Hummel, 2017, pp. 198–205)
[76] (Fischer et al., 2015)
[77] (Yew et al., 2016)
[78] (Fan et al., 2017)
[79] (Fischer et al., 2016)
[80] (Lušić et al., 2016)
[81] (Kaczmarek et al., 2015)
[82] (Prinz et al., 2017)
[83] (Rodriguez et al., 2015)
[84] (Villani et al., 2016)
[85] (Wang et al., 2014)
[86] (Vernim and Reinhart, 2016)
[87] (Kollatsch et al., 2014)
[88] (Pintzos et al., 2014)
[89] (Stork and Schubö, 2010)

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[74] (Brenner and Hummel, 2016, pp. 227–232)
[75] (Brenner and Hummel, 2017, pp. 198–205)
[76] (Fischer et al., 2015, pp. 65–70)
[77] (Yew et al., 2016, pp. 43–55)
[78] (Fan et al., 2017, pp. 425–432)
[79] (Fischer et al., 2016, pp. 242–247)
[80] (Lušić et al., 2016, pp. 1113-1118)
[81] (Kaczmarek et al., 2015, pp. 1–6)
[82] (Prinz et al., 2017, pp. 159–166)
[83] (Rodriguez et al., 2015, pp. 327–333)
[84] (Villani et al., 2016, pp. 277–282)
[85] (Wang et al., 2014, pp. 96–105)
[86] (Vernim and Reinhart, 2016, pp. 510–515)
[87] (Kollatsch et al., 2014, pp. 246–251)
[88] (Pintzos et al., 2014, pp. 132–137)
[89] (Stork and Schubö, 2010, pp. 320–328)

- **Provided Information – Machinery**

Research Question: How can the requirement "**Digital Information is provided automatically**" be implemented for the value-adding-factor "**Machinery**"? → Digital Information is provided automatically to the Machinery.

ID	Requirement	Value-Adding-Factor
R04VAF02	Provided Information: Digital Information is provided automatically	Machinery

Abstract Implementation Concepts and Concrete Examples

66. **Interfaces**

66.1. Implementation of a concept in the research project APPsist that was tested in the LPS Learning Factory. The APPsist system is constructed as a service-oriented architecture where the individual services fulfill their tasks independently and are linked to one another by a clearly defined interface. The whole system is linked to the infrastructure of the learning factory via the machine information service and collects operating and machine data via the OPC interface.

(Prinz et al., 2017)

66.2. See Concrete Implementation Concept Example Number 33.6.

66.3. See Concrete Implementation Concept Example Number 68.1.

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67. **Interface Modules**

67.1. See Concrete Implementation Concept Example Number 6.1.

67.2. See Concrete Implementation Concept Example Number 7.1.

67.3. See Concrete Implementation Concept Example Number 83.1.

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68. **Digital Communication Protocols**

68.1. CPS (Cyber Physical System) that consists of many sensors and instruments which follow different communication protocols, various communication data format. To simplify the data collection and management, a CPS-oriented middleware is created which is a kind of software system that can integrate the components of CPS (see Figure 125).

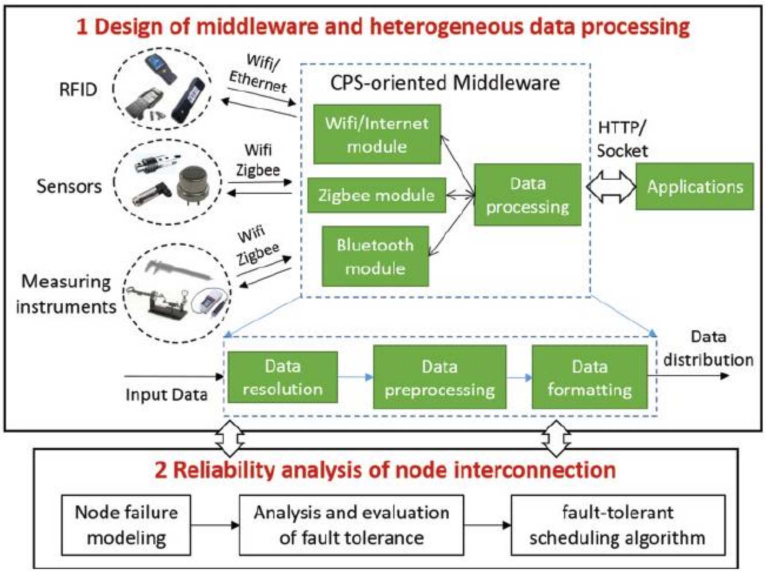

Figure 125: CPS-oriented middleware

The CPS-oriented middleware is a connection between the bottom sensors and the upper applications. The communication between the sensors and the middleware is realized directly through WIFI, Ethernet, zigbee or Bluetooth, and the middleware communicates with the upper applications through HTTP or SOCKET protocol after preprocessing of the data. The main function of the middleware is to unify data communication format.

Case Study: The case study was performed on an EMCO MILL55 that executes finish milling and drilling where the add-on CPS was implemented (see Figure 126). There are ten kinds of sensors and instruments, in which noise sensor, light intensity sensor, temperature sensor and humidity sensor are used to monitor the external environment. To monitor the state of the of the CNC machine a Janitza power sensor, an acceleration sensor and a photoelectric displacement sensor are used.

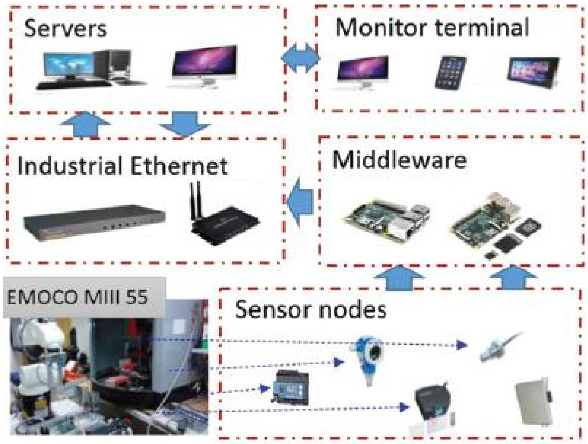

Figure 126: EMCO MILL55 add-on CPS

In addition, three RFID readers, a Vernier caliper, a digital dial gauge and a roughness tester are used to monitor the state and quality of the workpiece. To develop a middleware to integrate the gathered data, an Arduino-board is used. The industrial Ethernet is created through connecting industrial Ethernet switches and routers. Then the collected data are stored in the storage server and processed by a compute server. The results can be presented to the users through computer monitors or mobile terminals.

(Zhang et al., 2016)

68.2. Application of Programmable Logic Controller (PLC) to utilize totally integrated automation where the sequence of machine movements is controlled by a PLC that has to be complied with IEC61131 international standard and regarding communication technology also with IEC61158 and IEC62541 e.g. PROFINET and OPC UA protocol. The environment of human machine interaction is realized via smartphone.

The PROFINET protocol is an open communication protocol for industrial Ethernets built upon the standard Ethernet network. It is applied in TCP/IP and data exchange technologies and would be treated as a real-time Ethernet.

To realize smart machine, machinery and equipment must be provided with data sharing systems like PROFINET that comes with inbuilt industrial Ethernet (see Figure 127) and help decision-making processes for the operators and factory managers.

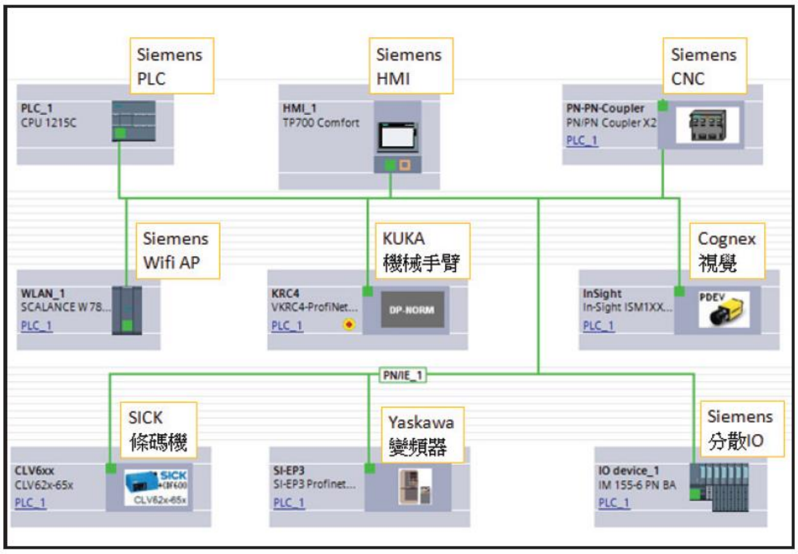

Figure 127: Totally integration automation platform

(Chen et al., 2017)

68.3. Information processing framework for high pressure die casting applications in modern manufacturing systems to face new challenges regarding planning, scheduling and analyzing of the underlying manufacturing process.

The implementation of the agile information processing system is evaluated by a use case in the Audi testing foundry. In the field level, the integration of different PLCs, sensors or serial signals into a holistic framework needs an adaptable and flexible standard and protocols like OPC-UA (Object linking and embedding for process control unified architecture) and MQTT (Message queue telemetry transport) which are upcoming solutions from the level of machine to machine communication up to the communication of World Wide Web. OPC is a standard protocol to provide a communication between PLCs and SCADA (Supervisory control and data acquisition). The MQTT protocol is also used for horizontal communication and implemented on fieldbus systems with higher latency in comparison to OPC-UA. For the case study the usage of UPC-UA was chosen.

Due to the high complexity and variety of process parameters in high pressure die casting, the different communication standards in this manufacturing domain, and the lack of information systems, make the case study ideal for refurbishing of older PLCs and the deployment of modular ICT. The initial situation is characterized by isolated solutions for information systems with different interfaces, paper-based quality acquisition and a high quantity of variant PLC and MES interfaces. To solve this challenge, the focus lies on the integration of these different interfaces into one service-based framework for foundry purposes which can be used easily for adding new components and devices. The service-oriented architecture is achieved by wrapping old systems into the framework and by creating new applications as services. To realize the communication on field level, like sensors or different PLCs, the OPC-UA standard is used to enable a fast integration methodology, linking serial signals via an OPC-UA server on an embedded device into the network. The OPC-UA clients, based on Java, are used to communicate with the embedded OPC-UA servers via Ethernet and TCP/IP which makes it possible to integrate different field level data sources into the agile information processing framework for high pressure die casting.

(Rix et al., 2016)

68.4. See Concrete Implementation Concept Example Number 35.1.

68.5. See Concrete Implementation Concept Example Number 69.1.

68.6. See Concrete Implementation Concept Example Number 83.1.

68.7. See Concrete Implementation Concept Example Number 85.1.

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69. MTConnect Standard

69.1. Securely and easily capture, transfer and analyze real-time streaming data from production machine tools to central IT systems. New CNC machines are enabled for MTConnect while many legacy machines will require hardware devices along with specific code to translate data to the MTConnect standard. Current advances in industrial communication protocols, such as in TCP/IP, MTQQ, Profinet have made it possible for shop-floor software solutions to capture streaming data.

A middleware software stack solution is presented which allows 3rd party software app integration to manufacturing machines on the shop-floor while using structured data schema.

Machine Setup and the Information Flow Diagram: The machine set-up is shown in Figure 128 and Figure 129. The process related machine data from a HAAS VF2 is stored in system variables or MACROS which are then read by an MTConnect hardware Adapter. In addition, sensory data from a Hall sensor measuring spindle power consumption and a three-axis accelerometer installed within the workpiece holding fixtures are also collected.

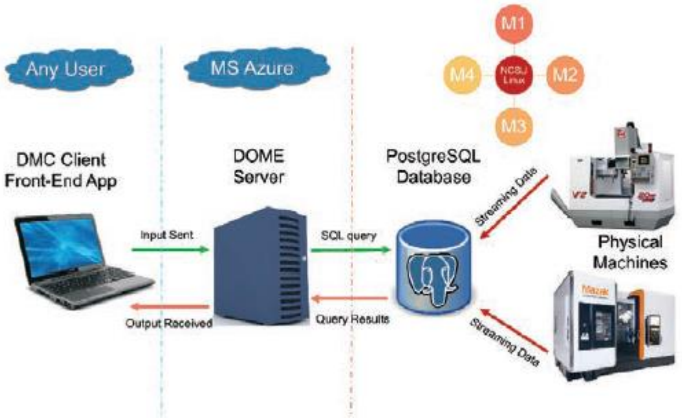

Figure 128: Information Flow from the Machine to the Client Applications

Figure 129 shows a local system that is used as the MTConnect adapter in combination with corresponding machine hardware available at the HAAS machine. Two modes were utilized of enabling legacy machines to be Ethernet compatible. For the first mode a low-cost computer was connected through the machines RS232 port. For the second mode there was no PLC or compatible ports to pull data from so a system-on-chip board such as the BeagieBone Black was utilized to directly interface with the machine control boards. In both cases, the machine data formatted through MTConnect standards was streamed through the Ethernet infrastructure to the local Database Server. The data collected by the adapter is filtered and stored in tags as defined by the MTConnect standard. Using the TCP/IP connection via the NCSU server, data is collected at a central system where it is produced as an XML output which is then pushed into relevant tables within the database.

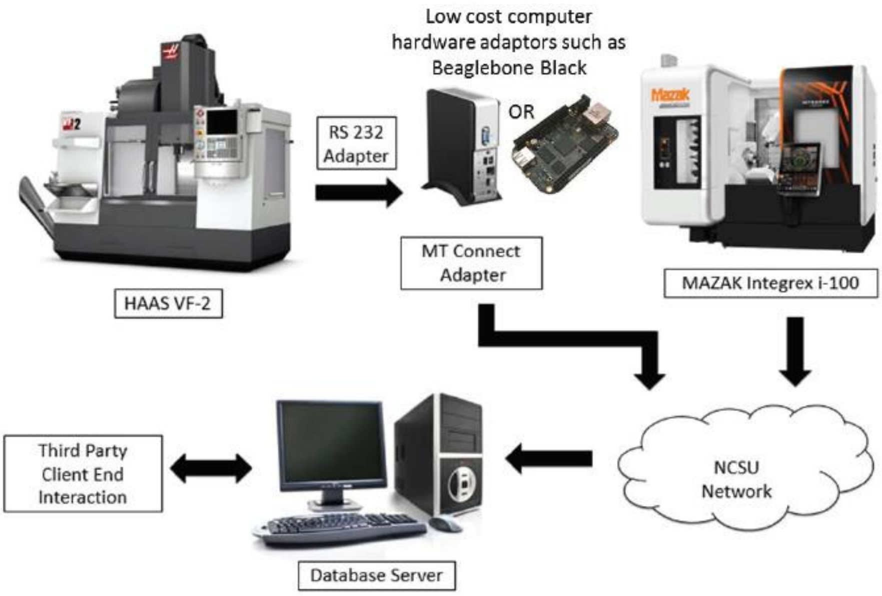

Figure 129: Detailed information flow from machine to third party client

Nachines that are MTConnect enabled like the MAZAK Integrex i-100ST can be connected directly to the network.

(Singh et al., 2017)

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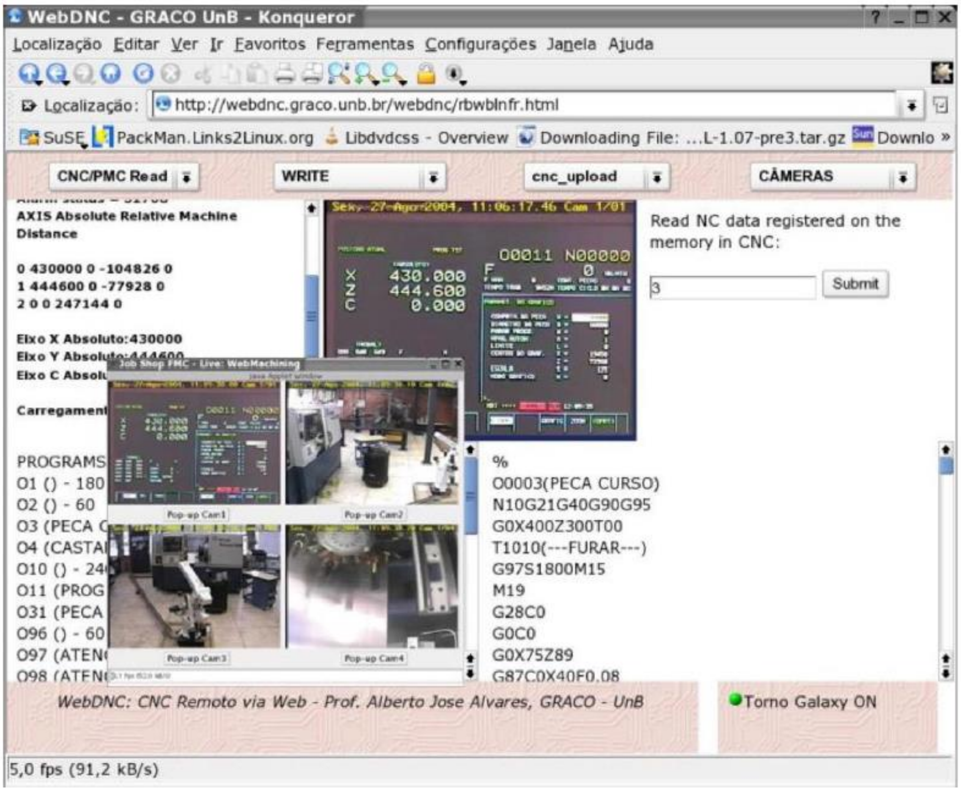
70. Interfaces and Digital Communication Protocols

70.1. Implementation of a remote manufacturing system (tele-manufacturing) called WebTurning aimed at manufacturing rotational parts in a CNC turning center (Galaxy 15M of Romi with CNC Fanuc 18i-ta). The system is split into three activities: graphical user interface (GUI) for teleoperation, WebCam for image/video capture and WebCNC for teleoperation of the CNC machine. The turning center teleoperation system is based in a client-server architecture. Three servers, represented by the system for capturing images in real time (WebCam) and programs stored in a computer with at a Linux platform, which are connected to the CNC machine tool through an Ethernet network interface and TCP/IP via the cgi-bin mechanism and intedt (WebCNC), and by the FOCAS1/DNC1 Server that is installed in the CNC 18i-ta Fanuc of the machine tool. And the clients, represented by Java Applets and HTML pages. The WebCNC teleoperation server consists of the video server and teleoperation servers of the machine that provides the command services, execution of programs, download and upload of programs, mistake proofing and other functions associated with the DNC2 communication protocol, available in CNC Fanuc 18i-TA. All the control actions are executed locally, based on the delay if the TCP/IP protocol. The video server is responsible for video and image capture using four cameras as well as for their distribution through the TCP/IP protocol.

The WebDNC graphic interface was developed based on Java and HTML (see Figure 130), from which it is possible to control the functions related to CNC, PLC and DNC.



```
AXIS Absolute Relative Machine
Distance

0 430000 0 -104826 0
1 444600 0 -77928 0
2 0 0 247144 0

Eixo X Absoluto:430000
Eixo Y Absoluto:444600
Eixo C Absolu

Carregament

PROGRAMS
O1 () - 180
O2 () - 60
O3 (PECA C
O4 (CASTAI
O10 () - 24
O11 (PROG
O31 (PECA
O96 () - 60
O97 (ATEN
O98 (ATEN
```

Read NC data registered on the memory in CNC:

3

```
%
O0003(PECA CURSO)
N10G21G40G90G95
G0X400Z300T00
T1010(---FURAR---)
G97S1800M15
M19
G28C0
G0C0
G0X75Z89
G87C0X40F0.08
```

Figure 130: WebTurning Graphical User Interface (GUI)

(Álvares and Ferreira, 2006)

70.2. Implementation of a web monitoring system and gateway for serial communication PLC. Industrial processes require interaction with the rest of the plant, being able to exchange data with other devises and monitoring systems to optimize production, reporting information and providing control capabilities to distant users. Thus, a webserver system is implemented under a Freescale microcontroller (see Figure 131), acting as a gateway for a simple PLC with single RS232 communication capabilities.

Figure 131: Freescale microcontroller board with embedded webserver and gateway

The modular webserver provides independent access to single I/O PLC locations. By combining the required I/O modules according to the required application without any change in the microcontroller programming, different webpage design can offer different monitoring capabilities. This solution enables a low cost and flexible monitoring solution to old or basic industrial processes controlled by PLC with low communication capabilities.

By using a web-browser, the system can be monitored from any internet device that is internet capable, like a PC, tablet, smartphone, etc. A case study was performed for a pneumatic PID levitation control system where a small commercial microcontroller board from Freescale, containing a M52259 Coldfire2 MCU (Micro Controller Unit) and different communication interfaces (see Figure 131) is used as a webserver and PLC gateway. The process controller is a Crouzet Millenium3 microPLC system with a single RS232 port for programming and external communication data exchange. There are two main objectives for the case study. First, the implementation of a serial RS232 communication interface for the Crouzet microPLC in order to read and write the specific PLC memory space. Second, a webserver must be running showing values read from the PLC and allowing introducing data to be written in the PLC. The general diagram of the system is shown in Figure 132.

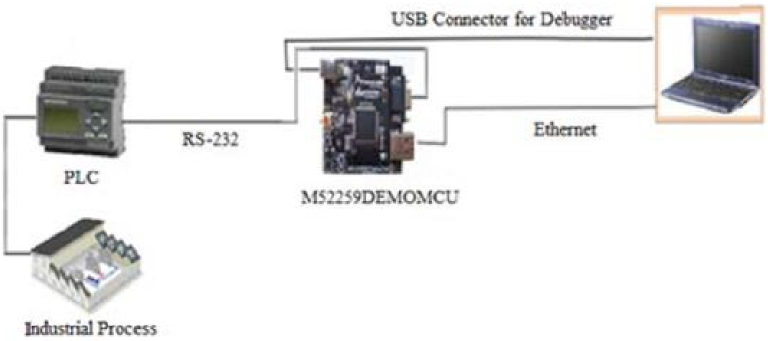


Figure 132: Diagram of the web monitoring system

(Rosado-Muñoz et al., 2012)

Presentation of an integration chain for data from field level to top-level information systems. Manufacturing Execution Systems or Enterprise Resource Planning tools are implemented in higher programming languages. Thus, the modeling of field level information hast to be adapted in terms of a semantic interpretation.
Most of the low-level production systems are based on traditional data acquisition technologies as the OPC (Object Linking and Embedding for Process Control) that is very limited in terms of connectivity to networks of higher information systems and leads to manually integration of data from field level devices. To face this problem, production environments can be equipped with novel technologies like OPC Unified Architecture (OPC-UA) standard, which makes it possible to configurate lightweight and quick connections over the internet to enable plug-and-produce capabilities.

(Hoffmann et al., 2016)

70.3. See Concrete Implementation Concept Example Number 8.1.

70.4. See Concrete Implementation Concept Example Number 8.2.

70.5. See Concrete Implementation Concept Example Number 32.1.

Derived from the following Literature

[90] (Prinz et al., 2017)
[91] (Zhang et al., 2016)
[92] (Singh et al., 2017)
[93] (Álvares and Ferreira, 2006)
[94] (Chen et al., 2017)

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[90] (Prinz et al., 2017, pp. 159–166)
[91] (Zhang et al., 2016, pp. 360–365)
[92] (Singh et al., 2017, pp. 1020–1030)
[93] (Álvares and Ferreira, 2006, pp. 251–259)
[94] (Chen et al., 2017, pp. 150–155)

[95] (Rix et al., 2016)
[96] (Rosado-Muñoz et al., 2012)
[97] (Hoffmann et al., 2016)

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[95] (Rix et al., 2016, pp. 1084–1089)
[96] (Rosado-Muñoz et al., 2012, pp. 296–301)
[97] (Hoffmann et al., 2016, pp. 496–501)

- **Provided Information – Tools**

Research Question: How can the requirement "**Digital Information is provided automatically**" be implemented for the value-adding-factor "**Tools**"? → Digital Information is provided automatically to the Tools.

ID	Requirement	Value-Adding-Factor
R04VAF03	Provided Information: Digital Information is provided automatically	Tools
Abstract Implementation Concepts and Concrete Examples		
71. Interface Modules **71.1.** See Concrete Implementation Concept Example Number 7.1.		
Derived from the following Literature		

- **Provided Information – Mounting Device**

Research Question: How can the requirement “**Digital Information is provided automatically**” be implemented for the value-adding-factor “**Mounting Device**”? → Digital Information is provided automatically to the Mounting Device.

ID	Requirement	Value-Adding-Factor
R04VAF04	Provided Information: Digital Information is provided automatically	Mounting Device Fixture Systems

Abstract Implementation Concepts and Concrete Examples

72. RFID-Technology

72.1. Automatic access or feedback of information by using RFID-technology embedded on jigs.

(Brenner and Hummel, 2016)

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73. Sensor Equipped Fixture Systems

73.1. Presentation of state-of-the-art fixture systems for the manufacture and assembly of rigid components where work holding devices, fixtures and jigs are used to construct a critical interface between a workpiece and an end-effector. The interface performs the location of the workpiece in the Euclidean space and preservation of the workpiece position against loads. Examples of such fixtures with integrated sensing technologies are given: **Hybrid fixture systems for single components:** Bringing together the sensory capabilities of the instrumented fixtures and the mechanical adaptability of conformable clamping and location systems resulting in systems with a greater capacity to cater for complex part geometries and workpiece variance, while improving part quality through adaptive process adjustments and feedback.

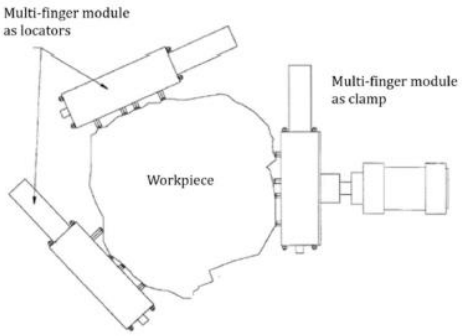

Figure 133: Modular multi-finger fixture

An example is a multi-finger modular system that combines the advantages of modularity along with automatic reconfiguration (see Figure 133). Each module consists of four fingers controlled by one motor and two mechanical systems to give the fingers a total of eight degrees-of-freedom to conform the surface of the workpiece. The different fixture configurations are achieved by combining several of the modules that are controlled by a NC system that allows direct programming and control of the fixture without the need for an external device like a robot.

Another hybrid system for the holding of prismatic components during machining operations is shown in Figure 134. The system consists of a series of modules containing intelligent hydraulic actuators that act as locating, supporting or clamping pins. Each hydraulic actuator is equipped with sensors that enable values for the displacement and reaction forces to be fed back to the control system.

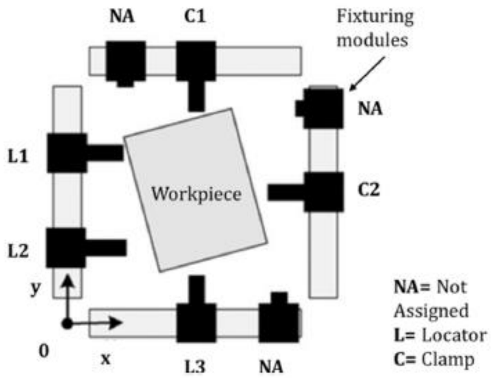

Figure 134: Active/reconfigurable fixture

Another technology is called “Swarm fixturing” that applies the long-standing biomimicry field of swarm robotics to fixturing. This concept, that is based on Parallel Kinematics Mechanism (PKM) platforms, uses multiple independent autonomous robots to achieve complex goals through cooperative group behaviors. Figure 135 (left) shows the schematic of the concept where a series of PKM agents (1) preventing the forces exerted by the cutting tool (4) from deforming the workpiece (5).

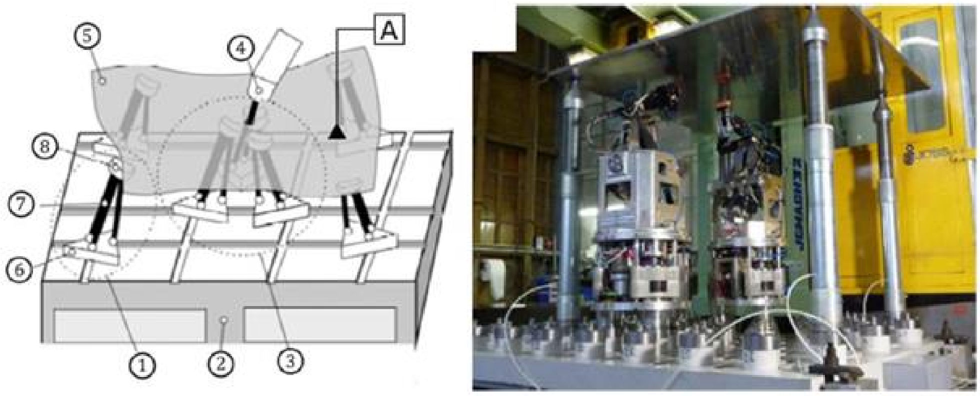

Figure 135: Swarm fixture concept (left) and prototype of the system (right)

Instrumented Fixtures: Instrumented assembly fixtures integrated with a series of optical sensors to validate correct insertion of the components into the base-plate, detect the presence of a workpiece and control the overall clamping process. The sensing scheme, as shown in Figure 136, is based on the use of a Y-guide proximity sensor (a), a v-block (b) and horizontal and vertical locators (c).

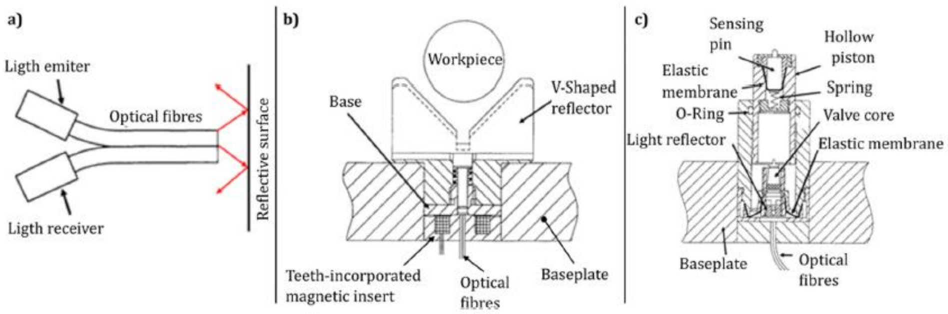

Figure 136: Schematic of the Y-Guide proximity sensor (a), smart v-block (b) and sensing vertical-locator (c)

Another use of sensors in modular fixturing for the use within a sheet metal welding process within the automotive industry is a locator for an assembly fixture that has been integrated with a Lead Zirconate Titanate (LZT) piezoelectric sensor. These sensors permitted the monitoring of the possible damage to the locator's touch surface, either by wear or fracture thus, allowing the fixture to be repaired or changed before issues permeate to impact the quality of the final assembly process.

The automatic reconfigurable fixture for the assembly of five different aero engine types within the fixture, shown in Figure 137, consists of a series of three DC servomotor actuators that generate variable clamping forces and a series of stepper motors that are responsible for the positioning of the parts.

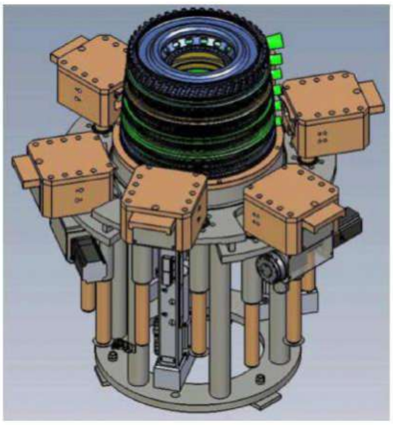

Figure 137: Reconfigurable fixture system for stack-up assemblies

These automatically reconfigurable fixtures and sensory based information allows the compensation of positioning and tolerance errors ins assembly setup using the closed-loop fixture system Metrology Assisted Assembly (MAA), which was presented as the evolution of open-loop fixtures. MAA relies on the use of metrology systems to ensure the alignment and assembly of the components.

Other embodiments of MAA include Affordable Reconfigurable Tooling (ART). ART was developed for the aircraft industries in collaboration with SAAB aero-structures aa shown in Figure 138.

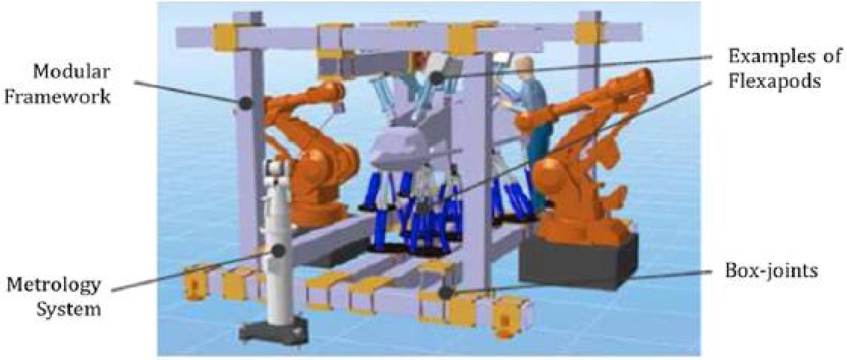

Figure 138: Affordable Reconfigurable Tooling (ART) concept

The fixture concept consists of a modular frame combined with flexapods which conform to a large variety of geometries. This concept has also been expanded upon to be used in the automotive industry through Coordinate Control Fixturing (CCF).

(Gameros et al., 2017)

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74. **MTConnect Standard**

74.1. See Concrete Implementation Concept Example Number 14.1.

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75. **Interfaces**

75.1. See Concrete Implementation Concept Example Number 15.1.

75.2. See Concrete Implementation Concept Example Number 15.2.

Derived from the following Literature

[98] (Brenner and Hummel, 2016)
[99] (Gameros et al., 2017)

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[98] (Brenner and Hummel, 2016, pp. 227–232)
[99] (Gameros et al., 2017, pp. 1–21)

- **Provided Information – Measuring & Test Device**

Research Question: How can the requirement "**Digital Information is provided automatically**" be implemented for the value-adding-factor "**Measuring & Test Device**"? → Digital Information is provided automatically to the Measuring & Test Device.

ID	Requirement	Value-Adding-Factor
R04VAF05	Provided Information: Digital Information is provided automatically	Measuring & Test Device
Abstract Implementation Concepts and Concrete Examples		
76. Interface Modules **76.1.** See Concrete Implementation Concept Example Number 16.4. ------------ **77. MTConnect Standard** **77.1.** See Concrete Implementation Concept Example Number 48.1.		
Derived from the following Literature		

- **Provided Information – Logistics Worker**

Research Question: How can the requirement "**Digital Information is provided automatically**" be implemented for the value-adding-factor "**Logistics Worker**"? → Digital Information is provided automatically to the Logistics Worker.

ID	Requirement	Value-Adding-Factor
R04VAF09	Provided Information: Digital Information is provided automatically	Logistics Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Logistics Worker" can be found in the matching model box with the **ID R04VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Provided Information – Conveying Device**

Research Question: How can the requirement "**Digital Information is provided automatically**" be implemented for the value-adding-factor "**Conveying Device**"? → Digital Information is provided automatically to the Conveying Device.

ID	Requirement	Value-Adding-Factor
R04VAF10	Provided Information: Digital Information is provided automatically	Conveying Device
Abstract Implementation Concepts and Concrete Examples		
78. Digital Communication Protocols **78.1.** See Concrete Implementation Concept Example Number 21.1. ------------ **79. Interfaces and Digital Communication Protocols** **79.1.** See Concrete Implementation Concept Example Number 140.2.		
Derived from the following Literature		

- **Provided Information – Conveying System**

Research Question: How can the requirement “**Digital Information is provided automatically**” be implemented for the value-adding-factor “**Conveying System**”? → Digital Information is provided automatically to the Conveying System.

ID	Requirement	Value-Adding-Factor
R04VAF11	Provided Information: Digital Information is provided automatically	Conveying System
Abstract Implementation Concepts and Concrete Examples		
80. Digital Communication Protocols **80.1.** See Concrete Implementation Concept Example Number 23.1.		
Derived from the following Literature		

- **Provided Information – Warehouse Worker**

Research Question: How can the requirement "**Digital Information is provided automatically**" be implemented for the value-adding-factor "**Warehouse Worker**"? → Digital Information is provided automatically to the Warehouse Worker.

ID	Requirement	Value-Adding-Factor
R04VAF13	Provided Information: Digital Information is provided automatically	Warehouse Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Warehouse Worker" can be found in the matching model box with the **ID R04VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Provided Information – Warehouse Facility**

Research Question: How can the requirement “**Digital Information is provided automatically**” be implemented for the value-adding-factor “**Warehouse Facility**”? → Digital Information is provided automatically to the Warehouse Facility.

ID	Requirement	Value-Adding-Factor
R04VAF14	Provided Information: Digital Information is provided automatically	Warehouse Facility
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Provided Information – Loading Aid**

Research Question: How can the requirement “**Digital Information is provided automatically**” be implemented for the value-adding-factor “**Loading Aid**”? → Digital Information is provided automatically to the Loading Aid.

ID	Requirement	Value-Adding-Factor
R04VAF16	Provided Information: Digital Information is provided automatically	Loading Aid
Abstract Implementation Concepts and Concrete Examples		
81. Digital Communication Protocols **81.1.** See Concrete Implementation Concept Example Number 110.1.		
Derived from the following Literature		

3.2.5 Relation of Integrated Information and Value-Adding-Factors

- **Integrated Information – Production Worker**

Research Question: How can the requirement “**Digital Information is integrated automatically**” be implemented for the value-adding-factor “**Production Worker**”? → Digital Information about the Production Worker is integrated automatically with all relevant data.

ID	Requirement	Value-Adding-Factor
R05VAF01	Integrated Information: Digital Information is integrated automatically	Production Worker

Abstract Implementation Concepts and Concrete Examples

82. Wireless Local Area Network (WLAN)

82.1. See Concrete Implementation Concept Example Number 3.1.

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83. Not suitable for this Matching-Box

83.1. Development of a system for real-time monitoring to monitor the clamping and balance condition of the mounted tool, as well of the process forces of high-speed spindle operations using infrared data transmission based on the IrDA protocol. A sensor-integrated machining spindle using thin-film sensor systems was developed to realize the system. The interface to the sensors is an analog-digital converter to allow the use of any sensor, like strain gauge, piezoelectric sensor, with the system.
Setup of the Infrared Data Transmission Unit: Figure 139 shows the setup of the unit that is based on two systems, the embedded electronics within a rotating spindle shaft and a stationary evaluation unit.

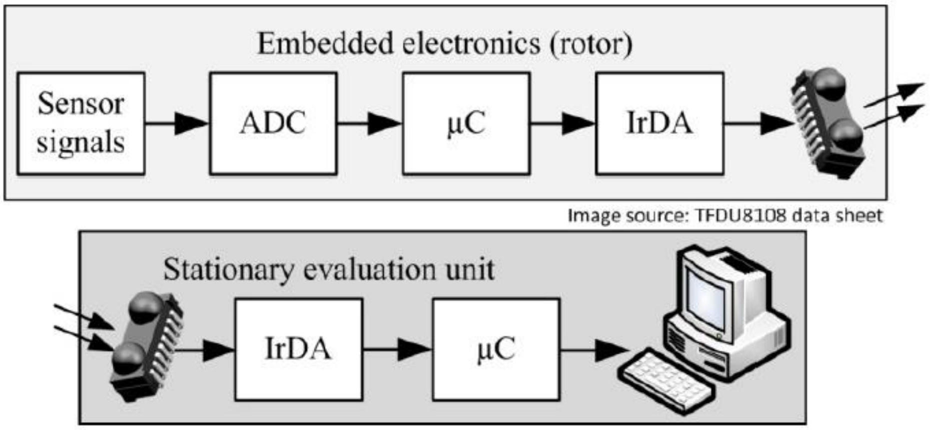

Image source: TFDU8108 data sheet

Fig. 3: Setup of the infrared data transmission unit

Figure 139: Infrared data transmission unit - setup

In the embedded electronics on the rotating part (see Figure 140), the amplified sensor signals are converted using a four channel ADC (MAX11047) that is connected to an Atmel 32-bit microcontroller (µC). The IrDA protocol controller (IPMS_IRHSP) is a separate integrated circuit used as a data streaming system using two TFDU8108 transceiver modules that are connected to the IPMS_IRHSP.

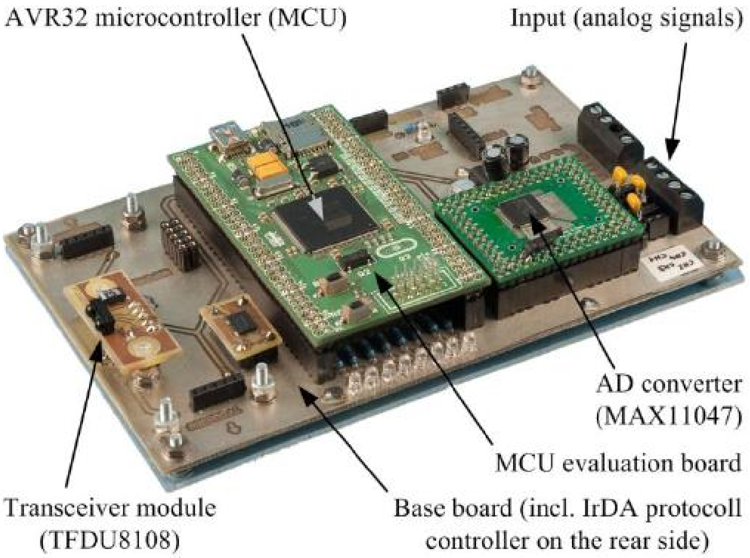

Figure 140: Evaluation board of the rotating part

On the stationary evaluation unit (see Figure 141), a more powerful microcontroller can be used to run process monitoring calculations or for data transmission using USB protocols.

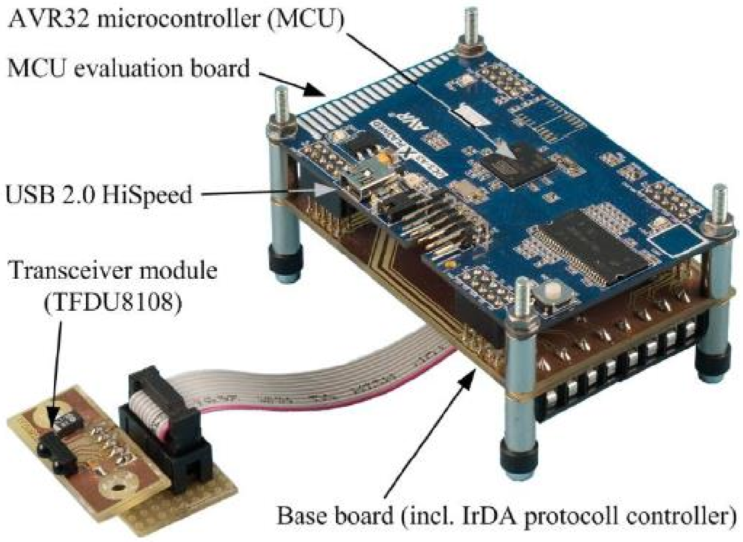

Figure 141: Evaluation board of the stationary unit

Experimental setup of the real-time monitoring system: The experimental setup of the monitoring system is shown in Figure 142. The setup consists of the basic components of the infrared data transmission unit with a more powerful microcontroller on the stationary side to carry out all required calculations within the microcontroller. The microcontroller is connected to a personal computer for visualization purposes in real-time. To investigate a continuous, contact-less data transmission from a rotating shaft to a stationary unit, the monitoring system was built into an experimental setup.

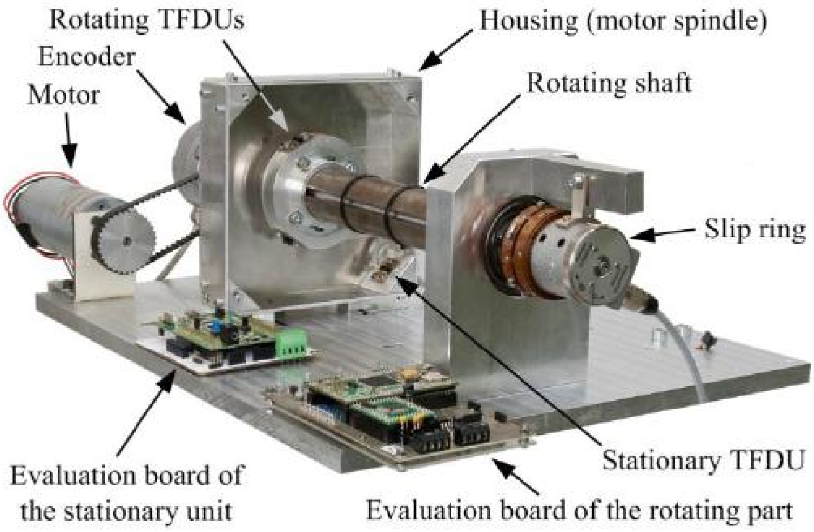

Figure 142: Experimental setup of the real-time monitoring system

(Dröder et al., 2014)

Derived from the following Literature

[100] (Dröder et al., 2014)

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[100] (Dröder et al., 2014, pp. 488–493)

- **Integrated Information – Machinery**

Research Question: How can the requirement "**Digital Information is integrated automatically**" be implemented for the value-adding-factor "**Machinery**"? → Digital Information about the Machinery is integrated automatically with all relevant data.

ID	Requirement	Value-Adding-Factor
R05VAF02	Integrated Information: Digital Information is integrated automatically	Machinery
Abstract Implementation Concepts and Concrete Examples		

84. MTConnect Adapter

84.1. Introducing a web-based machine monitoring system that provides data collection, analysis, and machine event notification by using the MTConnect standard to enable accurately and consistently data collection from any MTConnect compatible machine, regardless of its brand or origin. DMG MORI SEIKI implemented the MTConnect standard within its MAPPS HMI system and used the standardized XML output of the MTConnect Agent to build the monitoring system that collects data from the machine. They developed a solution called Messenger, which is based on the MTConnect standard which is used throughout the machine tool industry to allow access to machine tool information in a standardized way, over a TCP/IP network. All DMG MORI SEIKI machines run on an HMI called MAPPS software, which itself runs on an embedded Windows PC, and supports standard Ethernet networking. By building an MTConnect Adapter into MAPPS, DMG MORI SEIKI was able to make all machine MTConnect compatible to connect and communicate with external machine tools, computers in factory floor offices, and remote monitoring systems. The MTConnect compatible machines provide data to Messenger that analyses the data and produces graphical reports which can be viewed through any modern web browser including browsers in mobile and tablet devices. The main component of MTConnect is the MTConnect Agent which connects to devices and collects machine data. The data is then provided to a client as a standardized XML file via HTTP by the Agent. Another component is the MTConnect Adapter that allows machines containing different controller types to communicate with tan MTConnect Agent. The basic architecture of the MTConnect protocol is shown in Figure 143.

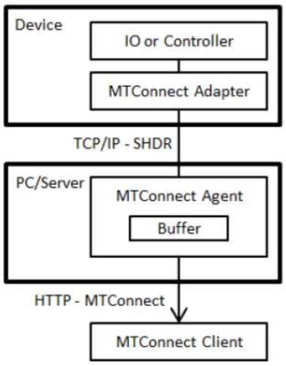


Figure 143: MTConnect architecture

The system architecture of the monitoring system is shown in Figure 144. The MAPPS HMI is responsible for communication with the machine controller and passing information from the controller to the MTConnect Adapter which then transmits this data to the MTConnect Agent running on the Messenger server. The MTConnect Agent processes the machine data and presents it in a standard XML format based on the MTConnect Standard.

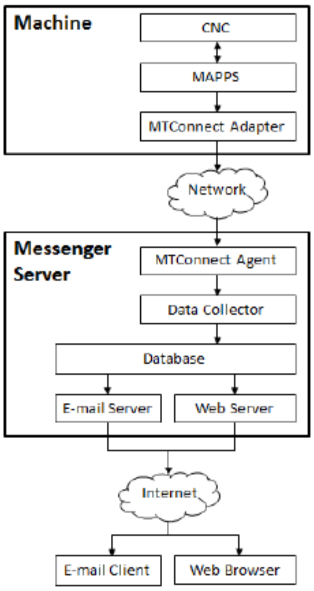
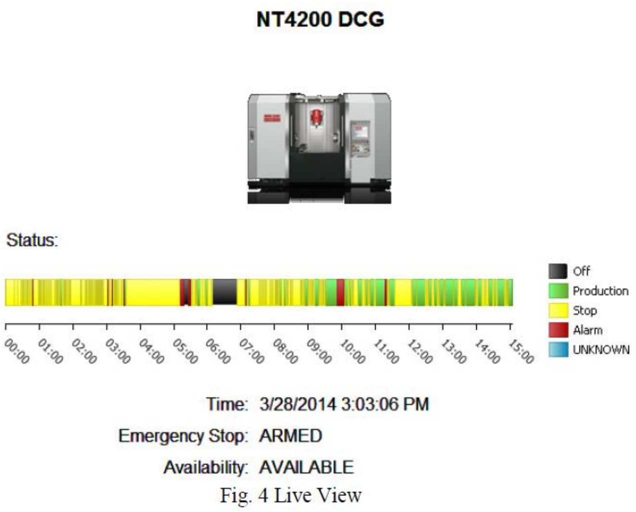


Figure 144: Monitoring system architecture

From this point the data collector reads the data from the MTConnect Agent and populates the Messenger database. This data is then queried to generate reports which can be sent via e-mail and SMS notifications to machine operators and managers.

There is also the functionality to show a History report that provides a record of each change in the controller mode including machine starts, stops, alarm states and mode changes between Automatic, Manual, etc. (see Figure 145).



Time: 3/28/2014 3:03:06 PM
Emergency Stop: ARMED
Availability: AVAILABLE

Fig. 4 Live View

Figure 145: MTConnect History Report

(Edrington, 2014)

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85. Cloud Environment

85.1. Introduction of cloud-based intuitive robot programming and program verification with the help of augmented reality. The services for path planning and localization of the robot were performed in an external cloud environment. The program generation and visualization are executed on a separate PC or Virtual Machine with a remaining control stub responsible for low level motion commands and TCP/IP communication at the machine cabinet. The user can decide between different subtasks like PLACE and PICK or MOVE and combine them to form a robot program which is then visualized on top of a camera image observing the robotic cell. A robot simulation is showing the user the planned trajectory as well as the moving 3D model of the robot during path execution, as shown in Figure 146.

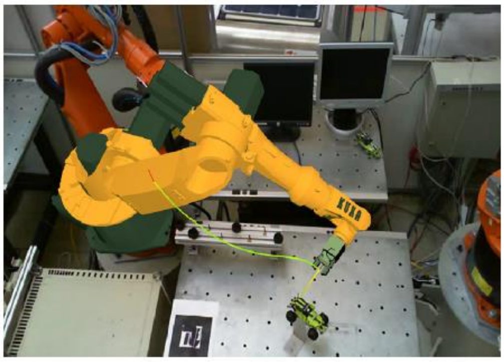

Figure 146: Intuitive task-oriented programming and verification with Augmented Reality

After verification is finished, the program is executed with the physical robot ins the same robotic cell.

(Krüger et al., 2017)

85.2. See Concrete Implementation Concept Example Number 35.1.

85.3. See Concrete Implementation Concept Example Number 36.2.

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86. Wireless Local Area Network (WLAN)

86.1. See Concrete Implementation Concept Example Number 4.3.

86.2. See Concrete Implementation Concept Example Number 6.3.

86.3. See Concrete Implementation Concept Example Number 33.2.

86.4. See Concrete Implementation Concept Example Number 34.1.

86.5. See Concrete Implementation Concept Example Number 68.1.

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87. Ethernet Connection

87.1. See Concrete Implementation Concept Example Number 6.1.

87.2. See Concrete Implementation Concept Example Number 32.6.

87.3. See Concrete Implementation Concept Example Number 36.2.

87.4. See Concrete Implementation Concept Example Number 68.1.

87.5. See Concrete Implementation Concept Example Number 68.3.

87.6. See Concrete Implementation Concept Example Number 69.1.

87.7. See Concrete Implementation Concept Example Number 70.1.

87.8. See Concrete Implementation Concept Example Number 84.1.

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88. LAN Connection

88.1. See Concrete Implementation Concept Example Number 6.2.

88.2. See Concrete Implementation Concept Example Number 33.3.

88.3. See Concrete Implementation Concept Example Number 36.1.

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89. **Satellite-based Communication Connection**

89.1. See Concrete Implementation Concept Example Number 33.4.

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90. **BUS Connection**

90.1. See Concrete Implementation Concept Example Number 33.5.

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91. **NC-based Communication**

91.1. See Concrete Implementation Concept Example Number 7.3.

91.2. See Concrete Implementation Concept Example Number 33.6.

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92. **RS232 Communication**

92.1. See Concrete Implementation Concept Example Number 69.1.

92.2. See Concrete Implementation Concept Example Number 70.2.

92.3. See Concrete Implementation Concept Example Number 93.2.

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93. **Not suitable for this Matching-Box**

93.1. Replacement of expensive conveyor and transport systems by more flexible lower-cost mobile and bin-picking robots that allow reconfigurable chaining of material transport between machines. By combining lightweight robots with mobile platforms, location flexible robot systems can provide parts provision in combination with picking and placing functions. An example of the Kuka KMR iiwa system (left) and a mobile storage solution (right) is shown in Figure 147.

Figure 147: Kuka KMR iiwa system (left) and mobile storage solution (right)

Figure 148 shows two neighboring machining centers with loading and unloading belts need to be fed with new workpieces from bins whereas machined parts need to be taken unladed from the output belt onto gratings for further processing. The handling of the workpieces is realized by an industrial robot installed on a freely navigating mobile platform.

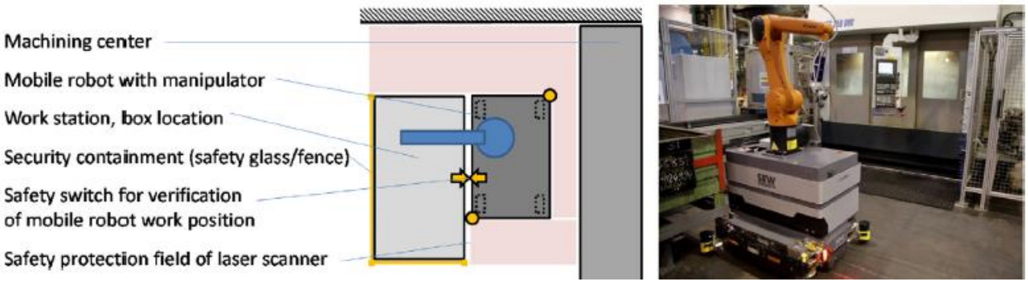


Figure 148: Mobile manipulation for machine loading/unloading

To guarantee a safety suitable layout and configuration of the mobile robot system, the robot/manipulator is equipped with a KUKA-safety controller that safely detects human entrance into defined protective fields trough two laser scanners.

(Krüger et al., 2017)

93.2. Presentation of a multimodal assembly controller (MAC) approach to embed and effectively enhance knowledge into industrial robots working in multimodal real-world scenarios such as assembly during kitting operations with varying shapes and tolerances.

The robotic test bed is formed by a six degrees of Freedom KUKA KR16 industrial robot, KRC2 robot controller, KUKA control panel, master computer, JR3 F/T sensor attached to the robot wrist and an eye-in-hand Basler 641 fc camera as shown in Figure 149.

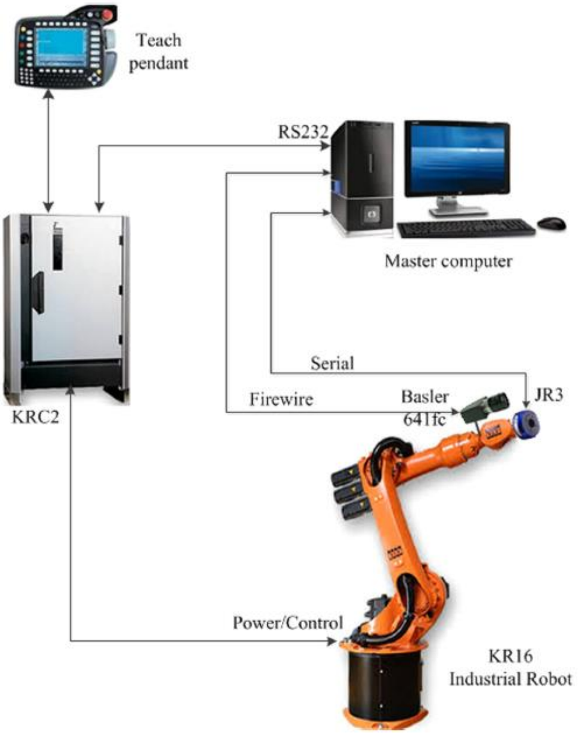
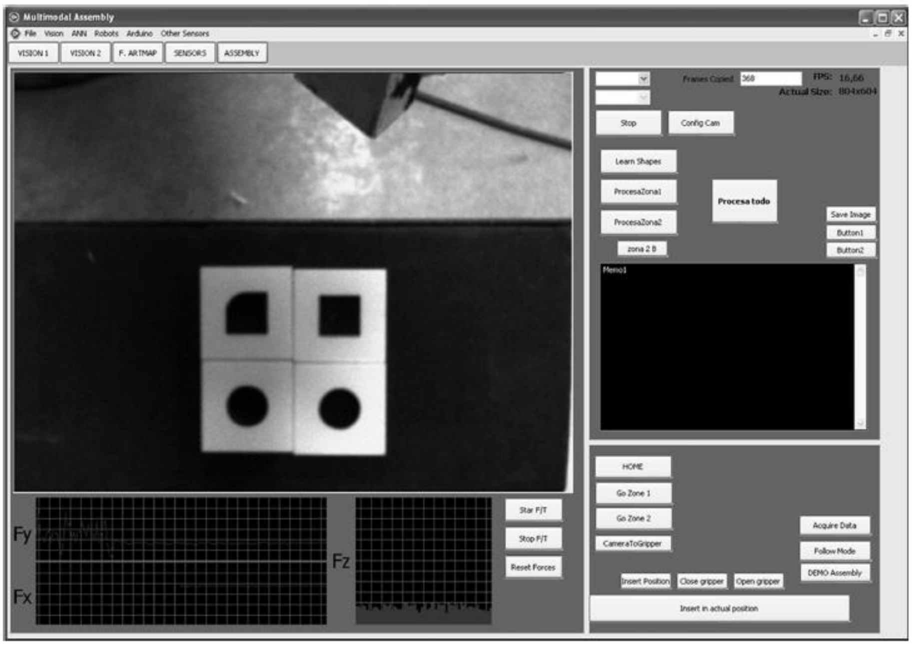


Figure 149: Robotic test bed

The KRC2 controller houses all the components that control and power the arm of the robot. The master computer hosts the DSP-based JR3 F/T sensor card that communicates with the sensor. In addition, the master computer also communicates with the robot controller via RS232C standard.

Figure 150 shows the programmed interface that shows the F/T measurements and the camera workspace are displayed. The JR3 F/T sensor measures the contact forces of the robot arm.



Frames Copied 368
FPS: 16,66
Actual Size: 804x604

Figure 150: User interface of the system

(Navarro-Gonzalez et al., 2015)

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94. Gateways

94.1. See Concrete Implementation Concept Example Number 6.3.

94.2. See Concrete Implementation Concept Example Number 32.1.

94.3. See Concrete Implementation Concept Example Number 35.1.

94.4. See Concrete Implementation Concept Example Number 70.2.

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95. Zigbee Communication

95.1. See Concrete Implementation Concept Example Number 68.1.

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96. Bluetooth Communication

96.1. See Concrete Implementation Concept Example Number 68.1.

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97. Optical Data Transmission Systems

97.1. See Concrete Implementation Concept Example Number 83.1.

Derived from the following Literature
[101] (Edrington et al., 2014) [102] (Krüger et al., 2017) [103] (Navarro-Gonzalez et al., 2015)

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[101] (Edrington et al., 2014, pp. 92–97)
[102] (Krüger et al., 2017, pp. 707–730)
[103] (Navarro-Gonzalez et al., 2015, pp. 78–89)

- **Integrated Information – Tools**

Research Question: How can the requirement "**Digital Information is integrated automatically**" be implemented for the value-adding-factor "**Tools**"? → Digital Information about the Tools is integrated automatically with all relevant data.

ID	Requirement	Value-Adding-Factor
R05VAF03	Integrated Information: Digital Information is integrated automatically	Tools

Abstract Implementation Concepts and Concrete Examples

98. Wireless Local Area Network (WLAN)

98.1. In the context of industrial internet there is a demand for connected devices like a screwdriver that is embedded into networks via cable or wireless local area network (WLAN).

(Fischer et al., 2016)

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99. Optical Data Transmission Systems

99.1. See Concrete Implementation Concept Example Number 9.3.

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100. Wireless Data Transmission Systems

100.1. See Concrete Implementation Concept Example Number 10.1.

100.2. See Concrete Implementation Concept Example Number 115.2.

Derived from the following Literature

[104] (Fischer et al., 2016)

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[104] (Fischer et al., 2016, pp. 242–247)

- **Integrated Information – Mounting Device**

Research Question: How can the requirement "**Digital Information is integrated automatically**" be implemented for the value-adding-factor "**Mounting Device**"? → Digital Information about the Mounting Device is integrated automatically with all relevant data.

ID	**Requirement**	**Value-Adding-Factor**
R05VAF04	Integrated Information: Digital Information is integrated automatically	Mounting Device
Abstract Implementation Concepts and Concrete Examples		
101. Wireless Data Transmission System **101.1.** See Concrete Implementation Concept Example Number 15.2.		
Derived from the following Literature		

- **Integrated Information – Measuring & Test Device**

Research Question: How can the requirement “**Digital Information is integrated automatically**” be implemented for the value-adding-factor “**Measuring & Test Device**”? → Digital Information about the Measuring & Test Device is integrated automatically with all relevant data.

ID	Requirement	Value-Adding-Factor
R05VAF05	Integrated Information: Digital Information is integrated automatically	Measuring & Test Device

Abstract Implementation Concepts and Concrete Examples

102. Wireless Data Transmission System

102.1. See Concrete Implementation Concept Example Number 16.2.

102.2. See Concrete Implementation Concept Example Number 16.3.

102.3. See Concrete Implementation Concept Example Number 16.4.

102.4. See Concrete Implementation Concept Example Number 16.5.

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103. Hard-Wired Data Transmission System

103.1. See Concrete Implementation Concept Example Number 16.2.

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104. Internet Connection

104.1. See Concrete Implementation Concept Example Number 48.1.

Derived from the following Literature

- **Integrated Information – Furniture**

Research Question: How can the requirement “**Digital Information is integrated automatically**” be implemented for the value-adding-factor “**Furniture**”? → Digital Information about the Furniture is integrated automatically with all relevant data.

ID	**Requirement**	**Value-Adding-Factor**
R05VAF07	Integrated Information: Digital Information is integrated automatically	Furniture
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Integrated Information – Logistics Worker**

Research Question: How can the requirement "**Digital Information is integrated automatically**" be implemented for the value-adding-factor "**Logistics Worker**"? → Digital Information about the Logistics Worker is integrated automatically with all relevant data.

ID	**Requirement**	**Value-Adding-Factor**
R05VAF09	Integrated Information: Digital Information is integrated automatically	Logistics Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Logistics Worker" can be found in the matching model box with the **ID R05VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Integrated Information – Conveying Device**

Research Question: How can the requirement “**Digital Information is integrated automatically**” be implemented for the value-adding-factor “**Conveying Device**”? → Digital Information about the Conveying Device is integrated automatically with all relevant data.

ID	Requirement	Value-Adding-Factor
R05VAF10	Integrated Information: Digital Information is integrated automatically	Conveying Device

Abstract Implementation Concepts and Concrete Examples

105. Wireless Local Area Network (WLAN)

105.1. See Concrete Implementation Concept Example Number 21.1.

105.2. See Concrete Implementation Concept Example Number 140.1.

105.3. See Concrete Implementation Concept Example Number 140.4.

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106. BUS Connection

106.1. See Concrete Implementation Concept Example Number 140.2.

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107. Wireless Data Transmission System

107.1. See Concrete Implementation Concept Example Number 142.1.

Derived from the following Literature

- **Integrated Information – Conveying System**

Research Question: How can the requirement “**Digital Information is integrated automatically**” be implemented for the value-adding-factor “**Conveying System**”? → Digital Information about the Conveying System is integrated automatically with all relevant data.

ID	**Requirement**	**Value-Adding-Factor**
R05VAF11	Integrated Information: Digital Information is integrated automatically	Conveying System
Abstract Implementation Concepts and Concrete Examples		
108. Wireless Local Area Network (WLAN) **108.1.** See Concrete Implementation Concept Example Number 23.1.		
Derived from the following Literature		

- **Integrated Information – Warehouse Worker**

Research Question: How can the requirement "**Digital Information is integrated automatically**" be implemented for the value-adding-factor "**Warehouse Worker**"? → Digital Information about the Warehouse Worker is integrated automatically with all relevant data.

<table>
<tr><th>ID</th><th>Requirement</th><th>Value-Adding-Factor</th></tr>
<tr><td>R05VAF13</td><td>Integrated Information:
Digital Information is integrated automatically</td><td>Warehouse Worker</td></tr>
<tr><th colspan="3">Abstract Implementation Concepts and Concrete Examples</th></tr>
<tr><td colspan="3">The abstract implementation concepts and concrete examples of the value-adding-factor "Warehouse Worker" can be found in the matching model box with the **ID R05VAF01**.
By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.</td></tr>
<tr><th colspan="3">Derived from the following Literature</th></tr>
<tr><td colspan="3"></td></tr>
</table>

- **Integrated Information – Warehouse Facility**

Research Question: How can the requirement "**Digital Information is integrated automatically**" be implemented for the value-adding-factor "**Warehouse Facility**"? → Digital Information about the Warehouse Facility is integrated automatically with all relevant data.

ID	Requirement	Value-Adding-Factor
R05VAF14	Integrated Information: Digital Information is integrated automatically	Warehouse Facility
Abstract Implementation Concepts and Concrete Examples		
109. Wireless Local Area Network (WLAN) **109.1.** See Concrete Implementation Concept Example Number 128.1.		
Derived from the following Literature		

- **Integrated Information – Loading Aid**

Research Question: How can the requirement "**Digital Information is integrated automatically**" be implemented for the value-adding-factor "**Loading Aid**"? → Digital Information about the Loading Aid is integrated automatically with all relevant data.

ID	Requirement	Value-Adding-Factor
R05VAF16	Integrated Information: Digital Information is integrated automatically	Loading Aid

Abstract Implementation Concepts and Concrete Examples

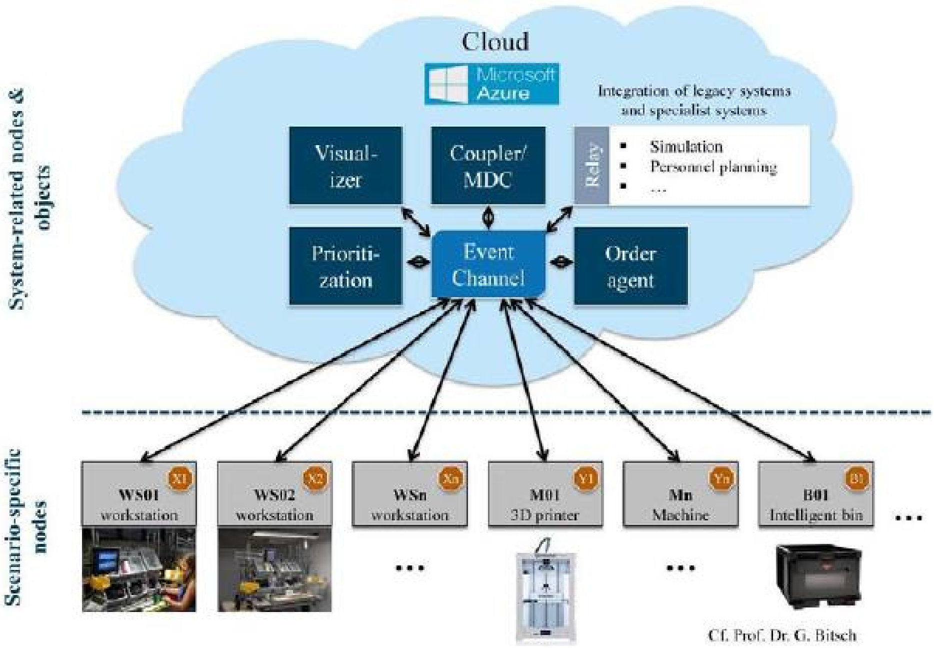
110. Cloud-based and Event-oriented Self-Execution System (SES)

110.1. Intelligent bin system to establish decentrally controlled material flow systems in value chain networks as well as the intralogistics level. These intelligent bins have to be integrated into an overall decentralized monitoring and control approach to interact with humans and other entities. To realize this system, an intelligent bin system is currently developed at the ESB Logistics Learning Factory and will be integrated into the self-developed, cloud-based and event-oriented SES (Self-Execution System) system which goes beyond the common functionalities and capabilities of traditional Manufacturing Execution Systems (MES).

At the small load carrier level, the first intelligent bins are under development or already available on the market, like the "inBin" developed by the Fraunhofer-Institute for Material Flow and Logistics (IML). This bin system is equipped with a micro-processor which adds a wireless communication module into the actual bin to make it capable of communicating and interacting with humans and machines and to make decisions autonomously. Wireless connection technologies are used to communicate with other transport units, conveyor systems, machines or software services, whereas the interaction with humans is supported by a graphical display e.g. to provide guidance for picking tasks. The "inBin" is also able to locate itself and to capture storage conditions like the temperature based on sensors.

Another example for an intelligent small load carrier for C-parts is the "iBin" developed by the company Würth Industrie Service, which uses an integrated camera to generate filling level, counting and order information on bin level enabling a real-time C-part management.

Decentralized Control System Framework: The Self-Execution-System (SES) architecture is based on an event-oriented concept enriched with a specific cloud data-storage structure for central and decentral system entities that serves as a framework for the development of control methods. Figure 151 shows a simplified structure of the SES autonomous and decentralized control approach. The SES is composed of “system-related nodes and objects” and “scenario-specific nodes” which provide different services within the production system to enable decentralized control. “Nodes” is standing for autonomous software agents providing specific services and interacting with other agents within the system.



Cf. Prof. Dr. G. Bitsch

Figure 151: SES basic structure

“System-related nodes and objects” agents cover amongst other things functionalities respectively services like order management and prioritization of production orders. “Scenario-specific nodes” for additional resources like workers, collaborative robots, workstations or intelligent bins offering specific assembly or logistics services and can be modeled and integrated in the SES.

Technical Setup: To ensure that an overall technical design is used which can be applied uniformly for all applications and can be adaptable to different purposes by specific reconfigurations, the hard- and software components were split into a common and adaptable component. The common component takes over basic functionalities that are common for all intelligent bins and consists of the layers of communication, localization and battery monitoring. For the bin location an ultrasonic based indoor location system is used. The connection to the SES via the communication layer enables message to transmit queries (of sensors) or instructions (on actuators) directly from the SES to the bin. The sensors (such as weight measurement sensors, mechanical and optical switches and inductive sensors) were selected following the requirement to capture the content of the bin. An ESP8266 microcontroller with integrated WLAN chip was

	selected and the MQTT (Message Queue Telemetry Transport) communication protocol with a JSON data was used. The interaction with humans was realized through different actuators and displays to assist the worker e.g. with picking instructions on the display and signal lights on the bin. (Schuhmacher et al., 2017)
Derived from the following Literature	
[105] (Schuhmacher et al., 2017)	

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[105] (Schuhmacher et al., 2017, pp. 135–142)

3.2.6 Relation of Object Detection and Value-Adding-Factors

As already mentioned in chapter 3.1.1 not every Matching Box makes sense and has to be checked for meaningfulness with the results, that the requirement 2.1 (R06: Physical objects are detected automatically) is covered by the requirement 2.2 (R07: Physical objects are identified automatically). Therefore, the requirement 2.1 is not considered further.

3.2.7 Relation of Object Identification and Value-Adding-Factors

- **Object Identification – Production Worker**

Research Question: How can the requirement "**Physical Objects are identified automatically**" be implemented for the value-adding-factor "**Production Worker**"? → The Physical Objects (Production Worker) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF01	Object Identification: Physical Objects are identified automatically	Production Worker

Abstract Implementation Concepts and Concrete Examples

111. RFID- and QR-Technology

111.1. Coupling the digital and the real world with the indoor localization system in the ESB Logistics Learning Factory where the worker and the production-controlled product can be located and identified at anytime and anywhere using RFID and QR technology.

(Brenner and Hummel, 2017a)

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112. Biometrical Data Identification Systems

112.1. Automatic face-detection with the Becos Apps to identify workers at the ESB Logistics Learning Factory.

(Brenner and Hummel, 2017a)

112.2. See Concrete Implementation Concept Example Number 34.1.

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113. Not suitable for this Matching-Box

113.1. RFID (radio Frequency Identification) is a wireless communication technology used to capture data linked to different identification attributes (serial number, colour, position, date of purchase, etc.) of entities carrying RFID tags. The data collection process is based on an exchange of electromagnetic waves between RFID readers and RFID tags.
Components of a RFID System: A basic RFID system consists of RFID tags fixed to entities with unique electronic product code (EPC) per entity, networked RFID readers, real-time databases and RFID antennas for information exchange between the tags wireless network and middleware/control platforms. There are two types of RFID tags, passive and active RFID tags. A passive tag is powered by the electromagnetic

energy radiated from RFID reader antenna, so it can't transmit radio waves of its own. An active tag is powered by an on-board battery to allow independent communication capability within greater range.

RFID Lab at Universite de Moncton: The RFID Lab with special focus on shop-floor automation contains the following equipment:

- IF61 smart reader (Intermec Inc.)
- ALR-9650 reader (Alien, Inc.)
- IA33A circularly polarized antennas (Intermec Inc.)
- IT65 rigid passive UHF tags (Intermec Inc.)
- ALN-9540 passive UHF Squiggle™ tags (Alien Inc.)
- RFID simpleware from BlueBean, Inc.
- Twido-40DRF programmable logic controller, and TwidoSuite language (Schneider Electric Inc.).
- Pallets and reconfigurable conveyor (FlexLink Inc.)

The overview of the RFID Lab is shown in Figure 152, with the conveyor that can be fully controlled by programmable logic controller (PLC).

Figure 152: RFID Lab at Universite de Moncton

The IA33A circular antennas are used to support the communication between the RFID tags that are fixed on pallets and the RFID readers. The IF61 RFID reader (see Figure 153) features computing and networking capabilities and is also responsible for middleware coded languages that can be executed on it, enabling it to filter, store and manipulate information received from RFID tags and direct them to the user personal computer.

Figure 153: IF61 reader linked to a user personal computer

The user personal computer is connected to the PLC to control the conveyor and its different stations.
IA33A circular antenna is installed beside each station to detect the arrived pallets and send their capture tag data to the IF61 reader where the RFID data are decoded and validated.

(Chetouane, 2015)

113.2. Definition of a standard for all objects and the respective interfaces to the software tools where every object has its own IP-address to be identified.

(Brenner and Hummel, 2017a)

Derived from the following Literature

106 (Brenner and Hummel, 2017)
107 (Chetouane, 2015)

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[106] (Brenner and Hummel, 2017, pp. 198–205)

[107] (Chetouane, 2015, pp. 382–387)

- **Object Identification – Machinery**

Research Question: How can the requirement "**Physical Objects are identified automatically**" be implemented for the value-adding-factor "**Machinery**"? → The Physical Objects (Machinery) are identified automatically.

ID	**Requirement**	**Value-Adding-Factor**
R07VAF02	Object Identification: Physical Objects are identified automatically	Machinery
Abstract Implementation Concepts and Concrete Examples		
114. IP-Address **114.1.** Definition of a standard for all objects, like machinery, and the respective interfaces to the software tools where every object has its own IP-address to be identified. (Brenner and Hummel, 2017)		
Derived from the following Literature		
[108] (Brenner and Hummel, 2017)		

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[108] (Brenner and Hummel, 2017, pp. 198–205)

- **Object Identification – Tools**

Research Question: How can the requirement "**Physical Objects are identified automatically**" be implemented for the value-adding-factor "**Tools**"? → The Physical Objects (Tools) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF03	Object Identification: Physical Objects are identified automatically	Tools

Abstract Implementation Concepts and Concrete Examples

115. RFID-Technology

115.1. Application of RFID tags on the tool holder con to memorize data directly on the tool itself. After applying a tool room has been realized, where the operator could make the operations of research tools and presetting tools during working cycles. These tool room, with RFID tagged tools allowed to keep the tool inserts in the tool room (eliminate stock on machine board), to prepare tools and make presetting in the tool room and to identify uniquely the tool and its information by RFID on machine rack (see Figure 154).

Figure 154: Tools with RFID tags on the machine rack

(Dovere et al., 2015)

115.2. Precise locating of objects in manual assembly verification workshops by light-responsive RFID tags. The first experiments of exemplary application of the concept for screwing operations performed with cordless angle screwdriver in manual tail light assembly are presented. The key screw spots are marked with LR RFID tags and a LR RFID reader is installed to read the tags close to screw spots. A light source (built in led light) is installed on a cordless screwdriver to screw spots. The gathered and combined data from the LR RFID and the cordless screwdriver are then transferred to a sensor network management platform. The reader would identify exact spots where the screw is screwed.

	The employees' task is to screw few screws from inside of a vehicle during manual assembly. This manual operation cannot be seen by any cameras and only the tool sensor (wireless screwdriver) can provide information if screwing action was performed via Bluetooth. The LR RFID tags applied closely to the thread are illuminated when worker is screwing and the LR RFID reader can identify proper tag that responds to light so the thread where screw was tightened is defined. The chosen screwdriver model for the experiment was the Makita BLF201R that is able to communicate via Bluetooth and sends information like tool ID, target and final torque value and tolerance, target and final angle value and tolerance and also an error code (OK/NOK). (Gladysz and Lysiak, 2016)
Derived from the following Literature	
[109] (Dovere et al., 2015) [110] (Gladysz and Lysiak, 2016)	

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[109] (Dovere et al., 2015, pp. 1007–1012)
[110] (Gladysz and Lysiak, 2016, pp. 951–956)

- **Object Identification – Mounting Device**

Research Question: How can the requirement “**Physical Objects are identified automatically**” be implemented for the value-adding-factor “**Mounting Device**”? → The Physical Objects (Mounting Device) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF04	Object Identification: Physical Objects are identified automatically	Mounting Device

Abstract Implementation Concepts and Concrete Examples

116. **RFID-Technology**

116.1. Automatic access or feedback of information by using RFID-technology embedded on jigs for identification.

(Brenner and Hummel, 2016)

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117. **IP-Address**

117.1. Definition of a standard for all objects, like mounting devices, and the respective interfaces to the software tools where every object has its own IP-address to be identified.

(Brenner and Hummel, 2017a)

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118. **Marker-Based QR-Code**

118.1. Using an Augmented Reality (AR) framework for assembly line scenarios where the specific data of a product and graphics have to be implemented. To identify a specific workpiece and visualize the process data, a marker-based tracking method is used as seen in Figure 155.

Figure 155: Augmented Reality monitoring example with marker-based tracking

Attaching a marker to every workpiece is not always possible, therefore it is more suitable to track the workpiece holders of an assembly line. The current workpiece is referenced to a specific workpiece holder by the control system.

(Kollatsch et al., 2014)

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119. Not suitable for this Matching-Box

119.1. Using new fixture technologies, such as sensor-based fixtures in multi-station machining processes to significantly improve part quality through cutting-tool path compensations.

This new methodology involves an identification of station-induced variations, a sensor placement optimization method for designing sensor-based fixtures and a compensation analysis. In this research a sensor-based modular fixture is developed that is equipped with sensors that can detect the variations of the workpiece from its nominal location. Figure 156 shows an example of such a fixture composed of a set of inductive precision sensors (ZX-EM02T and ZX-ED01T). The inductive precision sensors will measure the variations of the workpiece.

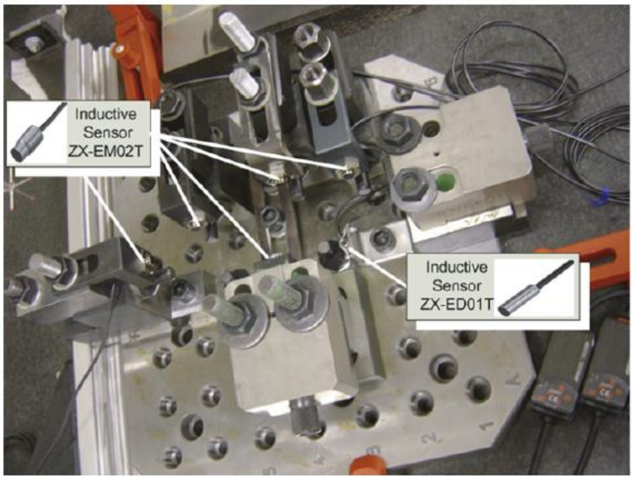
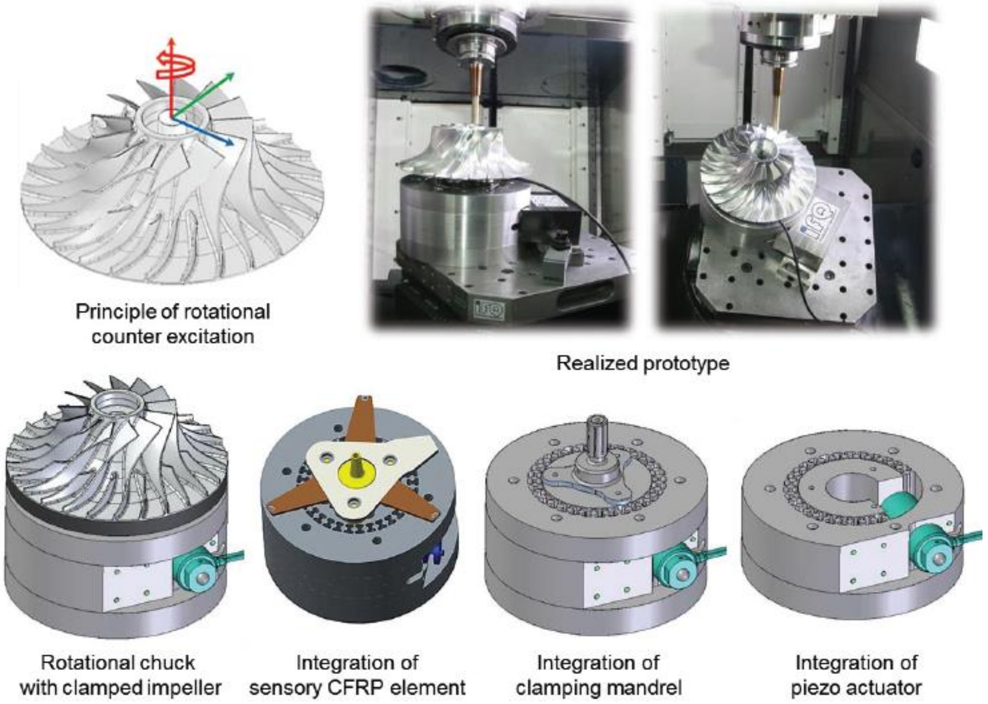


Figure 156: Sensor-based fixture with inductive precision sensors

(Abellan-Nebot et al., 2012)

119.2. In the European research project INTEFIX, fixture solutions are developed which enable the detection and compensation of chatter vibrations during machining of thin-walled workpieces, for example milling of impeller blades. To identify critical vibrations on the tool and the workpiece, piezo patch transducers are embedded in CFRP (Carbon Fiber Reinforced Plastic) fixture components.

To implement counter excitations of the clamped impeller during milling processes, an intelligent rotation chuck was developed, as shown in Figure 157. A CFRP element with integrated piezo patch transducers is attached at the inner rotating core of the actuated structure which carries a clamping mandrel to fixate the workpiece. The CFRP provides sensor arms which are pre-stressed against the bottom surface of the workpiece during the clamping to guarantee the contact of the sensory element with the workpiece and to improve the sensitivity of the sensor.


Principle of rotational counter excitation

Realized prototype

Rotational chuck with clamped impeller

Integration of sensory CFRP element

Integration of clamping mandrel

Integration of piezo actuator

Figure 157: Rotating intelligent chuck with sensors and actuators

(Möhring et al., 2016)

Derived from the following Literature

[111] (Brenner and Hummel, 2016)
[112] (Brenner and Hummel, 2017)
[113] (Kollatsch et al., 2014)
[114] (Abellan-Nebot et al., 2012)
[115] (Möhring et al., 2016)

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[111] (Brenner and Hummel, 2016, pp. 227–232)
[112] (Brenner and Hummel, 2017, pp. 198–205)
[113] (Kollatsch et al., 2014, pp. 246–251)
[114] (Abellan-Nebot et al., 2012, pp. 208–219)
[115] (Möhring et al., 2016, pp. 120–128)

- **Object Identification – Measuring & Test Device**

Research Question: How can the requirement “**Physical Objects are identified automatically**” be implemented for the value-adding-factor “**Measuring & Test Device**”? → The Physical Objects (Measuring & Test Device) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF05	Object Identification: Physical Objects are identified automatically	Measuring & Test Device
Abstract Implementation Concepts and Concrete Examples		
120. IP-Address **120.1.** Definition of a standard for all objects, like measuring and test devices, and the respective interfaces to the software tools where every object has its own IP-address to be identified. (Brenner and Hummel, 2017a)		
Derived from the following Literature		
[116] (Brenner and Hummel, 2017)		

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[116] (Brenner and Hummel, 2017, pp. 198–205)

- **Object Identification – Furniture**

Research Question: How can the requirement “**Physical Objects are identified automatically**” be implemented for the value-adding-factor “**Furniture**”? → The Physical Objects (Furniture) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF07	Object Identification: Physical Objects are identified automatically	Furniture

Abstract Implementation Concepts and Concrete Examples

121. IP-Address

121.1. Definition of a standard for all objects, like furniture, and the respective interfaces to the software tools where every object has its own IP-address to be identified.

(Brenner and Hummel, 2017a)

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122. RFID-Technology

122.1. Attachment of RFIDs to objects to identify materials and goods, furniture, equipment, food and liquids. The use of RFID technology helps to manage efficiently warehouses and retails and to simplify the inventory.

(Borgia, 2014)

Derived from the following Literature

[117] (Brenner and Hummel, 2017)
[118] (Borgia, 2014)

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[117] (Brenner and Hummel, 2017, pp. 198–205)
[118] (Borgia, 2014, pp. 1–31)

- **Object Identification – Logistics Worker**

Research Question: How can the requirement “**Physical Objects are identified automatically**” be implemented for the value-adding-factor “**Logistics Worker**”? → The Physical Objects (Logistics Worker) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF09	Object Identification: Physical Objects are identified automatically	Logistics Worker

Abstract Implementation Concepts and Concrete Examples

The abstract implementation concepts and concrete examples of the value-adding-factor “Logistics Worker” can be found in the matching model box with the **ID R07VAF01**.

By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.

Derived from the following Literature

- **Object Identification – Conveying Device**

Research Question: How can the requirement "**Physical Objects are identified automatically**" be implemented for the value-adding-factor "**Conveying Device**"? → The Physical Objects (Conveying Device) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF10	Object Identification: Physical Objects are identified automatically	Conveying Device

Abstract Implementation Concepts and Concrete Examples

123. IP-Address

123.1. Definition of a standard for all objects, like a conveying device, and the respective interfaces to the software tools where every object has its own IP-address to be identified.

(Brenner and Hummel, 2017a)

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124. RFID-Technology

124.1. See Concrete Implementation Concept Example Number 26.2.

Derived from the following Literature

[119] (Brenner and Hummel, 2017)

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[119] (Brenner and Hummel, 2017, pp. 198–205)

- **Object Identification – Conveying System**

Research Question: How can the requirement “**Physical Objects are identified automatically**” be implemented for the value-adding-factor “**Conveying System**”? → The Physical Objects (Conveying System) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF11	Object Identification: Physical Objects are identified automatically	Conveying System

Abstract Implementation Concepts and Concrete Examples

125. IP-Address

125.1. Definition of a standard for all objects, like a conveying system, and the respective interfaces to the software tools where every object has its own IP-address to be identified.

(Brenner and Hummel, 2017)

Derived from the following Literature

[120] (Brenner and Hummel, 2017)

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[120] (Brenner and Hummel, 2017, pp. 198–205)

- **Object Identification – Warehouse Worker**

Research Question: How can the requirement "**Physical Objects are identified automatically**" be implemented for the value-adding-factor "**Warehouse Worker**"? → The Physical Objects (Warehouse Worker) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF13	Object Identification: Physical Objects are identified automatically	Warehouse Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Warehouse Worker" can be found in the matching model box with the **ID R07VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Object Identification – Warehouse Facility**

Research Question: How can the requirement “**Physical Objects are identified automatically**” be implemented for the value-adding-factor “**Warehouse Facility**”? → The Physical Objects (Warehouse Facility) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF14	Object Identification: Physical Objects are identified automatically	Warehouse Facility

Abstract Implementation Concepts and Concrete Examples

126. IP-Address

126.1. Definition of a standard for all objects, like warehouse facility, and the respective interfaces to the software tools where every object has its own IP-address to be identified.

(Brenner and Hummel, 2017)

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127. RFID-Technology

127.1. Proposal of a smart warehouse environment where not only inventory items but also the shelves are tracked by an RFID-based system in real-time. This is realized by incorporating antenna-equipped moveable warehouse shelves as trackable items that can be reallocated to another location at low operational cost. The shelves are also equipped with a reader, allowing to form a Machine to Machine (M2M) network. RFID-tagged items can be freely dropped off or picked up and the system is aware of its location change and new status (e.g. in working order or temporarily out of service) that allows workers to freely or even randomly move inventory items at the highest convenience without any need to remember or search for exact drop-off locations, because of the RFID-based tracking system. The fluid warehousing concept enables adjustment of warehousing configurations like location, capacity, routine, etc. in real-time according to the dynamics of demand.

(Zhou et al., 2017)

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128. Not suitable for this Matching-Box

128.1. Development of a RFID case-based logistics resource management system (R-LRMS) for managing order-picking operations in warehouses.

Architecture framework of the R-LRMS: The architecture framework of R-LRMS, which is a three-tier system is shown in Figure 158. The first tier is responsible for data collection through which the raw warehouse operation information is collected by RFID adopted devices to collect data like locations and quantities of SKUs (Stock Keeping Units), locations of forklifts/warehouse staff members and the status of order-picking operations. Wireless network, i.e. 801.11 g WIFI network, the collected data is transferred and stored in the centralized database.

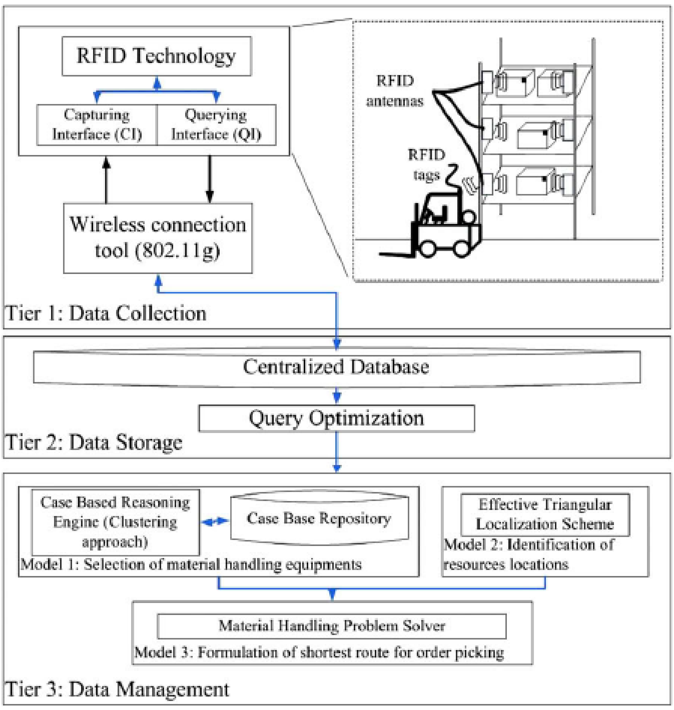

Figure 158: Architecture framework R-LRMS

In the second tier, the retrieved information is systematically stored in a centralized database. It adapts the database management system (DBMS) and structured query language (SQL) statement for data provision for users.

The third tier is the core of the R-LRMS which encompasses the relevant operational components for formulation of the pick-up routes by effectively transforming the data into meaningful information for efficient and reliable material handling solutions.

Case study of the R-LRMS: A radio frequency identification case-based logistics resource management system (R-LRMS) for tracking the SKUs and the forklifts is piloted.

Passive middle-sized RFID tags are selected for the experiment and stuck onto the surface of each SKU and forklift which are directly facing the RFID readers and antennae. One set of reader and antenna is installed in each level of the rack which is fully covered by the radio frequency from the RFID reader and antenna (see Figure 159).

Information about forklifts is captured when the forklifts pass the antennas and stored in in the centralized database for further processing like location tracking of SKUs.

Figure 159: RFID technology implementation in warehouse environment for R-LRMS

(Poon et al., 2009)

Derived from the following Literature

[121] (Brenner and Hummel, 2017)
[122] (Zhou et al., 2017)
[123] (Poon et al., 2009)

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[121] (Brenner and Hummel, 2017, pp. 198–205)
[122] (Zhou et al., 2017, pp. 99–112)
[123] (Poon et al., 2009, pp. 8277–8301)

- **Object Identification – Loading Aid**

Research Question: How can the requirement "**Physical Objects are identified automatically**" be implemented for the value-adding-factor "**Loading Aid**"? → The Physical Objects (Loading Aid) are identified automatically.

ID	Requirement	Value-Adding-Factor
R07VAF16	Object Identification: Physical Objects are identified automatically	Loading Aid

Abstract Implementation Concepts and Concrete Examples

129. IP-Address

129.1. Definition of a standard for all objects, like a loading aid, and the respective interfaces to the software tools where every object has its own IP-address to be identified.

(Brenner and Hummel, 2017)

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130. RFID-Technology

130.1. IoT systems, composed of RFID-equipped items, like loading aids, and smart shelves for tracking items in real time to reduce material waste.

(Borgia, 2014)

130.2. Transformation of a physical object into intelligent actor (smart object), who can interact with other objects by using automatic identification technologies by radio frequency (RFID) and Universal Plug and Play (UPnP) technology.

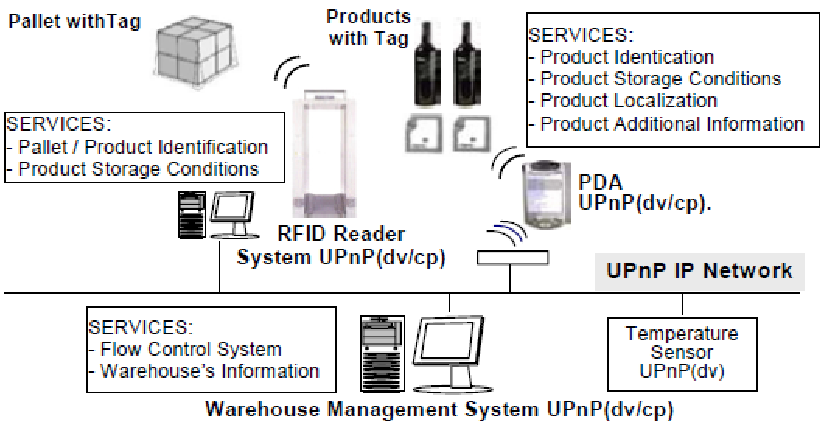

Figure 160: Components architecture in a warehouse

A case study was executed in a warehouse that is a traffic place of products, in which they are located and stored. The basic system consists of pallets and products identifiable due to RFID tags, RFID readers, PDA’s, UPnP control points and Temperature Sensors. The components of the test case UPnP architecture are shown in Figure 160. To determine the product position RFID reader systems UPnP are situated at the entrance, at the exit and appropriate fixed places inside the warehouse. The RFID tags allow the pallet and product identification and in addition the tag contains information like storage temperature, product dimensions, weight and expiration date.

(Bajic and Cea, 2005)

130.3. Automatic identification and localization of transport units by automatic identification technologies (RFID) in the automotive industry. The aim of the research was to identify all RFID identifiers placed on selected components like pallet and containers and to localize position signals from front lights, which was stored on pallet.

<u>Identification of pallets and floodlights:</u> The tests focused in identifying the left and right front floodlights that are packed and stored on plastic pallet (see Figure 161), in six plastic boxes, in three layers of two lights.

Figure 161: Identification pallets and floodlights - first layer

Passive UHF RFID identifiers were used with the RFID printer, which was located at the end of the selected production line. For data capturing from the tag RFID reader Motorola FX7400 was used.

<u>Localization of floodlights by RFID technology:</u> In addition to objects identitication with the RFID technology also an increasing interest in using this technology for 3D localization is coming up. In this example the scienbtists worked with the so called RSSI value. RSSI (Received Signal Strength Indicator) is a dimensionless unich which represents the strength of the signal received via the RFID reader antenna from RFID identifier antenna to determine the distance between RFID antennas and RFID tags. The setup of the antennas to the tab labelled RFID device is shown in Figure 162.

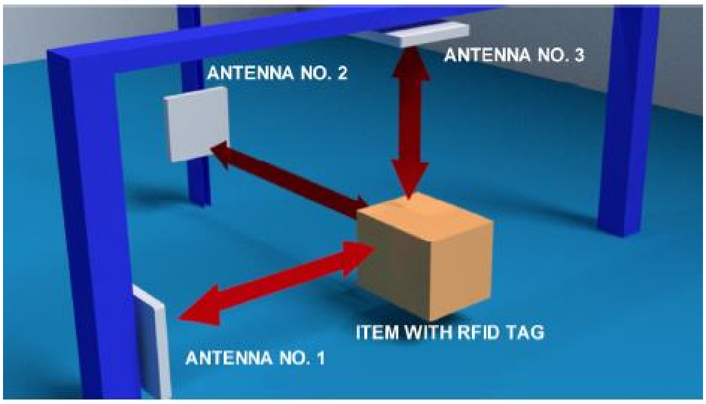

Figure 162: 3D localization by RFID technology

(Tengler et al., 2017)

130.4. See Concrete Implementation Concept Example Number 26.3.

130.5. See Concrete Implementation Concept Example Number 113.1.

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131. Optical Identification Systems

131.1. See Concrete Implementation Concept Example Number 140.3.

Derived from the following Literature

[124] (Brenner and Hummel, 2017)
[125] (Borgia, 2014)
[126] (Bajic and Cea, 2005)
[127] (Tengler et al., 2017)

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[124] (Brenner and Hummel, 2017, pp. 198–205)
[125] (Borgia, 2014, pp. 1–31)
[126] (Bajic and Cea, 2005, pp. 25–30)
[127] (Tengler et al., 2017, pp. 491–500)

3.2.8 Relation of Object Tracking and Value-Adding-Factors

- **Object Tracking – Production Worker**

Research Question: How can the requirement "**Physical Objects are tracked automatically**" be implemented for the value-adding-factor "**Production Worker**"? → The Physical Objects (Production Worker) are tracked automatically.

ID	Requirement	Value-Adding-Factor
R08VAF01	Object Tracking: Physical Objects are tracked automatically	Production Worker

Abstract Implementation Concepts and Concrete Examples

132. RFID-Technology

132.1. Indoor localization system in the ESB Logistics Learning Factory with sensor mounted autonomous navigation transport vehicles and workers by RFID or QR technology.

(Brenner and Hummel, 2017)

132.2. See Concrete Implementation Concept Example Number 111.1.

132.3. See Concrete Implementation Concept Example Number 128.1.

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133. Localization Sensor System

133.1. Localization of the worker and the product plus the bin by the Telocate sensor software in the ESB Logistics Learning Factory.

(Brenner and Hummel, 2017)

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134. Microphone-based motion tracking system

134.1. Motion-based assembly monitoring system AssyControl, which is a marker based ultrasonic solution. The system uses an array of microphones that track the movements of a marker which is attached to the hands of the worker. The tracked movements of the worker are compared to predefined motions to track the actual progress and status of the assembly.

(Kaczmarek et al., 2015)

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135. Optical sensor-based motion tracking system

135.1. Status monitoring that is realized by splitting the assembly process into different steps, that can be recognized by the used sensor. The used sensor for the experimental setup is a 3D image sensor Microsoft Kinect, which monitors the assembly work station and combines an infrared (IR) projector, an IR camera and an RGB camera in a single housing and collects depth information by a depth sensor.

(Kaczmarek et al., 2015)

135.2. Propose of three types of sensors, namely the optical, force and tool embedded sensors (such as electric screw drivers to provide process related information like torque, start and finish time of a process, etc.), to record human motions during assembly operations on an automotive differential. A second-generation Kinect sensor has been chosen as the optical sensor that can track 25 joints of the human body and store the related information into a structured form. The used force sensors provide information by expressing the force applied to them.

The above-mentioned sensors produce data that is then used to identifying and properly recognizing the captured motions. Through various motion captures, common patterns are sought after to identify specific motions of the worker. The following so called Elementary Actions can be recognized: Walk, Walk Inverse, Pick, Place, Carry, Carry Inverse, Sidestep and Sidestep-Carry.

(Pintzos et al., 2016)

135.3. Human oriented and adaptive assembly workplaces, including optical and sensor-based tracking technologies as well as an assistance system called “cubu:S” (see Figure 163).

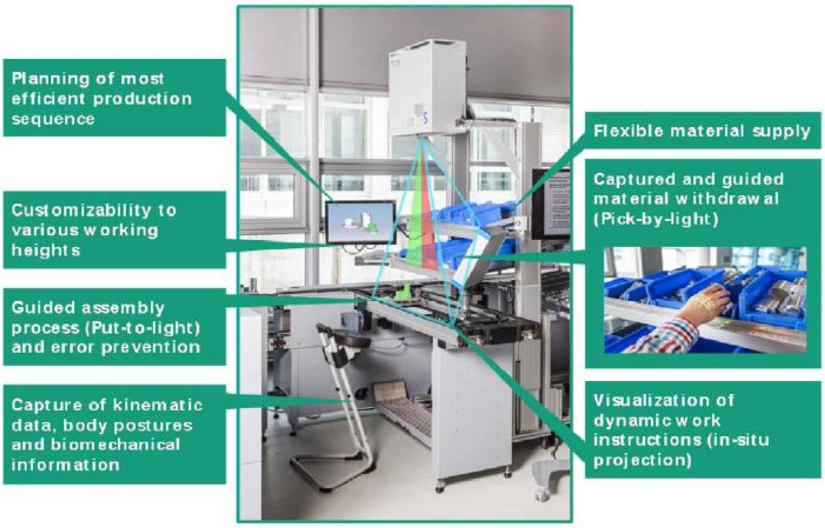

Figure 163: Human oriented and adaptive assembly workplace including the cubu:s assistance system

The focus is on the optimal design of the work process and work system for the human worker as well as an improvement of the process efficiency and quality of work.

The workplace has been designed adaptively to enable ergonomic height-adjustments to the worker along with adjustable flexible material supply with various box sizes. A real-time verification of the orientation by part recognition displays and controls the assembly location to enable a guided assembly process with error prevention.

To enable evaluation of kinematic data, body postures, load situations and biomechanical information, additional sensor and human measurement systems, such as sensor-based suits, optical motion detection devices and sensor floors are installed that gather data of the worker and of the individual process steps.

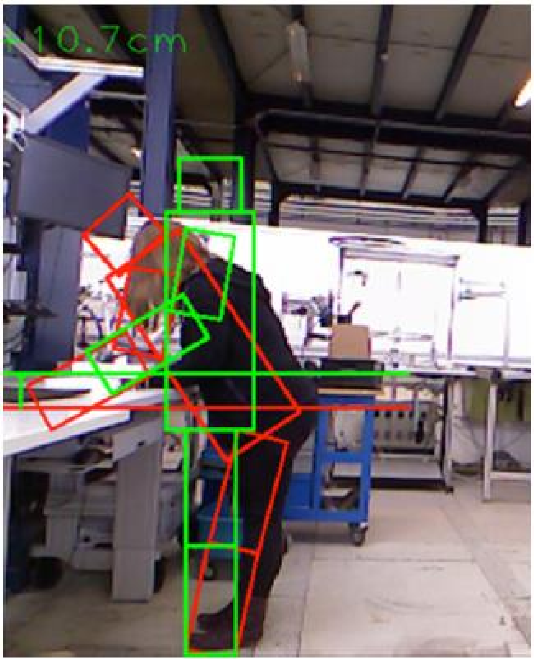

Figure 164: Working Posture Controller (WPC)

Figure 164 shows the Working Posture Controller (WPC), which monitors the worker’s posture and adjusts the workplace in a way that the worker can adopt ergonomically postures while performing the task. The controller consists of a posture assessment module and a posture optimization module. 2D and 3D sensor technology in combination with computer vision techniques can be applied, to localize landmarks of the body, such as hands, shoulders or chest without the use of markers.

(Krüger et al., 2017)

135.4. See Concrete Implementation Concept Example Number 64.2.

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136. Mobile and Wearable Devices

136.1. Indoor positioning system in combination with the workers smartphone or tablet GPS sensor to capture and process the worker´s location.

(Gorecky et al., 2013)

136.2. Implementation of an Augmented Reality System for placing and delivering to and from the warehouse (so called Pick-By-Vision solution) where companies like SAP, Knapp and Ubimax are currently in test phase. The concept is shown in Figure 165, where a stock keeper wears special glasses which displays the current warehousing task. For instance, the stock keeper is navigated by addition of 2D and 3D objects displayed in the glasses. The location of the worker can be evaluated by the AR-glasses.

1. Stock keeper wears Vuzix glasses

3. View through glasses: Aisle navigation

2. View through glasses: Pick requirement

4. View through glasses: Place navigation

Figure 165: Pick-By-Vision for SAP company

(Hořejší, 2015)

136.3. See Concrete Implementation Concept Example Number 2.1.

136.4. See Concrete Implementation Concept Example Number 135.3.

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137. Wireless Nearfield Localization

137.1. Real-time indoor tracking system in smartphones by fusing WiFi Receiving Signal Strength Indicator (RSSI) readings, IMUs (Inertial Measurement Units), and floor plan information into an enhanced particle filter. Monte Carlo Localization (MCL) with Bayesian filtering is applied to solve the localization problem to enable a terminal-based system, which consists of commercial smartphones and WiFi access points. The system architecture of the proposed approach is shown in Figure 166.

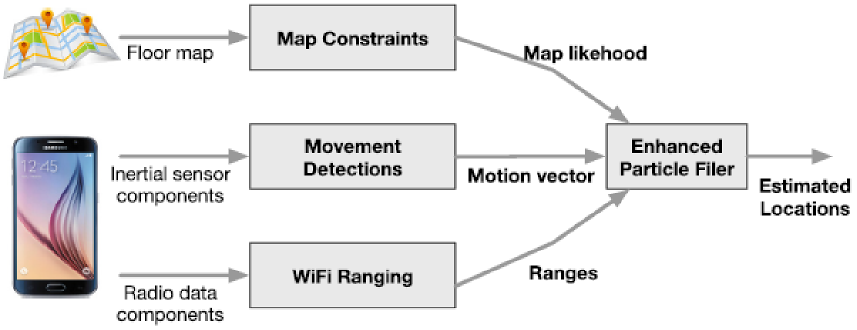

Figure 166: Real-time indoor localization system architecture

(Carrera V. et al., 2017)

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138. Magnetic Field Tracking System

138.1. See Concrete Implementation Concept Example Number 64.4.

Derived from the following Literature

[128] (Brenner and Hummel, 2017)
[129] (Gorecky et al., 2013)
[130] (Kaczmarek et al., 2015)
[131] (Pintzos et al., 2016)
[132] (Krüger et al., 2017)
[133] (Hořejší, 2015)
[134] (Carrera V. et al., 2017)

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[128] (Brenner and Hummel, 2017, pp. 198-205)
[129] (Gorecky et al., 2013, pp. 90-97)
[130] (Kaczmarek et al., 2015, pp. 1–6)
[131] (Pintzos et al., 2016, pp. 752–758)
[132] (Krüger et al., 2017, pp. 707–730)
[133] (Hořejší, 2015, pp. 699–706)
[134] (Carrera V. et al., 2017, pp. 1–12)

- **Object Tracking – Tools**

Research Question: How can the requirement "**Physical Objects are tracked automatically**" be implemented for the value-adding-factor "**Tools**"? → The Physical Objects (Tools) are tracked automatically.

ID	**Requirement**	**Value-Adding-Factor**
R08VAF03	Object Tracking: Physical Objects are tracked automatically	Tools
Abstract Implementation Concepts and Concrete Examples		
139. Wireless Nearfield Localization **139.1.** Wireless nearfield localization of a manually guided nut runner for joining processes that is equipped with a transponder and used for manual assembly processes based on an autonomous radiolocation positioning system. (Fischer et al., 2016)		
Derived from the following Literature		
[135] (Fischer et al., 2016)		

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[135] (Fischer et al., 2016, pp. 242–247)

- **Object Tracking – Measuring & Test Device**

Research Question: How can the requirement "**Physical Objects are tracked automatically**" be implemented for the value-adding-factor "**Measuring & Test Device**"? → The Physical Objects (Measuring & Test Device) are tracked automatically.

ID	Requirement	Value-Adding-Factor
R08VAF05	Object Tracking: Physical Objects are tracked automatically	Measuring & Test Device
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Object Tracking – Logistics Worker**

Research Question: How can the requirement "**Physical Objects are tracked automatically**" be implemented for the value-adding-factor "**Logistics Worker**"? → The Physical Objects (Logistics Worker) are tracked automatically.

ID	Requirement	Value-Adding-Factor
R08VAF09	Object Tracking: Physical Objects are tracked automatically	Logistics Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Logistics Worker" can be found in the matching model box with the **ID R08VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Object Tracking – Conveying Device**

Research Question: How can the requirement “**Physical Objects are tracked automatically**” be implemented for the value-adding-factor “**Conveying Device**”? → The Physical Objects (Conveying Device) are tracked automatically.

ID	Requirement	Value-Adding-Factor
R08VAF10	Object Tracking: Physical Objects are tracked automatically	Conveying Device

Abstract Implementation Concepts and Concrete Examples

140. Wireless Sensor Network and Localization System

140.1. Global localization, position tracking, path planning and communication of a swarm of Automated Guided Vehicles (AGVs) that can be used in warehouses, distribution centers and manufacturing plants to automate the internal material flow. Each AGV is equipped with Mecanum wheels, which was designed to transport Euro-bins in a distribution center or warehouse.

Global localization is realized through a technique based on range measurements obtained from an IEEE 802.15.4a Wireless Sensor Network (WSN). The WSN is also used for communication of the AGVs with the central warehouse computer as well as for communication within the AGV-swarm. The position tracking task is solved by sensor fusion of two safety laser range finders which are also used to detect pairs of landmarks to provide accurate positioning as well as for safety.

Figure 167: Sensor equipped omnidirectional transport robot

Figure 167 shows the AGV which was built by the University of Applied Sciences and Arts in Dortmund. The AGV is designed to transport bins with Euro footprint (600x400mm) and is equipped with four Mecanum wheels to provide omnidirectional motion and with two laser range finders (SICK S300 Professional) which provide operational safety. A Monte Carlo

Particle Filter (MCP) is used to deal with non-Gaussian motion and sensor models and to solve the global localization task. To detect pairs of landmarks two laser range finders are used to provide the accuracy necessary for docking maneuvers. To localize the AGVs, the distances and angles to landmarks are fused with the range measurements.

(Kirsch and Röhrig, 2011)

140.2. High-accuracy vehicle localization system for autonomous warehousing is depicted in Figure 168. The algorithm stack consists of three steps: Adaptive Monte Carlo Localization (AMCL) Iterative Closest Point (ICP) optimization and a Fourier Transformation-based position refinement (FT), yielding the final pose estimate.

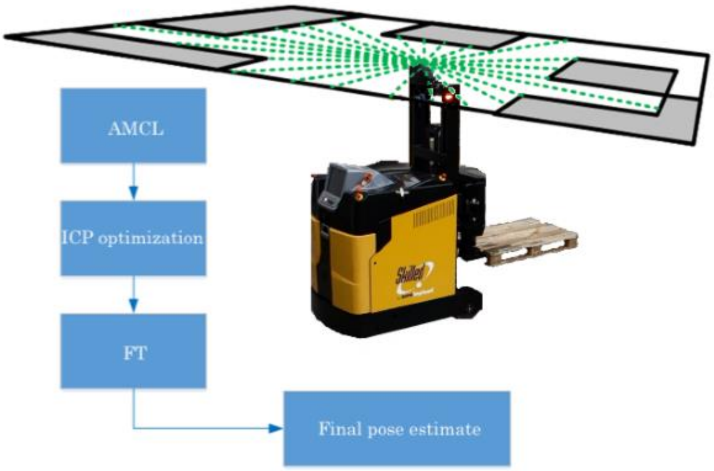

Figure 168: High-accuracy vehicle localization system using the Skilled 1000 autonomous forklift

The AMCL algorithm fuses odometry data with laser range readings to provide a robot pose estimate with a known covariance. That result is then used as the initial estimate for the scan matching ICP algorithm and finally the FT returns the results.
The experiment was conducted using the Skilled 1000 autonomous forklift (see Figure 168) manufactured by Euroimpianti company. The autonomous forklift is controlled by controlling the velocity and the angle of the front wheel. All the algorithms of the presented navigation and localization system were implemented on a notebook PC that was interfaced to several systems of the forklift (see Figure 169). Communication to the motor drivers is realized by CAN bus for gathering odometry data and for controlling vehicle motion. To receive the range data from the NAV350 scanner the ethernet interface was used. The ModbusTCP protocol was used for communication with the system

computer. Data from the safety scanners that are also mounted on the forklift was retrieved through the RS422 interface.

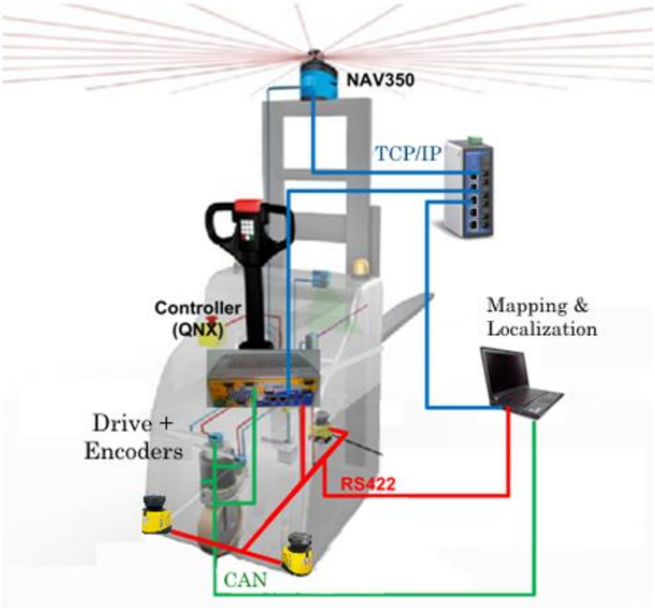

Figure 169: Interface of the control computer to the autonomous forklift

Six locations within the marker equipped warehouse-area were chosen as docking stations where the localization system accuracy was evaluated. All the paths taken from the autonomous forklift during the experiments are shown with blue lines in

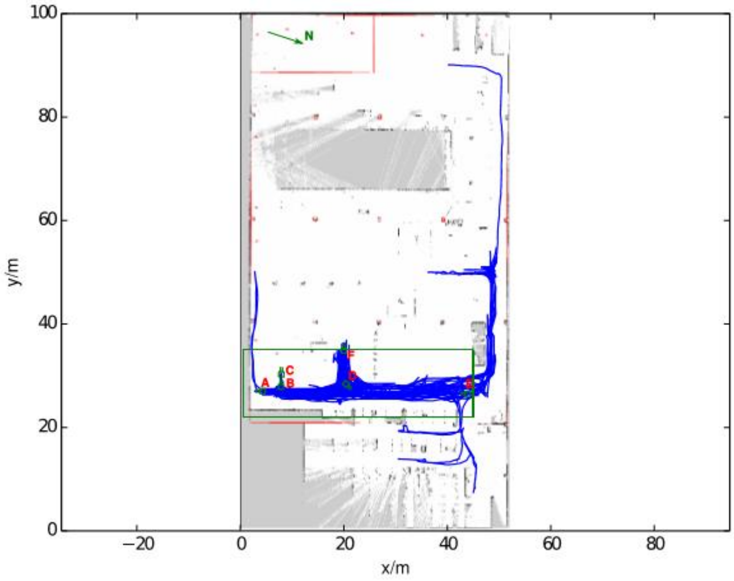

Figure 170: Floorplan of the facility with the paths travelled by the vehicle

(Vasiljević et al., 2016)

140.3. Development of a detection system, based on 2D pattern recognition, to detect, identify and track pallets in the working environment of autonomous mobile forklifts. The automation package designed to retrofit the vehicle includes a PLC to handle the hardware elements, two cameras, two laser sensors and a software control framework that allows operating in autonomous working mode (see Figure 171).

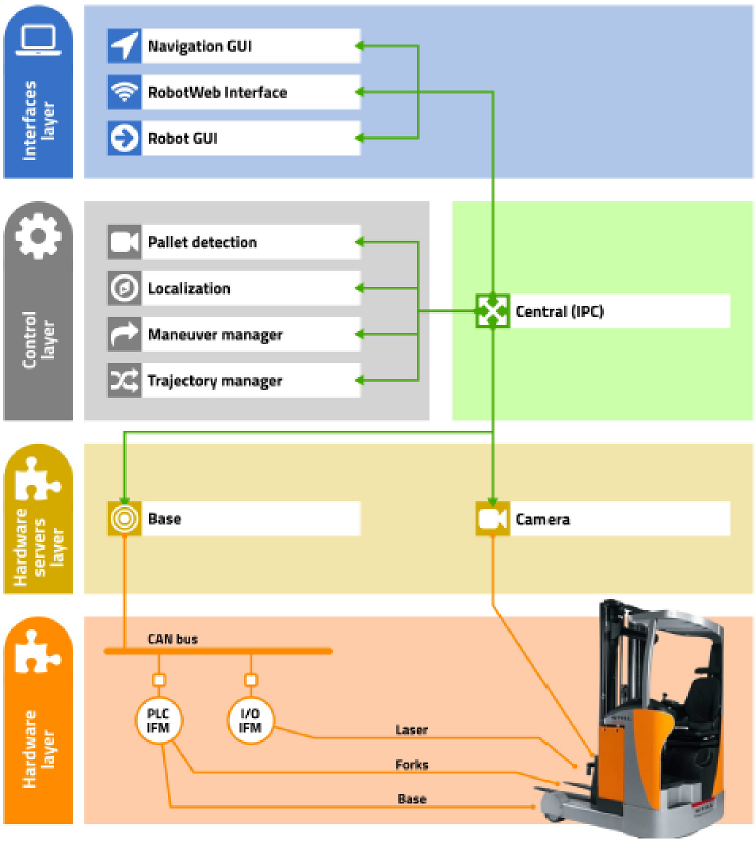

Figure 171: Control architecture of the autonomous forklift

The detection system uses two industrial HD cameras, one of them NIR installed between the forks and the other one RGB installed on the top of the forklift. The lower camera is used to locate pallets on shelves and perform load and unload operations and the upper camera is used to locate pallets on the floor (see Figure 172).

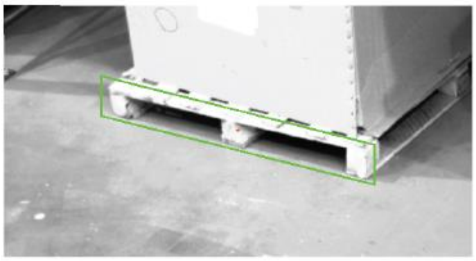

Figure 172: Pallet detection on full resolution

(Casado et al., 2017)

140.4. Autonomous navigation of an automated guided vehicle in industrial warehouse environments that consists of the set of automatic tasks, such as planner, perception, path planning and path tracking, that the vehicle must perform to accomplish the task required by the operator. To develop the flexible AGV system a set of techniques has been integrated following the scheme shown in Figure 173.

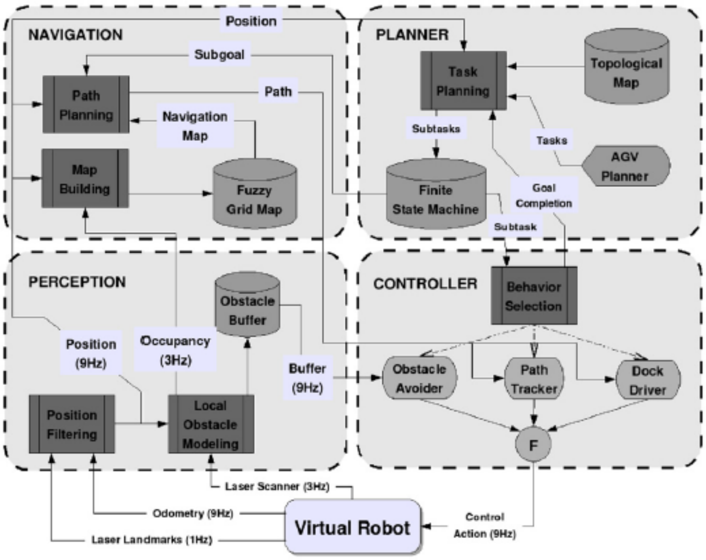

Figure 173: Techniques integrated to develop the flexible AGV system

Experimental Setup: The AGV used for this experiment is a modified OMG 808 FS commercial fork-lift truck (see Figure 174). The fork-lift truck is equipped with an industrial computer which communicates through a wireless WiFi network.

Figure 174: Modified OMG 808 FS fork-lift truck

It is also equipped with a SICK PLS security laser scanner, which provides local information about the environment around the robot and switches off if it detects an object inside a predefined security area, and a SICK NAV200 laser navigation system, which provides the location in the environment. To control the AGV's motors, two custom microcontroller boards for the traction, steering and lifting motor control, and for controlling the encoder data acquisition, security signals monitoring, lights control, and buzzer activation are installed.

The connection of the laser-based sensors to the main CPU is realized by a serial link, whereas the microcontroller boards are connected to the main CPU by a standard CAN bus.

<u>Path tracking experiment:</u> The guidance system depends on both the controller and the localization system; hence, the validation of the path tracker technique also validates the localization system, which integrates the estimations provided by the popular SICK NAV200 laser navigation system with the odometry information by using an extended Kalman filter. The path tracker is based on screw theory using a vector-pursuit strategy which is adjusted by empirically configuring a look-ahead distance. The resulting trajectories followed by the AGV are shown in Figure 175.

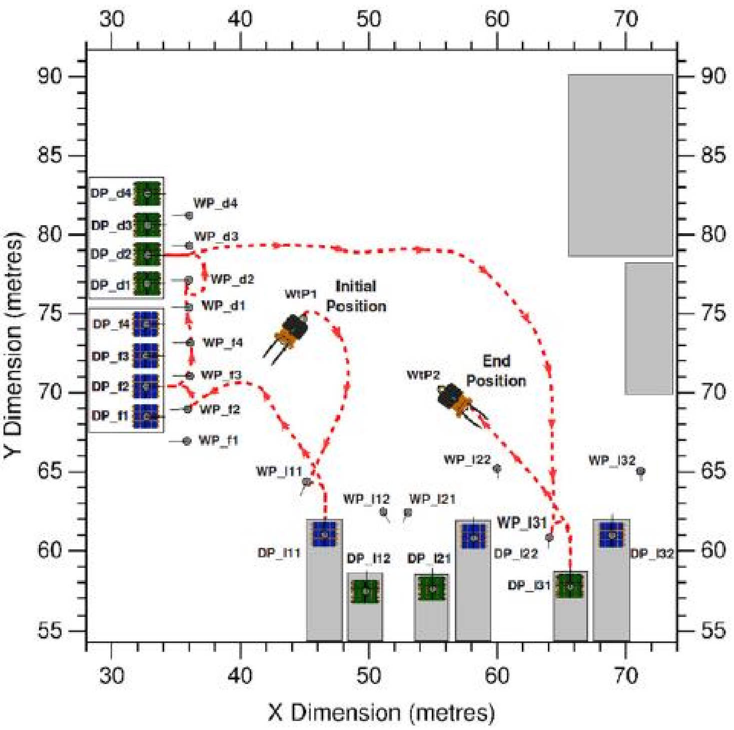

Figure 175: Trajectories followed by the AGV in a real factory

(Martínez-Barberá and Herrero-Pérez, 2010)

140.5. See Concrete Implementation Concept Example Number 20.1.

140.6. See Concrete Implementation Concept Example Number 22.1.

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141. Trajectory Tracking

141.1. Trajectory tracking control for automated guides vehicles (AGVs) that remains invariant and flexible to arbitrary number of wheels.

The control system consists of a three-stage cascade control strategy in which the control design for the vehicle chassis is separated from the wheel-tire modules. For a given AGV reference trajectory defined at the first stage, the outer controller determines the required forces and moment inputs to the AGV chassis in a time receding fashion. The second stage allocates the optimal inputs for the required forces and moment inputs for each wheel and tire. A local tire controller tracks the desired tire forces at each wheel-tire module by applying optimal control inputs for driving and steering actuators.

(Das et al., 2017)

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142. Magnet Spot Localization

142.1. Indoor navigation of automated guided vehicles (AGVs) using a magnet spot guidance system with a differential drive. Furthermore, encoders, hall-effect sensors, and counters are employed to achieve control and continuous guidance.

A magnetic spot is installed on the floor surface of an AGV navigation system, and the hall-effect sensor is used for the measurement of the magnetic flux density from the magnet spots. Real-time corrections for wheel-skidding errors are accomplished with a fuzzy controller.

Control system of the proposed AGV: The AGV consists of a magnet spot, hall-effect sensor, guidance controller, laser safety device, driving axle and driver, guide recognition and position recognition device, wireless communication system and a hydraulic system. It is controlled by a programmable logic controller (PLC) system and it is operating using two driving wheels and four idle wheels (casters).

To calculate the position and steering angle of the AGV an encoder and a sensor are used. External errors in path tracking resulting from wheel skidding or floor curvature require external sensors, like a counter, to measure the errors and correct the steering angle error along with the encoder. The magnetic flux density distribution of the magnet spot was measured using a hall-effect sensor which was then used as a guidance for the AGV.

Figure 176 shows the relationship between the magnet spot and the hall-effect sensor installed in the AGV to locate the current position of the AGV. The hall-effect sensor is used to identify the movement and position of the AGV and updates the AGV position as it passes a magnet spot.

The position tracking of the AGV is accomplished by dead reckoning based on the number of pulses from the encoder and counter. The encoder measures the rotations per minute of the motor when an AGV moves and calculates the distance that the AGV moved.

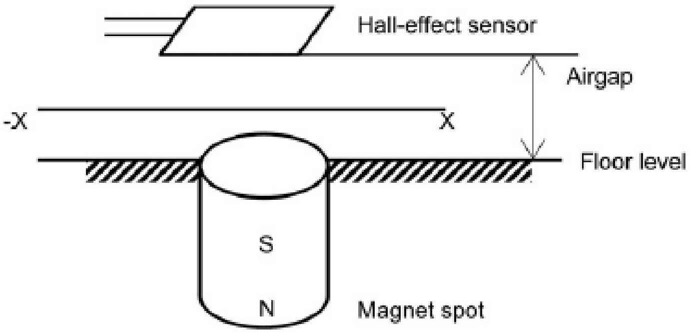

Figure 176: Installation of the hall-effect sensor and magnet spot

Figure 177 shows the AGVs in a real manufacturing environment.

Figure 177: Real-time navigation of AGVs

(Lee and Yang, 2012)

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143. Optical Localization System

143.1. See Concrete Implementation Concept Example Number 21.1.

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144. RFID-Technology

144.1. See Concrete Implementation Concept Example Number 128.1.

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145. Not suitable for this Matching-Box

145.1. Research in the field of humanoid dual-arm robots (examples are shown in Figure 178) focuses on mapping human abilities, like the bi-manual parts handling, to robotic systems.

Figure 178: Dual-arm robot examples. Left to right YuMi (ABB), SDA 10F (Motoman/Yaskawa), Workerbot (pi4/Fraunhofer IPK)

These robots can be used for transport as well as for manual assembly operations. In combination with a portable or mobile platform, these dual-arm robots can be used as flexible robots that assist workers by handling tools or other objects.

(Krüger et al., 2017)

145.2. Concept to emancipate production processes from fixed conveyor belt stations and fixed production cycles in the automotive industry to agile process modules realized by developing mobile automated guided vehicles (AGV). A concept that shows the use of these technology was recently introduced in the Audi R8 final assembly in Heilbronn (Germany), where a fleet of AGVs individually routes car bodies through the assembly stations (see Figure 179). The AGVs take a major role in the integration of the work stations because they can navigate in changing environment and lift the various bodies to ergonomic positions.

Figure 179: Mobile AGV robots for final car assembly

(Krüger et al., 2017)

Derived from the following Literature

[136] (Krüger et al., 2017)
[137] (Kirsch and Röhrig, 2011)
[138] (Vasiljević et al., 2016)
[139] (Casado et al., 2017)
[140] (Martínez-Barberá and Herrero-Pérez, 2010)
[141] (Das et al., 2017)
[142] (Lee and Yang, 2012)

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[136] (Krüger et al., 2017, pp. 707–730)
[137] (Kirsch and Röhrig, 2011, pp. 14036–14041)
[138] (Vasiljević et al., 2016, pp. 1–16)
[139] (Casado et al., 2017, pp. 63–71)
[140] (Martínez-Barberá and Herrero-Pérez, 2010, pp. 296–311)
[141] (Das et al., 2017, pp. 303–308)
[142] (Lee and Yang, 2012, pp. 425–436)

- **Object Tracking – Warehouse Worker**

Research Question: How can the requirement "**Physical Objects are tracked automatically**" be implemented for the value-adding-factor "**Warehouse Worker**"? → The Physical Objects (Warehouse Worker) are tracked automatically.

ID	Requirement	Value-Adding-Factor
R08VAF13	Object Tracking: Physical Objects are tracked automatically	Warehouse Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Warehouse Worker" can be found in the matching model box with the **ID R08VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Object Tracking – Loading Aid**

Research Question: How can the requirement "**Physical Objects are tracked automatically**" be implemented for the value-adding-factor "**Loading Aid**"? → The Physical Objects (Loading Aid) are tracked automatically.

ID	Requirement	Value-Adding-Factor
R08VAF16	Object Tracking: Physical Objects are tracked automatically	Loading Aid

Abstract Implementation Concepts and Concrete Examples

146. RFID-Technology and Wireless Sensor Networks

146.1. Dynamic indoor localization approach which is based on spatial reasoning by observing the relationship between Received Signal Strength Indicator (RSSI) values in wireless sensor networks (WSN) for transport logistics.
In the setup RFID technology is combined with a WSN that is applied as the environmental supervision system in containers during the transport processes. The WSN within the container consists of anchor sensor nodes attached on the container walls. The positioning approach exploits the straightforward movement of the "palette-accompanying" sensor nodes, which are distributed in palettes during loading processes.
With additional position information WSN can provide a precise description of the environmental parameter distribution inside the container. The RSSI on the sensor platform is a favorite distance measuring tool for indoor localization.

(Wang et al., 2011)

146.2. See Concrete Implementation Concept Example Number 27.1.

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147. RFID Technology and Mobile Devices

147.1. See Concrete Implementation Concept Example Number 65.1.

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148. RFID-Technology

148.1. See Concrete Implementation Concept Example Number 130.3.

Derived from the following Literature
[143] (Wang et al., 2011)

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[143] (Wang et al., 2011, pp. 421–428)

3.2.9 Relation of Object Handling and Value-Adding-Factors

- **Object Handling – Production Worker**

Research Question: How can the requirement "**Physical Objects are handled automatically**" be implemented for the value-adding-factor "**Production Worker**"? → The Physical Objects (Production Worker) are handled automatically.

ID	Requirement	Value-Adding-Factor
R09VAF01	Object Handling: Physical Objects are handled automatically	Production Worker
Abstract Implementation Concepts and Concrete Examples		
149. Exoskeleton Suits **149.1.** See Concrete Implementation Concept Example Number 58.2.		
Derived from the following Literature		

- **Object Handling – Tools**

Research Question: How can the requirement "**Physical Objects are handled automatically**" be implemented for the value-adding-factor "**Tools**"? → The Physical Objects (Tools) are handled automatically.

ID	**Requirement**	**Value-Adding-Factor**
R09VAF03	Object Handling: Physical Objects are handled automatically	Tools

Abstract Implementation Concepts and Concrete Examples

150. Collaborative Robots

150.1. Implementation of two collaborative robots (Rethink Robotics Baxter and Universal Robots UR10) into the work system to automate specific processes or to facilitate the work of the workers.
Through sonar and tactile sensors, these robots can collaborate with the workers without the need of protective fences. These robots should not replace the worker but assist him/her in a practice-oriented manner. As an example, these robots can handle parts for assembly as well as tools.

(Brenner and Hummel, 2016)

150.2. See Concrete Implementation Concept Example Number 145.1.

Derived from the following Literature

[144] (Brenner and Hummel, 2016)

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[144] (Brenner and Hummel, 2016, pp. 227–232)

- **Object Handling – Mounting Device**

Research Question: How can the requirement "**Physical Objects are handled automatically**" be implemented for the value-adding-factor "**Mounting Device**"? → The Physical Objects (Mounting Device) are handled automatically.

ID	Requirement	Value-Adding-Factor
R09VAF04	Object Handling: Physical Objects are handled automatically	Mounting Device
Abstract Implementation Concepts and Concrete Examples		

151. Parallel Actuator Robots

151.1. Presentation of an approach for flexible automated assembly systems for large Carbon Fiber Reinforced Plastic CFRP-Structures (for the Airbus A350XWB). Flexible automated assembly systems are workstations in assembly lines in which parts are automatically joined together that are divided into two main components, the automated joining process (AJP) and the flexible automated holding fixture (FAHF) (see Figure 180). The AJP can do tasks like treating the surfaces of parts to be joined together, joining of small components such as clips, and applying the necessary adhesives on those surfaces. The FAHF is in charge of the secure 6D-positioning and shaping, support and handle of the CFRP-structure of the airplane.

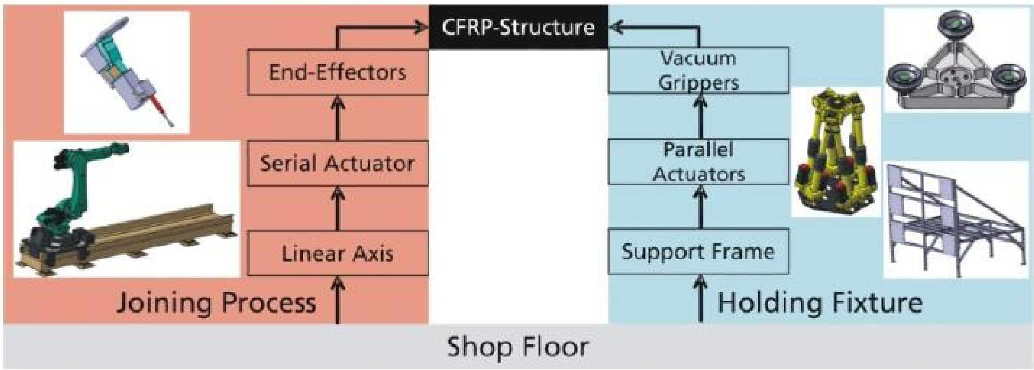

Figure 180: Flexible Automated Assembly System

Flexible Automated Holding Fixture (FAHF): Figure 181 shows the prototype concept for a FAHF holding a CFRP-structure. The concept divides the system into various components, e.g. support frame, actuators, grippers, measuring system and control system.
The support frame is needed to be the connection between the shop floor and the actuators and bringing them in their optimal position.

The chosen actuators, Fanuc F-200ib hexapod robots (see Figure 181 – right), need to have a high-positioning accuracy. The robots have a repeatability accuracy under ±0.1mm and are controlled by a unit from where it is possible to get its current pose, set a new pose and move synchronized within a group of actuators (cooperative movement).

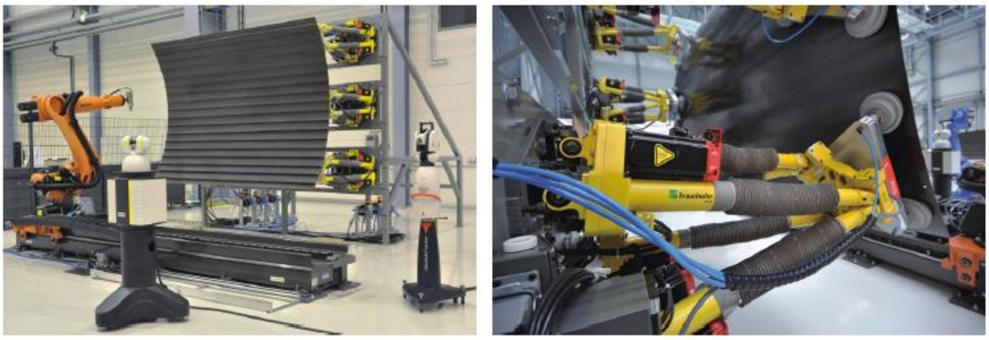

Figure 181: Prototype for Flexible Automated Holding Fixtures (FAHF). Fraunhofer IFAM

The grippers that are mounted to the actuators have the task to securely hold the CFRP-part by using a combination of vacuum cups and mechanical stops (see Figure 182 – marked with a red dot). The vacuum cups have the task to fix the CFRP-structure to the grippers and the mechanical stops define the contact points between the gripper and the CFRP-structure. 6D-force-torque sensors are placed between the grippers and the actuators to monitor the applied deformation load.

Figure 182: Gripper of the flexible automated holding figure. Fraunhofer IFAM

To ad intelligence to the system, measuring systems, control systems and its calibrated model of the FAHF are implemented. For machine measurement and referencing a laser tracker with the help of mirror targets is used. For 3D part surface measurements, the preferred system is a laser radar system. The control system interconnects measuring devices and actuators using interfaces for standard development kits (SDK) and it is capable of complex mathematical calculations. The

	machine operator can monitor and interact with the process using a Graphical User Interface (GUI). (Ramirez and Wollnack, 2014)
Derived from the following Literature	
[145] (Ramirez and Wollnack, 2014)	

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[145] (Ramirez and Wollnack, 2014, pp. 447–455)

- **Object Handling – Consumables Production**

Research Question: How can the requirement “**Physical Objects are handled automatically**” be implemented for the value-adding-factor “**Consumables Production**”? → The Physical Objects (Consumables Production) are handled automatically.

ID	Requirement	Value-Adding-Factor
R09VAF06	Object Handling: Physical Objects are handled automatically	Consumables Production
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Object Handling – Furniture**

Research Question: How can the requirement “**Physical Objects are handled automatically**” be implemented for the value-adding-factor “**Furniture**”? → The Physical Objects (Furniture) are handled automatically.

ID	Requirement	Value-Adding-Factor
R09VAF07	Object Handling: Physical Objects are handled automatically	Furniture
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Object Handling – Conveying Device**

Research Question: How can the requirement “**Physical Objects are handled automatically**” be implemented for the value-adding-factor “**Conveying Device**”? → The Physical Objects (Conveying Device) are handled automatically.

ID	Requirement	Value-Adding-Factor
R09VAF10	Object Handling: Physical Objects are handled automatically	Conveying Device

Abstract Implementation Concepts and Concrete Examples

152. Not suitable for this Matching-Box

152.1. Development of a precise transshipment system for automatic transporting material between an automated guided vehicle (AGV) and a load transfer station. To implement the alignment of the fixture base on board the AGV with that of the station, a pose measurement system is necessary that measures the pose of the AGV with respect to the station. The system combines four distance sensors with two CCD cameras. A 6-degree of freedom (DOF) pose alignment system based in 3-DOF positioners is used to correct the pose deviation. Figure 183 shows the main setup of the AGV system that consist of an automated guided vehicle, pose measurement system and pose alignment system.

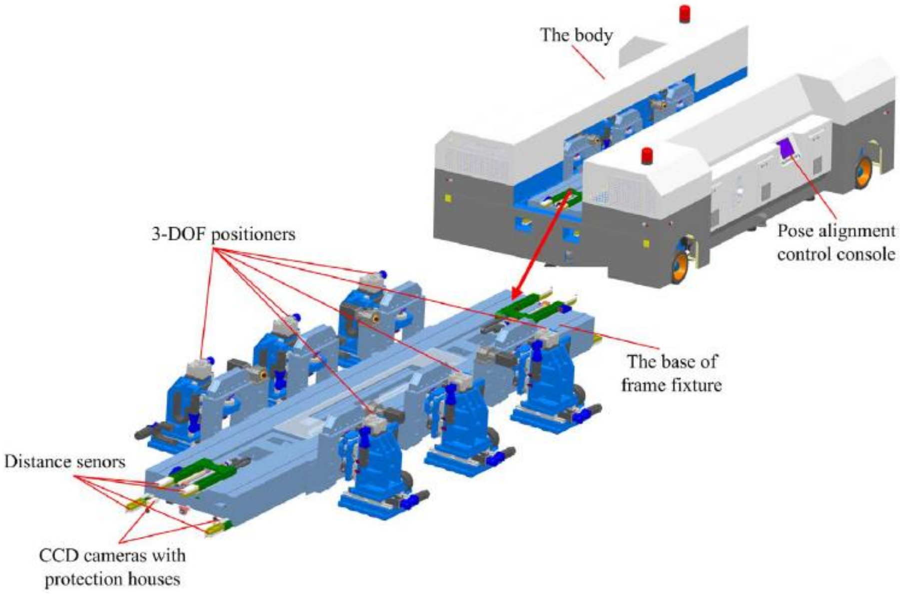

Figure 183: Setup of the AGV system

The pose measurement system consists of two CCD cameras and four distance sensors on each side of the vehicle and four dedicated calibration boards carrying with five circular landmarks. By driving the two linear axes,

	the 4 distance sensors will touch the corresponding calibration board resulting in four distance values that come out of the system. These distance values are then compared with the ideal distance corresponding to the goal pose. (Liu et al., 2017)
Derived from the following Literature	
[146] (Liu et al., 2017)	

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[146] (Liu et al., 2017, pp. 30–38)

- **Object Handling – Loading Aid**

Research Question: How can the requirement “**Physical Objects are handled automatically**” be implemented for the value-adding-factor “**Loading Aid**”? → The Physical Objects (Loading Aid) are handled automatically.

ID	Requirement	Value-Adding-Factor
R09VAF16	Object Handling: Physical Objects are handled automatically	Loading Aid
Abstract Implementation Concepts and Concrete Examples		
153. Automated Guided Vehicles (AGVs) **153.1.** See Concrete Implementation Concept Example Number 140.1.		
Derived from the following Literature		

- <u>**Object Handling – Consumables Packaging**</u>

Research Question: How can the requirement "**Physical Objects are handled automatically**" be implemented for the value-adding-factor "**Consumables Packaging**"? → The Physical Objects (Consumables Packaging) are handled automatically.

ID	**Requirement**	**Value-Adding-Factor**
R09VAF18	Object Handling: Physical Objects are handled automatically	Consumables Packaging
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

3.2.10 Relation of Condition Detection and Value-Adding-Factors

- <u>**Condition Detection – Production Worker**</u>

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Production Worker**"? → The Physical Object's (Production Worker) condition is detected automatically.

ID	Requirement	Value-Adding-Factor
R10VAF01	Condition Detection: The Physical Object's condition is detected automatically	Production Worker

Abstract Implementation Concepts and Concrete Examples

154. Augmented Reality – See-trough Display

154.1. Industrial tool, called Ceit Ergonomics Analysis Application (CERAA), of ergonomic to create healthy conditions at work for production and for non-production workers, assembly and logistics. It is a mobile application developed in CEIT Company in collaboration with the University of Zilina and Slovak ergonomic association that screens and evaluates space conditions and work positions of workers with the support of virtual and augmented reality.

Figure 184: Ergonomic evaluation by augmented reality (CERAA)

The evaluation of working conditions can be seen in Figure 184 and contents rating of working area during sitting or standing on the base of knowledge from anthropometry. Basic rules can be found for example minimal vacant area for legs and defined handling space. A second feature is the evaluation of chosen working positions (see Figure 184) that includes characteristics and criterions intended to determine about admissibility of individual positions with regards to torso position and position of the head, neck and upper limbs.

(Gašová et al., 2017)

154.2. See Concrete Implementation Concept Example Number 135.3.

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155. Wearable Devices

155.1. See Concrete Implementation Concept Example Number 2.1.

155.2. See Concrete Implementation Concept Example Number 135.3.

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156. Motion Capture Systems

156.1. See Concrete Implementation Concept Example Number 3.1.

156.2. See Concrete Implementation Concept Example Number 135.3.

Derived from the following Literature

[147] (Gašová et al., 2017)

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[147] (Gašová et al., 2017, pp. 219–224)

- **Condition Detection – Machinery**

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Machinery**"? → The Physical Object's (Machinery) condition is detected automatically.

ID	Requirement	Value-Adding-Factor
R10VAF02	Condition Detection: The Physical Object's condition is detected automatically	Machinery

Abstract Implementation Concepts and Concrete Examples

157. Sensor Integration

157.1. See Concrete Implementation Concept Example Number 4.1.

157.2. See Concrete Implementation Concept Example Number 4.3.

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158. Sensor Integration and Control Software Systems

158.1. See Concrete Implementation Concept Example Number 6.1.

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159. Data Acquisition from CNC and PLC System

159.1. See Concrete Implementation Concept Example Number 8.1.

159.2. See Concrete Implementation Concept Example Number 8.2.

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160. Internet-based Prognostics and Operations Systems

160.1. See Concrete Implementation Concept Example Number 33.2.

160.2. See Concrete Implementation Concept Example Number 33.3.

160.3. See Concrete Implementation Concept Example Number 35.1.

160.4. See Concrete Implementation Concept Example Number 36.2.

Derived from the following Literature

- **Condition Detection – Tools**

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Tools**"? → The Physical Object's (Tools) condition is detected automatically.

ID	Requirement	Value-Adding-Factor
R10VAF03	Condition Detection: The Physical Object's condition is detected automatically	Tools

Abstract Implementation Concepts and Concrete Examples

161. Sensor Integration

161.1. See Concrete Implementation Concept Example Number 4.1.

161.2. See Concrete Implementation Concept Example Number 9.4.

161.3. See Concrete Implementation Concept Example Number 9.6.

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162. Sensor Integration with CNC and PLC Control System

162.1. See Concrete Implementation Concept Example Number 7.1.

162.2. See Concrete Implementation Concept Example Number 7.2.

162.3. See Concrete Implementation Concept Example Number 7.3.

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163. Sensor Integration and A/D Converter

163.1. See Concrete Implementation Concept Example Number 10.1.

163.2. See Concrete Implementation Concept Example Number 10.2.

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164. Sensor Integration and Data Acquisition Card

164.1. See Concrete Implementation Concept Example Number 11.1.

164.2. See Concrete Implementation Concept Example Number 11.2.

164.3. See Concrete Implementation Concept Example Number 11.3.

164.4. See Concrete Implementation Concept Example Number 11.4.

164.5. See Concrete Implementation Concept Example Number 11.5.

Derived from the following Literature

- **Condition Detection – Measuring & Test Device**

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Measuring & Test Device**"? → The Physical Object's (Measuring & Test Device) condition is detected automatically.

ID	**Requirement**	**Value-Adding-Factor**
R10VAF05	Condition Detection: The Physical Object's condition is detected automatically	Measuring & Test Device
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Condition Detection – Furniture**

Research Question: How can the requirement “**The Physical Object’s condition is detected automatically**” be implemented for the value-adding-factor “**Furniture**”? → The Physical Object’s (Furniture) condition is detected automatically.

ID	Requirement	Value-Adding-Factor
R10VAF07	Condition Detection: The Physical Object’s condition is detected automatically	Furniture
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Condition Detection – Logistics Worker**

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Logistics Worker**"? → The Physical Object's (Logistics Worker) condition is detected automatically.

ID	Requirement	Value-Adding-Factor
R10VAF09	Condition Detection: The Physical Object's condition is detected automatically	Logistics Worker
Abstract Implementation Concepts and Concrete Examples		
The abstract implementation concepts and concrete examples of the value-adding-factor "Logistics Worker" can be found in the matching model box with the **ID R10VAF01**. By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.		
Derived from the following Literature		

- **Condition Detection – Conveying Device**

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Conveying Device**"? → The Physical Object's (Conveying Device) condition is detected automatically.

ID	Requirement	Value-Adding-Factor
R10VAF10	Condition Detection: The Physical Object's condition is detected automatically	Conveying Device
Abstract Implementation Concepts and Concrete Examples		
165. Sensor Integration **165.1.** See Concrete Implementation Concept Example Number 20.1.		
Derived from the following Literature		

- **Condition Detection – Conveying System**

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Conveying System**"? → The Physical Object's (Conveying System) condition is detected automatically.

ID	**Requirement**	**Value-Adding-Factor**
R10VAF11	Condition Detection: The Physical Object's condition is detected automatically	Conveying System
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Condition Detection – Warehouse Worker**

Research Question: How can the requirement “**The Physical Object’s condition is detected automatically**” be implemented for the value-adding-factor “**Warehouse Worker**”? → The Physical Object’s (Warehouse Worker) condition is detected automatically.

<table>
<tr><th>ID</th><th>Requirement</th><th>Value-Adding-Factor</th></tr>
<tr><td>R10VAF13</td><td>Condition Detection:
The Physical Object’s condition is detected automatically</td><td>Warehouse Worker</td></tr>
<tr><th colspan="3">Abstract Implementation Concepts and Concrete Examples</th></tr>
<tr><td colspan="3">The abstract implementation concepts and concrete examples of the value-adding-factor “Warehouse Worker” can be found in the matching model box with the **ID R10VAF01**.
By creating the abstract implementation concepts and the concrete examples no distinction between production, logistics and warehouse worker was made.</td></tr>
<tr><th colspan="3">Derived from the following Literature</th></tr>
<tr><td colspan="3"></td></tr>
</table>

- **Condition Detection – Warehouse Facility**

Research Question: How can the requirement "**The Physical Object's condition is detected automatically**" be implemented for the value-adding-factor "**Warehouse Facility**"? → The Physical Object's (Warehouse Facility) condition is detected automatically.

ID	Requirement	Value-Adding-Factor
R10VAF14	Condition Detection: The Physical Object's condition is detected automatically	Warehouse Facility
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

- **Condition Detection – Loading Aid**

Research Question: How can the requirement “**The Physical Object’s condition is detected automatically**” be implemented for the value-adding-factor “**Loading Aid**”?
→ The Physical Object’s (Loading Aid) condition is detected automatically.

ID	**Requirement**	**Value-Adding-Factor**
R10VAF16	Condition Detection: The Physical Object’s condition is detected automatically	Loading Aid
Abstract Implementation Concepts and Concrete Examples		
No abstract implementation concepts and concrete examples could be found by the systematic literature research.		
Derived from the following Literature		

3.3 Representation of the results – The Implementation Report

As mentioned above, each matching box (e.g.: R01VAF01: Digital Information – Production Worker) consists of different abstract implementation concepts (e.g.: Computer-based information). The latter can be evaluated on a scale from 1 (low implementation) to 5 (high implementation) (see Table 6). To enable the evaluation the abstract implementation concepts are filled with concrete best practice implementation examples from the systematic literature review.

The level of implementation for each abstract implementation concept of the value-added process to be evaluated can then be compared with the concrete best practice examples resulting in a rating from 1 to 5. To evaluate the degree of implementation of a matching box, the arithmetic means of all the abstract implementation concepts that are in this matching box is formed (see Formula 1):

$$I_{MB,n} = \frac{1}{j}\sum_{i=1}^{j} I_{AIC,i}$$

$$1 \leq I_{MB,n} \leq 5$$

$$1 \leq I_{AIC,i} \leq 5$$

$I_{MB,n\ldots} Implementation\ Level\ of\ the\ Matching\ Box, n$

$I_{AIC,i\ldots} Implementation\ Level\ of\ the\ Abstract\ Implementation\ Concept, i$

$j \ldots Numbers\ of\ Abstract\ Implementation\ Concepts\ of\ the\ Matching\ Box, n$

Formula 1: Formula used for calculating the Implementation Level of the Matching Boxes

If nothing useful was found in the systematic literature review for a specific matching box, the evaluation result is described with “Nothing found”. If a dimension doesn’t occur in the value-added process to be evaluated, the evaluation result is described with “Not implemented”. The affected matching boxes, which are mention above, are not considered in the formation of the arithmetic means.

The evaluation results of the level of implementation for each matching box are then transferred to the relation model as shown in Figure 185 (Figure 186 and Figure 187 show enlarged details of the overall view).

Nr. of Abstract Implementation Concept	**Matching Box ID: Description** Abstract Implementation Concepts	Results of the Evaluation (Scale: 1-5)
	R01VAF01: Digital Information – Production Worker	**(Arithmetic mean)** **3**
1.	Computer-based information	3
	R02VAF01: Collected Information – Production Worker	**3**
2.	Sensor-equipped Wearable Devices	3
3.	Motion Capture Systems	3
	R02VAF02: Collected Information – Machinery	**3**
4.	Sensor Integration	3
5.	Data Acquisition Card and Sensor Integration	3
6.	Data Acquisition Card, Sensor Integration and CNC/PLC Control System	3
7.	Sensor Integration with CNC and PLC Control System	3
…	….	…

Table 6: Evaluation List Explanation

Due to this transfer it is possible to calculate the degree of implementation of the dimensions as well as of the requirements (see Figure 185 to Figure 187, green filled boxes). To evaluate the degree of implementation of a dimension (Value-Adding-Factor), the arithmetic means of all the matching boxes listed in the column is formed (see Formula 2):

$$I_{DIM,m} = \frac{1}{x}\sum_{n=1}^{x} I_{MB,n}$$

$$1 \leq I_{DIM,m} \leq 5$$

$$1 \leq I_{MB,n} \leq 5$$

$I_{DIM,m}$…$Implementation\ Level\ of\ the\ Dimension, m$

$I_{MB,n}$…$Implementation\ Level\ of\ the\ Matching\ Box, n$

x … $Numbers\ of\ Matching\ Boxes\ listed\ in\ the\ column\ of\ the\ Dimension, m$

Formula 2: Formula used for calculating the Implementation Level of the Dimension

If matching boxes with the evaluation result “Nothing found” or “Not implemented” occur, these matching boxes are not considered in the formation of the arithmetic means.

The calculation of the implementation level for a requirement is the same as for the above mentioned dimension, but here the arithmetic mean is formed over the matching boxes that are listed in the row of the relation instead of the column of the dimension.

						Dimensions - Production Process						Dimesions - Material Flows			
						Production - Transformation Factors						Transport/Convey - Transformation Factors		Warehouse/Buffer - Transformation Factors	Transport- and Logistics Box, Consumables in the Logistics - Transformation Factors
						VAF01	VAF02	VAF03	VAF05	VAF04	VAF07	VAF10	VAF11	VAF14	VAF16
						Worker	Machinery	Tools	Measuring & Test Device	Mounting Device	Furniture	Conveying Device	Conveying System	Warehouse Facility	Loading Aid
				Short Name Requirement	Arithmetic mean	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00	3,00
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing an provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	**Requirement 1.1:** Information exists solely in digital form	R01	digital information	3,00	3	3	3	3	3	3	3	3	3	3
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	3,00	3	3	3	3	3	3	3	3	3	3
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	3,00	3	3	3	3	3	3	3	3	3	3
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	3,00	3	3	3	3	3	3	3	3	3	3
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	3,00	3	3	3	3	3	3	3	3	3	3
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	**Requirement 2.2:** Physical objects are identified automatically	R07	object identification	3,00	3	3	3	3	3	3	3	3	3	3
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	3,00	3	3	3	3	3	3	3	3	3	3
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	3,00	3	3	3	3	3	3	3	3	3	3
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	3,00	3	3	3	3	3	3	3	3	3	3

Figure 185: Evaluation Explanation - Relation Model Overall View

						Dimensions - Production Process					
						Production - Transformation Factors					
						VAF01	VAF02	VAF03	VAF05	VAF04	VAF07
						Worker	Machinery	Tools	Measuring & Test Device	Mounting Device	Furniture
				Short Name Requirement	Arithmetic mean	3,00	3,00	3,00	3,00	3,00	3,00
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing an provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	Requirement 1.1: Information exists solely in digital form	R01	digital information	3,00	3	3	3	3	3	3
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	3,00	3	3	3	3	3	3
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	3,00	3	3	3	3	3	3
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	3,00	3	3	3	3	3	3
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	3,00	3	3	3	3	3	3
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	Requirement 2.2: Physical objects are identified automatically	R07	object identification	3,00	3	3	3	3	3	3
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	3,00	3	3	3	3	3	3
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	3,00	3	3	3	3	3	3
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	3,00	3	3	3	3	3	3

Figure 186: Evaluation Explanation - Relation Model - Dimensions Production Process

						Dimesions - Material Flows			
						Transport/Convey - Transformation Factors		Warehouse/Buffer - Transformation Factors	Transport- and Logistics Box, Consumables in the Logistics - Transformation Factors
						VAF10	VAF11	VAF14	VAF16
						Conveying Device	Conveying System	Warehouse Facility	Loading Aid
				Short Name Requirement	Arithmetic mean	3,00	3,00	3,00	3,00
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing and provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	Requirement 1.1: Information exists solely in digital form	R01	digital information	3,00	3	3	3	3
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	3,00	3	3	3	3
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	3,00	3	3	3	3
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	3,00	3	3	3	3
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	3,00	3	3	3	3
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	Requirement 2.2: Physical objects are identified automatically	R07	object identification	3,00	3	3	3	3
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	3,00	3	3	3	3
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	3,00	3	3	3	3
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	3,00	3	3	3	3

Figure 187: Evaluation Explanation - Relation Model - Dimensions Materials Flow

The resulting is-state of the implementation level for all the 10 dimensions can additionally be presented in a radar chart (see Figure 188) where the already mentioned rating ranging from 1 (low implementation) to 5 (high implementation) can be seen.

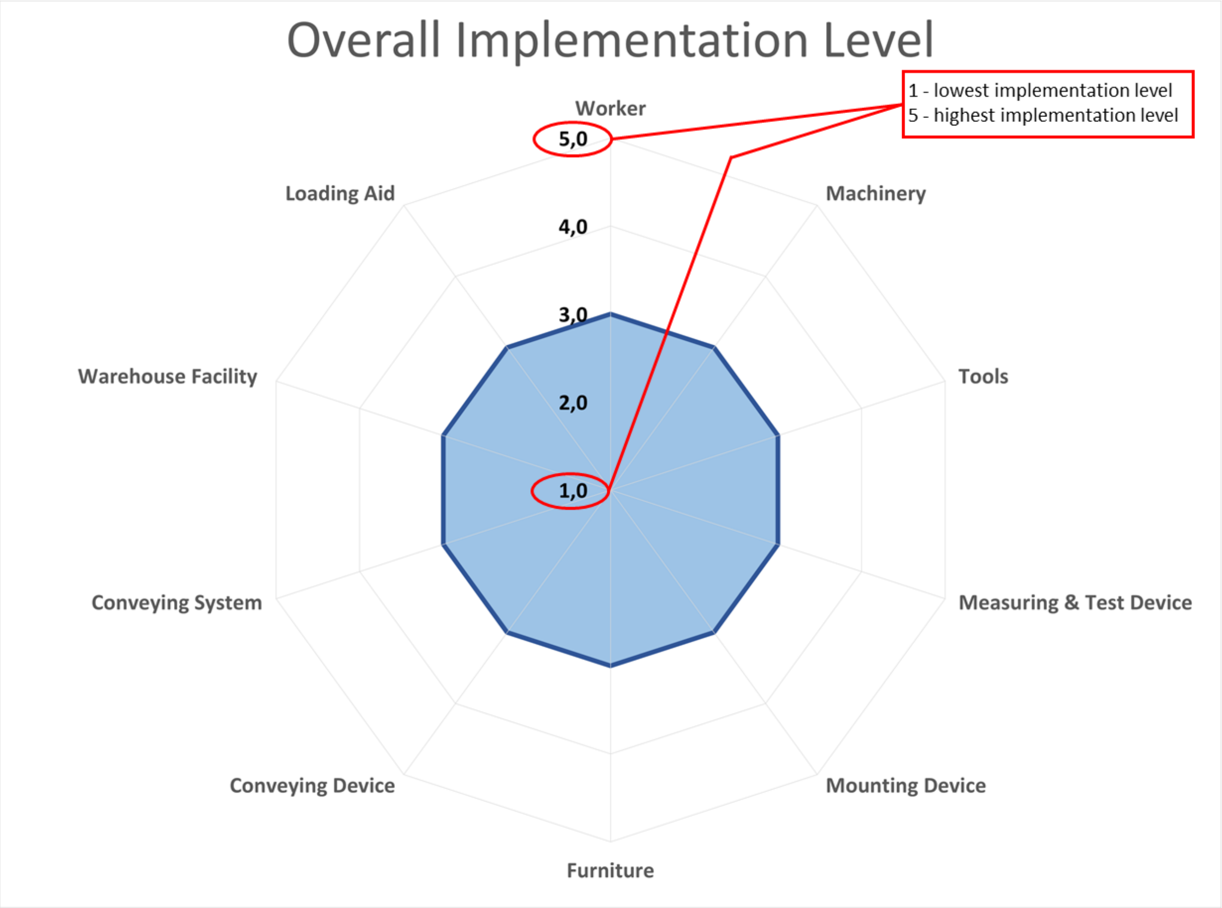


Figure 188: Radar Chart Explanation – Implementation Level of the Dimensions

4 Pilot-Testing of the Relation Model

To test the Relation Model in a suitable environment, it was pilot-tested in the Pilot Factory of the TU Wien in Vienna - Aspern. The demonstration product is a 3D-printer which can be manufactured, pre- and final assembled in different variations. This Pilot Factory enables Austrian companies to adjust on the future of industrial manufacturing as well as students to get access to industrial state of the art infrastructure.

4.1 Explanation of the Use-Case in the Pilot Factory of the TU Wien - Technical University of Vienna

Once a week it is possible to take a guided tour through the Pilot Factory where the entire value-added process chain is explained in detail. The first step of piloting the relation model was the participation in one factory tour. If a part of the value-added process was not explained exactly enough, specific questions were asked until the situation was clear enough for the evaluation. The second step consisted of working through the matching boxes, more precisely the abstract implementation concepts with their concrete implementation examples listed in chapter 3.2. Each abstract implementation concept was then evaluated on a scale from 1 (low implementation) to 5 (high implementation) according to the is-state, that could be seen during the factory tour of the Pilot Factory with the help of the concrete state-of the art examples resulting from the systematic literature review. Figure 189 shows an assembly workplace which is only a small part of the factory but sufficient for the explanation of the dimensions that could be seen there. If a dimension doesn't occur in the value-added process to be evaluated, the evaluation result is described with “Not implemented”.

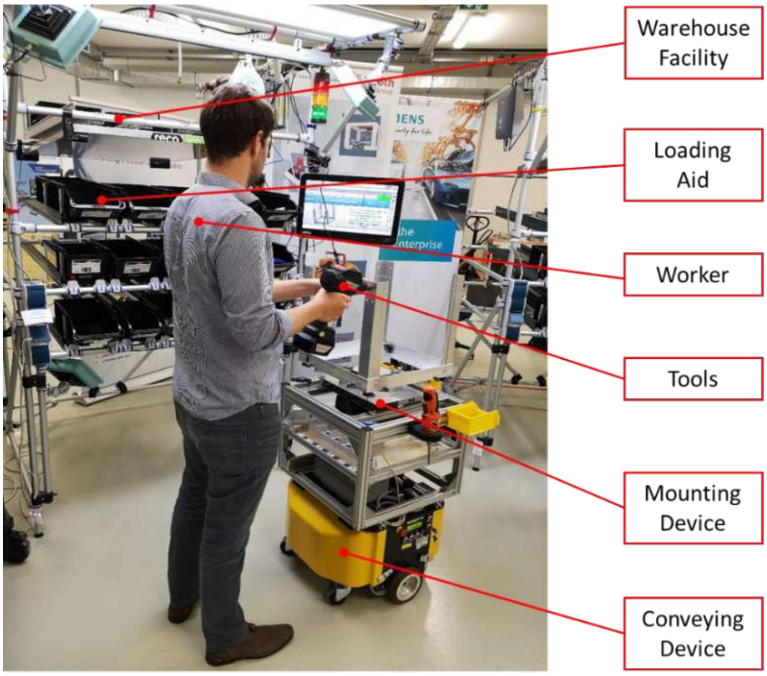
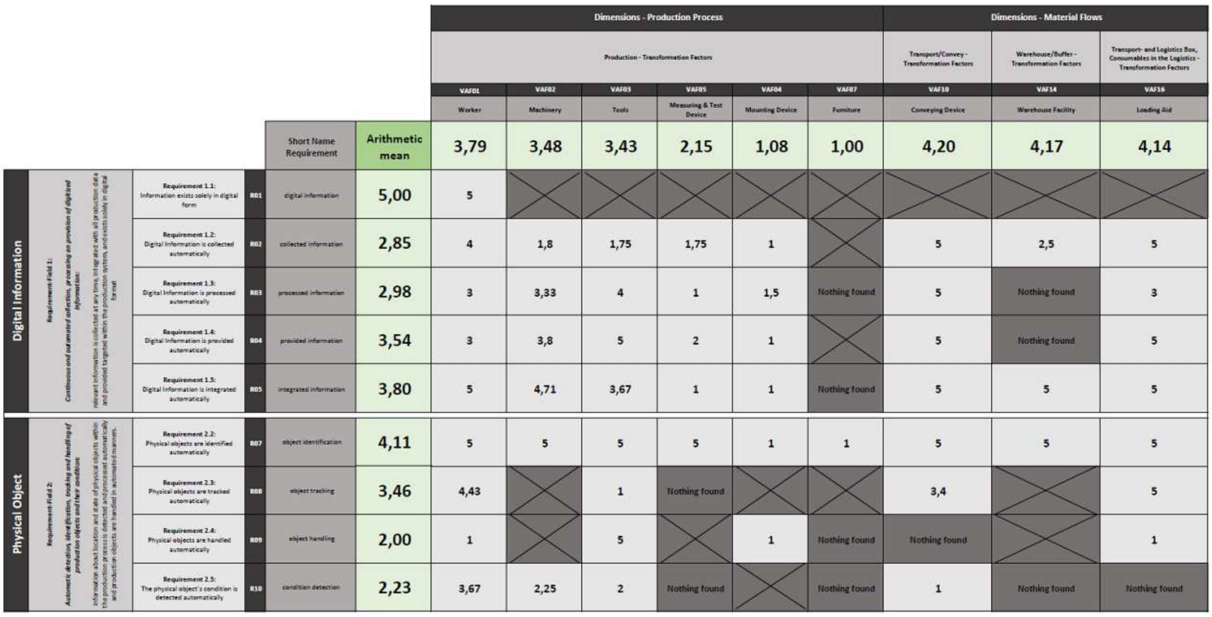


Figure 189: Example of Dimensions evaluated in the Pilot Factory

4.2 Detailed evaluation results

The evaluation results, more precisely the calculated degree of implementation of the dimensions as well as the requirements can be seen on Figure 190 to Figure 192.

To evaluate the degree of implementation of a dimension (Value-Adding-Factor), the arithmetic means of all the matching boxes listed in the column is formed according to Formula 2.



						Dimensions - Production Process						Dimensions - Material Flows		
						Production - Transformation Factors						Transport/Convey - Transformation Factors	Warehouse/Buffer - Transformation Factors	Transport- and Logistics Box, Consumables in the Logistics - Transformation Factors
						VAF01	VAF02	VAF03	VAF05	VAF04	VAF07	VAF10	VAF14	VAF16
						Worker	Machinery	Tools	Measuring & Test Device	Mounting Device	Furniture	Conveying Device	Warehouse Facility	Loading Aid
				Short Name Requirement	Arithmetic mean	3,79	3,48	3,43	2,15	1,08	1,00	4,20	4,17	4,14
Digital Information	Requirement-Field 1: Continuous and automated collection, processing an provision of digitized information: relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	Requirement 1.1: Information exists solely in digital form	R01	digital information	5,00	5	☒	☒	☒	☒	☒	☒	☒	☒
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	2,85	4	1,8	1,75	1,75	1	☒	5	2,5	5
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	2,98	3	3,33	4	1	1,5	Nothing found	5	Nothing found	3
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	3,54	3	3,8	5	2	1	☒	5	Nothing found	5
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	3,80	5	4,71	3,67	1	1	Nothing found	5	5	5
Physical Object	Requirement-Field 2: Automatic detection, identification, tracking and handling of production objects and their condition: Information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manner.	Requirement 2.2: Physical objects are identified automatically	R07	object identification	4,11	5	5	5	5	1	1	5	5	5
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	3,46	4,43	☒	1	Nothing found	☒	☒	3,4	☒	5
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	2,00	1	☒	5	☒	1	Nothing found	Nothing found	☒	1
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	2,23	3,67	2,25	2	Nothing found	☒	Nothing found	1	Nothing found	Nothing found

Figure 190: Pilot Testing Results - Relation Model Overall View

						Dimensions - Production Process					
						Production - Transformation Factors					
						VAF01	VAF02	VAF03	VAF05	VAF04	VAF07
						Worker	Machinery	Tools	Measuring & Test Device	Mounting Device	Furniture
				Short Name Requirement	Arithmetic mean	3,79	3,48	3,43	2,15	1,08	1,00
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing an provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	**Requirement 1.1:** Information exists solely in digital form	R01	digital information	5,00	5					
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	2,85	4	1,8	1,75	1,75	1	
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	2,98	3	3,33	4	1	1,5	Nothing found
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	3,54	3	3,8	5	2	1	
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	3,80	5	4,71	3,67	1	1	Nothing found
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	**Requirement 2.2:** Physical objects are identified automatically	R07	object identification	4,11	5	5	5	5	1	1
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	3,46	4,43		1	Nothing found		
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	2,00	1		5		1	Nothing found
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	2,23	3,67	2,25	2	Nothing found		Nothing found

Figure 191: Pilot Testing Results - Relation Model - Dimensions Production Process

						Dimensions - Material Flows		
						Transport/Convey - Transformation Factors	Warehouse/Buffer - Transformation Factors	Transport- and Logistics Box, Consumables in the Logistics - Transformation Factors
						VAF10	VAF14	VAF16
						Conveying Device	Warehouse Facility	Loading Aid
				Short Name Requirement	Arithmetic mean	4,20	4,17	4,14
Digital Information	Requirement-Field 1: *Continuous and automated collection, processing an provision of digitized information:* relevant information is collected at any time, integrated with all production data and provided targeted within the production system, and exists solely in digital format	**Requirement 1.1:** Information exists solely in digital form	R01	digital information	5,00	☒	☒	☒
		Requirement 1.2: Digital Information is collected automatically	R02	collected information	2,85	5	2,5	5
		Requirement 1.3: Digital Information is processed automatically	R03	processed information	2,98	5	Nothing found	3
		Requirement 1.4: Digital Information is provided automatically	R04	provided information	3,54	5	Nothing found	5
		Requirement 1.5: Digital Information is integrated automatically	R05	integrated information	3,80	5	5	5
Physical Object	Requirement-Field 2: *Automatic detection, identification, tracking and handling of production objects and their condition:* information about location and state of physical objects within the production process is detected and processed automatically and production objects are handled in automated manners.	**Requirement 2.2:** Physical objects are identified automatically	R07	object identification	4,11	5	5	5
		Requirement 2.3: Physical objects are tracked automatically	R08	object tracking	3,46	3,4	☒	5
		Requirement 2.4: Physical objects are handled automatically	R09	object handling	2,00	Nothing found	☒	1
		Requirement 2.5: The physical object's condition is detected automatically	R10	condition detection	2,23	1	Nothing found	Nothing found

Figure 192: Pilot Testing Results - Relation Model - Dimensions Materials Flow

4.3 The resulting Radar Chart

Figure 193 shows the resulting is-state of the implementation level of the existing dimensions visualized in a radar chart where the evaluation results can be seen.

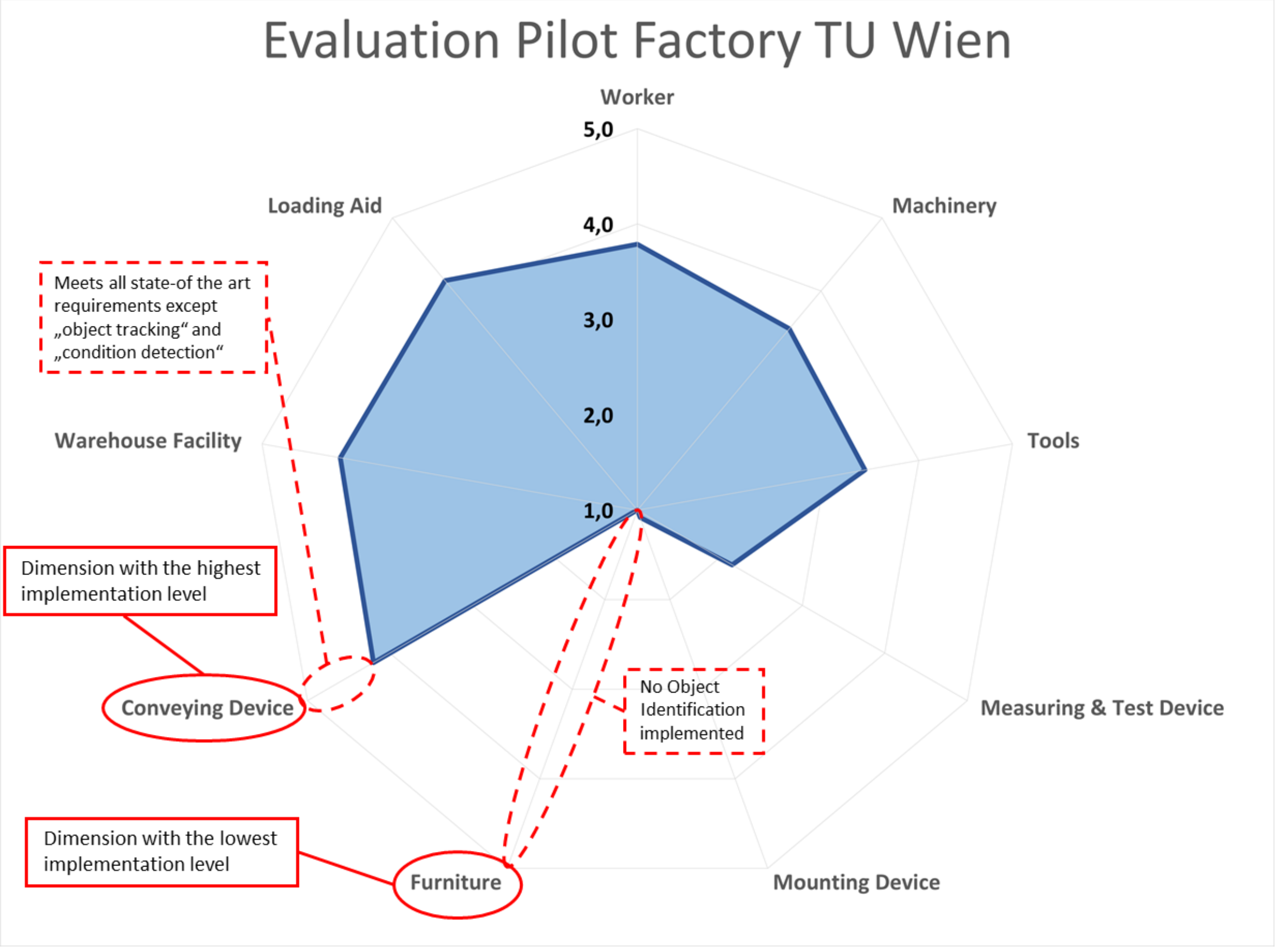


Figure 193: Radar Chart Pilot Testing - Implementation Level of the Dimensions

5 Discussion and Outlook

The aim of this thesis was to develop a relation model to link the requirements for a digitalized value-added process with its existing transformation factors to determine the degree of implementation for digitalization of value-added processes in manufacturing companies. Thus, the research question to be answered in this thesis has been defined as follows:

"How can the requirements for a digitalized value-added process be interlinked with its transformation factors and how can the requirements be implemented for the value-adding-factors?"

In the following chapters, the results of the thesis are discussed, and further research directions and developments of the relation model are outlined.

5.1 Summary of Results and Findings

The result of the thesis is a relation model that allows to determine the degree of implementation for digitalization in manufacturing companies in 10 dimensions (Worker, Machinery, Tools, Measuring & Test Device, Mounting Device, Furniture, Conveying Device, Conveying System, Warehouse Facility, Loading Aid). Each of these dimensions can be evaluated on a scale from 1 to 5 (1-low implementation to 5-high implementation) or in other words there exist 5 levels to represent the degree of implementation for digitalization of value-added processes. The evaluation is based on comparing the value-added processes of the company with 165 abstract implementation concepts where each of these concepts consists of a huge number of concrete best practice implementation examples elaborated from the literature research. Therefore, it must be clear that the person who carries out the evaluation must know the concrete implementation examples of each matching box. The result is then presented in a so-called implementation Microsoft Excel-report that consists of tables to see detailed results and a radar chart for an overall evaluation result.

In order, to fill the 89 matching boxes of the relation model with concrete implementation examples, a very time-consuming systematic literature review was conducted using the database "Science-Direct". For searching suitable literature, more than 1111 search terms were defined resulting in 8875 findings after applying the 1st degree inclusion/exclusion-criteria. After applying the 2nd degree criteria only 332 publications out of the 8875 findings were considered for the further development of the relation model. The reason for using only one database was the limited time while screening the findings. However, even using only one database resulted in very useful best practice implementation examples to create abstract implementation concepts for the evaluation.

After filling the matching boxes with implementation examples and clustering them to abstract concepts, the relation model has then been tested in the pilot factory of the TU Wien to ensure applicability and representative results. Although there is room for improvement the first test of the relation model was a success. During the evaluation in the pilot factory the main issue of the is-state of the relation model became visible. Due to the fact, that transferring the model into a practical tool was not part of the thesis, it was very tricky to evaluate the abstract implementation concepts without all the process knowledge. It was also very time-consuming going through all the concrete implementation examples which was necessary for the evaluation.

5.2 Further Research Directions

After testing the relation model in the pilot factory further research directions were discussed and defined:

- Additional literature research on concrete implementation examples on other online sources to increase the model’s density of examples
- Additional pilot-testing of the relation model in different manufacturing industries to verify the model’s applicability
- Transferring the model into a practical tool to enable the determination of the degree of implementation by asking specific questions

As already mentioned, due to limited time during the literature research only one online search-engine was used for searching concrete implementation examples. Although the number of findings and examples was adequate, there is still a risk of not mentioning a best-practice example which could have been found on another online search-engine. Based on this fact, an additional literature research on other online sources will be conducted in the future to increase the model’s density of concrete implementation examples.

One of the most time-consuming further research directions will be the task of transferring the model into a practical tool. This enables the determination of the degree of implementation by asking specific questions by following the value-stream of manufacturing companies. This tool will eliminate the need of knowing all the concrete implementation examples for the person who conducts the evaluation as well as the need of specific process knowledge by using easy to answer questions.

5.3 Conclusion of Thesis

By looking at the first part of the initially defined research question - How can the requirements for a digitalized value-added process be interlinked with its transformation factors? - the following answer can be given: A relation model links the requirements, more precisely the requirement-fields physical objects and information with its existing transformation factors (dimensions) in an L-shaped matrix.

Through this linkage, so-called “matching boxes“ were developed, which had to be filled with concrete implementation examples from literature in order to answer the question of how the requirements for the transformation factors (dimensions) can be implemented which answers the second part of the research question - How can the requirements be implemented for the value-adding-factors?

In addition to answer only the research question, the developed model also enables to determine implementation level for digitalization of manufacturing companies value-added processes in multiple dimensions in order to derive any potential for improvement and measures from this information.

6 Appendix

6.1 Full Results – Systematic literature review

In the following chapter the full results of the systematic literature review to fill the matching boxes of the relation model (see Chapter 3.2) are shown (see Table 7).

Term_ID	**Used Search-Term (as entered)**	**Results after general and 1st degree criteria**	**Results after 2nd degree criteria**
R04VAF01	**Provided Information-Digital Information is provided automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_1	Provided Information AND Production Worker	33	4
ST_2	Provided Information AND Production Employee	16	1
ST_3	Provided Information AND Production Staff	15	0
ST_4	Information Provision AND Production Worker	1	1
ST_5	Information Provision AND Production Employee	0	0
ST_6	Information Provision AND Production Staff	1	0
ST_7	"Worker Information System"	3	2
ST_8	Worker AND "Assistance System"	3	2
ST_9	Production AND "Assistance System"	11	1
ST_10	Manufacturing and "Assistance System"	6	0
ST_11	Assembly and "Assistance System"	4	0
ST_12	Worker AND "Information System"	36	4
ST_13	Production AND "Information System"	201	3
ST_14	Manufacturing and "Information System"	113	0
ST_15	Assembly and "Information System"	14	2
ST_16	Worker AND "Mobile Devices"	21	1
ST_17	Production AND "Mobile Devices"	41	5
ST_18	Manufacturing and "Mobile Devices"	20	4
ST_19	Assembly and "Mobile Devices"	5	0
ST_20	Visual AND "Assistance System"	10	0
ST_21	Digital AND "Assistance System"	9	0
ST_22	Information AND Production Worker	80	2
ST_23	Worker AND "Information Assistance"	0	0
ST_24	Production AND "Information Assistance"	0	0
ST_25	Manufacturing AND "Information Assistance"	0	0
ST_26	Assembly AND "Information Assistance"	0	0
ST_27	Worker AND Information Assistance	12	1
ST_28	Production AND Information Assistance	29	1
ST_29	Manufacturing AND Information Assistance	15	0
ST_30	Assembly AND Information Assistance	5	0

R01VAF01	**Digital Information-Information exists solely in digital form**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_31	Digital Information AND Production Worker	8	0
ST_32	Digital Information AND Production Employee	4	0
ST_33	Digital Information AND Production Staff	2	0
ST_34	Solely Digital Information AND Production	1	0
ST_35	Solely Digital Information AND Warehouse	0	0
ST_36	Solely Digital Information AND Logistics	0	0
ST_37	Digital AND "Information System"	105	0
ST_38	Worker AND "Digital Information"	2	0
ST_39	Production AND "Digital Information"	4	0
ST_40	Manufacturing and "Digital Information"	5	1
ST_41	Assembly and "Digital Information"	3	0
ST_42	Paperless AND Production	2	1
ST_43	Paperless AND Warehouse	0	0
ST_44	Paperless AND Factory	0	0
ST_45	Paperless AND Manufacturing	3	1
ST_46	Paperless AND Logistics	1	0
ST_47	"Solely Digital Information" AND Worker	0	0
R02VAF01	**Collected Information-Digital Information is collected automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_48	Collect Digital Information AND Production Worker	1	1
ST_49	Collect Digital Information AND Logistics Worker	0	0
ST_50	Collect Digital Information AND Warehouse Worker	0	0
ST_51	Collect Digital Information AND Production Employee	0	0
ST_52	Collect Digital Information AND Production Staff	0	0
ST_53	Information Collection AND Production Worker	5	0
ST_54	Information Collection AND Logistics Worker	0	0
ST_55	Information Collection AND Warehouse Worker	0	0
ST_56	Information Collection AND Production Employee	2	0
ST_57	Information Collection AND Production Staff	1	0
ST_58	Condition Monitoring AND Production Worker	8	0
ST_59	Condition Monitoring AND Logistics Worker	0	0
ST_60	Condition Monitoring AND Warehouse Worker	0	0
ST_61	Production Worker AND Sensors	20	4
ST_62	Logistics Worker AND Sensors	4	0
ST_63	Warehouse Worker AND Sensors	1	0
ST_64	Wearable Sensors AND Manufacturing	20	2
R02VAF02	**Collected Information-Digital Information is collected automatically**		
	Maschinery		
ST_65	"Collect Information" AND Machine	11	0
ST_66	Collect Digital Information AND Machine	17	0
ST_67	Information Collection AND "Machine Tools"	26	5
ST_68	"Condition Monitoring" AND "Machine Tools"	21	11
ST_69	"Collect Data" AND Machine	20	0
ST_70	"Data Collection" AND Machine	74	0
ST_71	"Information Acquisition" AND Machine	7	2
ST_72	"Machine Data Acquisition"	1	1

ST_73	Sensor AND "Machine Tools"	58	7
ST_74	"Smart Machine"	8	2
R02VAF03	**Collected Information-Digital Information is collected automatically**		
	Tools		
ST_75	"Collect Information" AND Tools	20	1
ST_76	Collect Digital Information AND Tools	55	0
ST_77	"Information Collection" AND Tools	9	0
ST_78	"Condition Monitoring" AND Tools	116	18
ST_79	"Collect Data" AND Tools	29	0
ST_80	"Data Collection" AND Tools	52	0
ST_81	"Information Acquisition" AND Tools	19	0
ST_82	"Tool Data Acquisition"	0	0
ST_83	"Smart Tools"	6	2
R02VAF04	**Collected Information-Digital Information is collected automatically**		
	Mounting Device		
ST_84	"Collect Information" AND Mounting Device	0	0
ST_85	Collect Digital Information AND "Mounting Device"	1	0
ST_86	Information Collection AND Mounting Device	2	0
ST_87	Condition Monitoring AND "Mounting Device"	0	0
ST_88	Collect Data AND "Mounting Device"	0	0
ST_89	Data Collection AND "Mounting Device"	0	0
ST_90	"Information Acquisition" AND "Mounting Device"	0	0
ST_91	"Mounting Device Data Acquisition"	0	0
ST_92	"Smart Mounting Device"	0	0
ST_93	"Collect Information" AND Mounting	3	0
ST_94	Collect Digital Information AND Mounting	5	0
ST_95	Information Collection AND Mounting	0	0
ST_96	"Condition Monitoring" AND Mounting	22	0
ST_97	"Collect Data" AND Mounting	7	0
ST_98	"Data Collection" AND Mounting	0	0
ST_99	"Information Acquisition" AND Mounting	0	0
ST_100	"Mounting Data Acquisition"	0	0
ST_101	"Smart Mounting"	0	0
ST_102	"Collect Information" AND "Holding Device"	0	0
ST_103	Collect Digital Information AND "Holding Device"	0	0
ST_104	Information Collection AND "Holding Device"	0	0
ST_105	"Condition Monitoring" AND "Holding Device"	0	0
ST_106	"Collect Data" AND "Holding Device"	0	0
ST_107	Data Collection AND "Holding Device"	0	0
ST_108	Information Acquisition AND "Holding Device"	0	0
ST_109	"Holding Device Data Acquisition"	0	0
ST_110	"Smart Holding Device"	0	0
R02VAF05	**Collected Information-Digital Information is collected automatically**		
	Measuring & Test Device		
ST_111	Collect Information AND "Measuring Device"	2	1
ST_112	Collect Digital Information AND "Measuring Device"	0	0
ST_113	Information Collection AND Measuring Device	17	0
ST_114	Condition Monitoring AND "Measuring Device"	4	0

ST_115	Collect Data AND "Measuring Device"	7	0
ST_116	Data Collection AND "Measuring Device"	0	0
ST_117	Information Acquisition AND "Measuring Device"	0	0
ST_118	"Measuring Device Data Acquisition"	0	0
ST_119	"Smart Measuring Device"	0	0
ST_120	Collect Information AND "Test Device"	0	0
ST_121	Collect Digital Information AND "Test Device"	0	0
ST_122	Information Collection AND "Test Device"	0	0
ST_123	Condition Monitoring AND "Test Device"	4	0
ST_124	Collect Data AND "Test Device"	4	0
ST_125	Data Collection AND "Test Device"	1	0
ST_126	Information Acquisition AND "Test Device"	1	0
ST_127	"Test Device Data Acquisition"	0	0
ST_128	"Smart Test Device"	0	0
R02VAF10	**Collected Information-Digital Information is collected automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_129	Collect Information AND intralogistics	0	0
ST_130	Collect Digital Information AND intralogistics	0	0
ST_131	Information Collection AND intralogistics	0	0
ST_132	Condition Monitoring AND intralogistics	1	1
ST_133	Collect Data AND intralogistics	1	0
ST_134	Data Collection AND intralogistics	0	0
ST_135	Information Acquisition AND intralogistics	0	0
ST_136	"conveying Data Acquisition" AND intralogistics	0	0
ST_137	Sensor AND intralogistics	1	0
ST_138	"Smart intralogistics"	0	0
ST_139	Condition Monitoring AND stacker crane	0	0
ST_140	Condition Monitoring AND industrial trucks	2	0
ST_141	Condition Monitoring AND Lift Truck	0	0
ST_142	Condition Monitoring AND Pallet Truck	1	0
ST_143	Condition Monitoring AND Automated Guided Vehicle System	2	2
ST_144	Condition Monitoring AND material handling trucks	0	0
ST_145	Condition Monitoring AND Bridge Crane	2	0
ST_146	Condition Monitoring AND monorail	0	0
R02VAF11	**Collected Information-Digital Information is collected automatically**		
	Conveying System (Continuous Conveyor)		
ST_147	Collect Information AND continuous conveyor	0	0
ST_148	Collect Digital Information AND continuous conveyor	0	0
ST_149	Information Collection AND continuous conveyor	0	0
ST_150	Condition Monitoring AND continuous conveyor	0	0
ST_151	Collect Data AND continuous conveyor	1	1
ST_152	Data Collection AND continuous conveyor	0	0
ST_153	Information Acquisition AND continuous conveyor	0	0
ST_154	"conveyor Data Acquisition"	0	0
ST_155	Sensor AND "continuous conveyor"	5	1
ST_156	"Smart continuous conveyor"	0	0
ST_157	Collect Information AND conveyor	2	1

ST_158	Collect Digital Information AND conveyor	1	0
ST_159	Information Collection AND conveyor	0	0
ST_160	Condition Monitoring AND conveyor	13	1
ST_161	Collect Data AND conveyor	8	0
ST_162	Data Collection AND conveyor	5	0
ST_163	Information Acquisition AND conveyor	3	1
ST_164	Sensor AND conveyor	55	4
ST_165	Smart AND conveyor	5	0
R02VAF14	**Collected Information-Digital Information is collected automatically**		
	Warehouse Facility (Shelfs, etc.)		
ST_166	Collect Information AND "warehouse facility"	3	0
ST_167	Collect Information AND stock	35	0
ST_168	Collect Information AND warehouse	38	0
ST_169	Collect Information AND shelf	20	1
ST_170	Collect Information AND assembly shelf	0	0
ST_171	Collect Information AND rack	2	0
ST_172	Collect Information AND Kanban Storage System	0	0
ST_173	Condition Monitoring AND "warehouse facility"	0	0
ST_174	Condition Monitoring AND warehouse	6	0
ST_175	Condition Monitoring AND shelf	37	0
ST_176	Condition Monitoring AND assembly shelf	3	0
ST_177	Condition Monitoring AND rack	10	0
ST_178	Condition Monitoring AND Kanban Storage	0	0
ST_179	Collect Data AND warehouse facility	3	1
ST_180	Collect Data AND warehouse	67	8
ST_181	Collect Data AND shelf	55	0
ST_182	Collect Data AND rack	11	0
ST_183	Collect Data AND Kanban Shelf	0	0
ST_184	Collect Data AND Kanban Storage	0	0
ST_185	"Warehouse Data Acquisition"	19	1
ST_186	Sensor AND warehouse	36	5
ST_187	Sensor AND shelf	230	0
ST_188	Sensor AND rack	14	0
ST_189	Sensor AND stock	56	0
ST_190	Sensor AND Kanban Storage	0	0
ST_191	Smart warehouse	16	4
ST_192	Smart shelf	47	0
ST_193	Smart assembly shelf	0	0
ST_194	Smart rack	4	0
ST_195	Smart Kanban Storage	0	0
R02VAF16	**Collected Information-Digital Information is collected automatically**		
	Loading Aid		
ST_196	Collect Information AND loading aid	5	0
ST_197	Collect Information AND large carrier	1	0
ST_198	Collect Information AND small load carrier	0	0
ST_199	Collect Information AND loading equipment	10	0
ST_200	Collect Information AND picking boxes	0	0
ST_201	Condition Monitoring AND loading aid	32	0

ST_202	Condition Monitoring AND large carrier	6	0
ST_203	Condition Monitoring AND small load carrier	0	0
ST_204	Condition Monitoring AND loading equipment	51	0
ST_205	Condition Monitoring AND picking boxes	1	0
ST_206	Collect Data AND loading aid	18	0
ST_207	Collect Data AND large carrier	7	0
ST_208	Collect Data AND small load carrier	0	0
ST_209	Collect Data AND loading equipment	43	0
ST_210	Collect Data AND picking boxes	0	0
ST_211	Sensor AND loading aid	35	0
ST_212	Sensor AND large carrier	76	0
ST_213	Sensor AND small load carrier	2	0
ST_214	Sensor AND loading equipment	73	0
ST_215	Sensor AND picking boxes	4	0
ST_216	Smart loading aid	13	0
ST_217	Smart large carrier	11	0
ST_218	Smart small load carrier	2	0
ST_219	Smart loading equipment	40	0
ST_220	Smart picking boxes	0	0
ST_221	Collect Information AND small parts carrier	0	0
ST_222	Condition Monitoring AND small parts carrier	0	0
ST_223	Collect Data AND small parts carrier	1	0
ST_224	Sensor AND small parts carrier	1	0
ST_225	Smart small parts carrier	0	0
ST_226	Collect Information AND container	10	0
ST_227	Condition Monitoring AND container	29	4
ST_228	Collect Data AND container	34	1
ST_229	Sensor AND container	88	6
ST_230	Smart container	25	0
ST_231	Collect Information AND bin	8	2
ST_232	Condition Monitoring AND bin	15	0
ST_233	Collect Data AND bin	27	0
ST_234	Sensor AND bin	49	1
ST_235	Smart bin	10	0
R03VAF01	**Processed Information-Digital Information is processed automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_236	Process Digital Information AND Production Worker	4	1
ST_237	Process Digital Information AND Logistics Worker	2	0
ST_238	Process Digital Information AND Warehouse Worker	0	0
ST_239	Handle Digital Information AND Production Worker	3	1
ST_240	Handle Digital Information AND Logistics Worker	2	0
ST_241	Digital Competence AND Production Worker	1	0
ST_242	Digital Competence AND Logistics Worker	1	0
ST_243	Digital Competence AND Warehouse Worker	0	0
ST_244	Digital Competence AND Production Employee	1	1
ST_245	Digital Competence AND Production Staff	0	0
ST_246	Digital Information AND Production Worker	8	3
ST_247	Digital Information AND Logistics Worker	2	0

ST_248	Digital Information AND Warehouse Worker	1	0
R03VAF02	**Processed Information-Digital Information is processed automatically**		
	Machinery		
ST_249	"Process Information" AND Machine	45	4
ST_250	Process Digital Information AND Machine	101	9
ST_251	"Process Information" AND Machine Tools	11	0
ST_252	Process Digital Information AND "Machine Tools"	35	2
ST_253	"Process Data" AND Machine	69	10
ST_254	"Machine Data Processing"	0	0
ST_255	"Process Data" AND Machine Tools	27	0
ST_256	"Data Analytics" AND Machine	109	6
R03VAF03	**Processed Information-Digital Information is processed automatically**		
	Tools		
ST_257	"Process Information" AND Tools	35	2
ST_258	Process Digital Information AND Tools	116	0
ST_259	"Information Processing" AND Tools	75	0
ST_260	"Process Data" AND Tools	80	2
ST_261	"Tool Data Processing"	1	0
ST_262	"Data Analytics" AND Tools	98	0
R03VAF04	**Processed Information-Digital Information is processed automatically**		
	Mounting Device		
ST_263	"Process Information" AND Mounting Device	0	0
ST_264	Process Digital Information AND Mounting Device	1	0
ST_265	"Information Processing" AND Mounting Device	1	0
ST_266	"Process Data" AND Mounting Device	1	0
ST_267	"Mounting Device Data Processing"	0	0
ST_268	"Mounting Device" AND "Data Analytics"	0	0
ST_269	"Process Information" AND "Holding Device"	0	0
ST_270	Process Digital Information AND "Holding Device"	0	0
ST_271	"Information Processing" AND "Holding Device"	0	0
ST_272	"Process Data" AND Holding Device	0	0
ST_273	"Holding Device Data Processing"	0	0
ST_274	"Holding Device" AND "Data Analytics"	0	0
ST_275	"Process Information" AND Fixture	0	0
ST_276	Process Digital Information AND Fixture	1	0
ST_277	"Information Processing" AND Fixture	0	0
ST_278	"Process Data" AND Fixture	2	0
ST_279	"Fixture Data Processing"	0	0
ST_280	Fixture AND "Data Analytics"	0	0
R03VAF05	**Processed Information-Digital Information is processed automatically**		
	Measuring & Test Device		
ST_281	"Process Information" AND "Measuring Device"	1	0
ST_282	Process Digital Information AND "Measuring Device"	1	0
ST_283	"Information Processing" AND "Measuring Device"	0	0
ST_284	"Process Data" AND "Measuring Device"	0	0
ST_285	"Measuring Device Data Processing"	0	0
ST_286	"Measuring Device" AND "Data Analytics"	0	0
ST_287	"Process Information" AND "Test Device"	0	0

ST_288	Process Digital Information AND "Test Device"	0	0
ST_289	"Information Processing" AND "Test Device"	0	0
ST_290	"Process Data" AND "Test Device"	0	0
ST_291	"Test Device Data Processing"	0	0
ST_292	"Test Device" AND "Data Analytics"	0	0
R03VAF10	**Processed Information-Digital Information is processed automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_293	"Process Information" AND "Conveying Device"	0	0
ST_294	Process Digital Information AND "Conveying Device"	0	0
ST_295	"Information Processing" AND "Conveying Device"	0	0
ST_296	"Process Data" AND "Conveying Device"	0	0
ST_297	"Conveying Device Data Processing"	0	0
ST_298	"Conveying Device" AND "Data Analytics"	0	0
ST_299	"Process Information" AND "Discontinuous Conveyor"	0	0
ST_300	Process Digital Information AND "Discontinuous Conveyor"	0	0
ST_301	"Information Processing" AND "Discontinuous Conveyor"	0	0
ST_302	"Process Data" AND "Discontinuous Conveyor"	0	0
ST_303	"Discontinuous Conveyor Data Processing"	0	0
ST_304	"Discontinuous Conveyor " AND "Data Analytics"	0	0
ST_305	Process Information AND "stacker crane"	0	0
ST_306	Process Information AND "industrial trucks"	0	0
ST_307	Process Information AND "Lift Truck"	0	0
ST_308	Process Information AND "Pallet Truck"	0	0
ST_309	Process Information AND "Automated Guided Vehicle"	1	1
ST_310	Process Information AND "material handling trucks"	0	0
ST_311	Process Information AND "Bridge Crane"	0	0
ST_312	Process Information AND monorail	0	0
R03VAF11	**Processed Information-Digital Information is processed automatically**		
	Conveying System (Continuous Conveyor)		
ST_313	Process Information AND "Conveying System"	1	0
ST_314	Process Digital Information AND "Conveying System"	0	0
ST_315	"Information Processing" AND "Conveying System"	0	0
ST_316	Process Data AND "Conveying System"	4	0
ST_317	"Conveying System Data Processing"	0	0
ST_318	"Conveying System" AND "Data Analytics"	0	0
ST_319	Process Information AND "Continuous Conveyor"	0	0
ST_320	Process Digital Information AND "Continuous Conveyor"	0	0
ST_321	"Information Processing" AND "Continuous Conveyor"	0	0
ST_322	Process Data AND "Continuous Conveyor"	1	1
ST_323	"Continuous Conveyor Data Processing"	0	0
ST_324	"Continuous Conveyor" AND "Data Analytics"	0	0
ST_325	Process Information AND Conveyor	23	2
ST_326	Process Digital Information AND Conveyor	2	0
ST_327	Information Processing AND Conveyor	23	0
ST_328	Process Data AND Conveyor	39	2
ST_329	"Conveyor Data Processing"	0	0
ST_330	Conveyor AND "Data Analytics"	0	0

R03VAF14	**Processed Information-Digital Information is processed automatically**		
	Warehouse Facility (Shelfs, etc.)		
ST_331	"Process Information" AND warehouse	1	0
ST_332	Process Digital Information AND warehouse	6	0
ST_315	"Information Processing" AND warehouse	2	0
ST_316	"Process Data" AND warehouse	12	0
ST_317	"warehouse Data Processing"	0	0
ST_318	warehouse AND "Data Analytics"	14	0
ST_319	"Process Information" AND stock	0	0
ST_320	Process Digital Information AND stock	4	0
ST_321	"Information Processing" AND stock	5	0
ST_322	"Process Data" AND stock	1	0
ST_323	"stock Data Processing"	0	0
ST_324	stock AND "Data Analytics"	7	0
ST_325	"Process Information" AND shelf	1	0
ST_326	Process Digital Information AND shelf	8	0
ST_327	"Information Processing" AND shelf	2	0
ST_328	"Process Data" AND shelf	2	0
ST_329	"shelf Data Processing"	0	0
ST_330	shelf AND "Data Analytics"	4	0
ST_331	"Process Information" AND rack	0	0
ST_332	Process Digital Information AND rack	0	0
ST_333	"Information Processing" AND rack	0	0
ST_334	"Process Data" AND rack	0	0
ST_335	"rack Data Processing"	0	0
ST_336	rack AND "Data Analytics"	0	0
R03VAF16	**Processed Information-Digital Information is processed automatically**		
	Loading Aid		
ST_337	"Process Information" AND loading aid	3	0
ST_338	Process Digital Information AND loading aid	1	0
ST_339	"Information Processing" AND loading aid	3	0
ST_340	"Process Data" AND loading aid	0	0
ST_341	"loading aid Data Processing"	0	0
ST_342	loading aid AND "Data Analytics"	0	0
ST_343	"Process Information" AND large carrier	0	0
ST_344	Process Digital Information AND large carrier	3	0
ST_345	"Information Processing" AND large carrier	1	0
ST_346	"Process Data" AND large carrier	0	0
ST_347	"large carrier Data Processing"	0	0
ST_348	large carrier AND "Data Analytics"	0	0
ST_349	"Process Information" AND small load carrier	0	0
ST_350	Process Digital Information AND small load carrier	0	0
ST_351	"Information Processing" AND small load carrier	0	0
ST_352	"Process Data" AND small load carrier	0	0
ST_353	"small load carrier Data Processing"	0	0
ST_354	small load carrier AND "Data Analytics"	0	0
ST_355	"Process Information" AND transport box	0	0
ST_356	Process Digital Information AND transport box	1	0

ST_357	"Information Processing" AND transport box	0	0
ST_358	"Process Data" AND transport box	0	0
ST_359	"transport box Data Processing"	0	0
ST_360	transport box AND "Data Analytics"	0	0
ST_361	"Process Information" AND container	1	0
ST_362	Process Digital Information AND container	3	0
ST_363	"Information Processing" AND container	0	0
ST_364	"Process Data" AND container	1	0
ST_365	"container Data Processing"	0	0
ST_366	container AND "Data Analytics"	1	0
ST_367	"Process Information" AND bin	0	0
ST_368	Process Digital Information AND bin	5	0
ST_369	"Information Processing" AND bin	2	0
ST_370	"Process Data" AND bin	1	0
ST_371	"bin Data Processing"	0	0
ST_372	bin AND "Data Analytics"	0	0
R04VAF02	**Provided Information-Digital Information is provided automatically**		
	Machinery		
ST_373	"Provide Information" AND Machine	44	1
ST_374	Provide Digital Information AND Machine	99	5
ST_375	"Provide Information" AND Machine Tools	11	0
ST_376	Provide Digital Information AND "Machine Tools"	1	0
ST_377	"Provide Data" AND Machine	22	0
ST_378	"Machine to Machine" AND Communication	17	4
ST_379	"Provide Data" AND Machine Tools	4	0
ST_380	"Communication Protocol" AND Machine	25	5
ST_381	"Communication Technology" AND Machine	35	10
ST_382	Digital Interface AND Machine	60	4
R04VAF03	**Provided Information-Digital Information is provided automatically**		
	Tools		
ST_383	"Provide Information" AND Tools	86	1
ST_384	Provide Digital Information AND Tools	126	0
ST_385	"Provide Data" AND Tools	30	0
ST_386	"Tool Data Provision"	0	0
ST_387	"Communication Protocol" AND Tools	44	5
ST_388	"Communication Technology" AND Tools	88	6
ST_389	Interface AND Production Tool	115	9
R04VAF04	**Provided Information-Digital Information is provided automatically**		
	Mounting Device		
ST_390	"Provide Information" AND Mounting Device	2	0
ST_391	Provide Digital Information AND Mounting Device	2	1
ST_392	"Provide Data" AND Mounting Device	1	0
ST_393	"Communication Protocol" AND Mounting Device	1	0
ST_394	"Communication Technology" AND Mounting Device	0	0
ST_395	Interface AND Mounting Device	69	0
ST_396	"Provide Information" AND Holding Device	4	0
ST_397	Provide Digital Information AND Holding Device	8	0
ST_398	"Provide Data" AND Holding Device	0	0

ST_399	"Communication Protocol" AND Holding Device	0	0
ST_400	"Communication Technology" AND Holding Device	4	0
ST_401	Interface AND Holding Device	57	2
ST_402	"Provide Information" AND Fixture	1	0
ST_403	Provide Digital Information AND Fixture	3	0
ST_404	"Provide Data" AND Fixture	1	0
ST_405	"Communication Protocol" AND Fixture	0	0
ST_406	"Communication Technology" AND Fixture	1	0
ST_407	Interface AND Fixture	60	4
R04VAF05	**Provided Information-Digital Information is provided automatically**		
	Measuring & Test Device		
ST_408	"Provide Information" AND "Measuring Device"	1	0
ST_409	Provide Digital Information AND "Measuring Device"	0	0
ST_410	"Provide Data" AND "Measuring Device"	0	0
ST_411	"Communication Protocol" AND "Measuring Device"	0	0
ST_412	"Communication Technology" AND "Measuring Device"	0	0
ST_413	Interface AND "Measuring Device"	13	1
ST_414	"Provide Information" AND "Test Device"	1	0
ST_415	Provide Digital Information AND "Test Device"	0	0
ST_416	"Provide Data" AND "Test Device"	0	0
ST_417	"Communication Protocol" AND "Test Device"	0	0
ST_418	"Communication Technology" AND "Test Device"	0	0
ST_419	Interface AND "Test Device"	14	0
R04VAF10	**Provided Information-Digital Information is provided automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_420	"Provide Information" AND "Conveying Device"	0	0
ST_421	Provide Digital Information AND "Conveying Device"	0	0
ST_422	"Provide Data" AND "Conveying Device"	0	0
ST_423	"Communication Protocol" AND "Conveying Device"	0	0
ST_424	"Communication Technology" AND "Conveying Device"	0	0
ST_425	Interface AND "Conveying Device"	0	0
ST_426	"Provide Information" AND "Discontinuous Conveyor"	0	0
ST_427	Provide Digital Information AND "Discontinuous Conveyor"	0	0
ST_428	"Provide Data" AND "Discontinuous Conveyor"	0	0
ST_429	"Communication Protocol" AND "Discontinuous Conveyor"	0	0
ST_430	"Communication Technology" AND "Discontinuous Conveyor"	0	0
ST_431	Interface AND "Discontinuous Conveyor"	0	0
ST_432	Provide Information AND "stacker crane"	0	0
ST_433	Provide Information AND "industrial trucks"	0	0
ST_434	Provide Information AND "Lift Truck"	0	0
ST_435	Provide Information AND "Pallet Truck"	1	0
ST_436	Provide Information AND "Automated Guided Vehicle"	1	1
ST_437	Provide Information AND "material handling trucks"	0	0
ST_438	Provide Information AND "Bridge Crane"	0	0
ST_439	Provide Information AND monorail	0	0

R04VAF11	**Provided Information-Digital Information is provided automatically**		
	Conveying System (Continuous Conveyor)		
ST_440	"Provide Information" AND "Conveying System"	0	0
ST_441	Provide Digital Information AND "Conveying System"	0	0
ST_442	"Provide Data" AND "Conveying System"	1	0
ST_443	"Communication Protocol" AND "Conveying System"	0	0
ST_444	"Communication Technology" AND "Conveying System"	0	0
ST_445	Interface AND "Conveying System"	1	0
ST_446	"Provide Information" AND "Continuous Conveyor"	0	0
ST_447	Provide Digital Information AND "Continuous Conveyor"	0	0
ST_448	"Provide Data" AND "Continuous Conveyor"	0	0
ST_449	"Communication Protocol" AND "Continuous Conveyor"	0	0
ST_450	"Communication Technology" AND "Continuous Conveyor"	0	0
ST_451	Interface AND "Continuous Conveyor"	0	0
ST_452	"Provide Information" AND Conveyor	1	0
ST_453	Provide Digital Information AND Conveyor	1	0
ST_454	"Provide Data" AND Conveyor	1	1
ST_455	"Communication Protocol" AND Conveyor	0	0
ST_456	"Communication Technology" AND Conveyor	1	0
ST_457	Interface AND Conveyor	9	1
R04VAF14	**Provided Information-Digital Information is provided automatically**		
	Warehouse Facility (Shelfs, etc.)		
ST_458	"Provide Information" AND warehouse	1	0
ST_459	Provide Digital Information AND warehouse	9	0
ST_460	"Provide Data" AND warehouse	2	0
ST_461	"Communication Protocol" AND warehouse	1	1
ST_462	"Communication Technology" AND warehouse	3	1
ST_463	Interface AND warehouse	41	0
ST_464	"Provide Information" AND stock	6	0
ST_465	Provide Digital Information AND stock	5	0
ST_466	"Provide Data" AND stock	1	0
ST_467	"Communication Protocol" AND stock	0	0
ST_468	"Communication Technology" AND stock	4	0
ST_469	Interface AND stock	44	0
ST_470	"Provide Information" AND shelf	4	0
ST_471	Provide Digital Information AND shelf	6	0
ST_472	"Provide Data" AND shelf	1	0
ST_473	"Communication Protocol" AND shelf	5	0
ST_474	"Communication Technology" AND shelf	4	0
ST_475	Interface AND shelf	86	1
ST_476	"Provide Information" AND rack	1	0
ST_477	Provide Digital Information AND rack	0	0
ST_478	"Provide Data" AND rack	0	0
ST_479	"Communication Protocol" AND rack	0	0
ST_480	"Communication Technology" AND rack	0	0
ST_481	Interface AND rack	21	0

R04VAF16	**Provided Information-Digital Information is provided automatically**		
	Loading Aid		
ST_482	"Provide Information" AND loading aid	2	0
ST_483	Provide Digital Information AND loading aid	1	0
ST_484	"Provide Data" AND loading aid	2	0
ST_485	"Communication Protocol" AND loading aid	0	0
ST_486	"Communication Technology" AND loading aid	0	0
ST_487	Interface AND "loading aid"	0	0
ST_488	"Provide Information" AND large carrier	2	0
ST_489	Provide Digital Information AND large carrier	4	0
ST_490	"Provide Data" AND large carrier	2	0
ST_491	"Communication Protocol" AND large carrier	0	0
ST_492	"Communication Technology" AND large carrier	0	0
ST_493	Interface AND "large carrier"	1	0
ST_494	"Provide Information" AND small load carrier	0	0
ST_495	Provide Digital Information AND small load carrier	0	0
ST_496	"Provide Data" AND small load carrier	0	0
ST_497	"Communication Protocol" AND small load carrier	0	0
ST_498	"Communication Technology" AND small load carrier	0	0
ST_499	Interface AND small load carrier	2	0
ST_500	"Provide Information" AND transport box	0	0
ST_501	Provide Digital Information AND transport box	1	0
ST_502	"Provide Data" AND transport box	1	0
ST_503	"Communication Protocol" AND transport box	0	0
ST_504	"Communication Technology" AND transport box	1	0
ST_505	Interface AND transport box	12	0
ST_506	"Provide Information" AND container	3	0
ST_507	Provide Digital Information AND container	5	1
ST_508	"Provide Data" AND container	3	0
ST_509	"Communication Protocol" AND container	0	0
ST_510	"Communication Technology" AND container	2	0
ST_511	Interface AND container	77	0
ST_512	"Provide Information" AND bin	3	0
ST_513	Provide Digital Information AND bin	2	0
ST_514	"Provide Data" AND bin	0	0
ST_515	"Communication Protocol" AND bin	0	0
ST_516	"Communication Technology" AND bin	0	0
ST_517	Interface AND bin	21	0
R05VAF01	**Integrated Information-Digital Information is integrated automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_518	"Integrate Information" AND Production Worker	0	0
ST_519	Integrate Digital Information AND Production Worker	4	0
ST_520	"Integrate Data" AND Production Worker	0	0
ST_521	"Data Transmission" AND Production Worker	0	0
ST_522	"Data Reception" AND Production Worker	0	0
ST_523	MES AND Production Worker	3	0
ST_524	"Integrate Information" AND Logistics Worker	0	0
ST_525	Integrate Digital Information AND Logistics Worker	1	0

ST_526	"Integrate Data" AND Logistics Worker	0	0
ST_527	"Data Transmission" AND Logistics Worker	0	0
ST_528	"Data Reception" AND Logistics Worker	0	0
ST_529	MES AND Logistics Worker	0	0
ST_530	"Integrate Information" AND Warehouse Worker	0	0
ST_531	Integrate Digital Information AND Warehouse Worker	1	0
ST_532	"Integrate Data" AND Warehouse Worker	0	0
ST_533	"Data Transmission" AND Warehouse Worker	0	0
ST_534	"Data Reception" AND Warehouse Worker	0	0
ST_535	MES AND Warehouse Worker	0	0
R05VAF02	**Integrated Information-Digital Information is integrated automatically**		
	Machinery		
ST_536	"Integrate Information" AND Machine	4	0
ST_537	Integrate Digital Information AND Machine	34	0
ST_538	"Integrate Data" AND Machine	4	0
ST_539	"Data Transmission" AND Machine	41	5
ST_540	"Data Reception" AND Machine	0	0
ST_541	MES AND Machine Integration	2	0
ST_542	MES AND Machine Data Integration	2	0
R05VAF03	**Integrated Information-Digital Information is integrated automatically**		
	Tools		
ST_543	"Integrate Information" AND Tools	17	0
ST_544	Integrate Digital Information AND Tools	80	3
ST_545	"Integrate Data" AND Tools	17	0
ST_546	"Data Transmission" AND Tools	38	0
ST_547	"Data Reception" AND Tools	1	1
ST_548	MES AND Tools Integration	11	0
R05VAF04	**Integrated Information-Digital Information is integrated automatically**		
	Mounting Device		
ST_549	"Integrate Information" AND Mounting Device	0	0
ST_550	Integrate Digital Information AND Mounting Device	0	0
ST_551	"Integrate Data" AND Mounting Device	0	0
ST_552	"Data Transmission" AND Mounting Device	2	0
ST_553	"Data Reception" AND Mounting Device	0	0
ST_554	MES AND Mounting Device	0	0
ST_555	"Integrate Information" AND Holding Device	0	0
ST_556	Integrate Digital Information AND Holding Device	2	0
ST_557	"Integrate Data" AND Holding Device	0	0
ST_558	"Data Transmission" AND Holding Device	3	0
ST_559	"Data Reception" AND Holding Device	0	0
ST_560	MES AND Holding Device	4	0
ST_561	"Integrate Information" AND Fixture	0	0
ST_562	Integrate Digital Information AND Fixture	0	0
ST_563	"Integrate Data" AND Fixture	0	0
ST_564	"Data Transmission" AND Fixture	1	0
ST_565	"Data Reception" AND Fixture	0	0
ST_566	MES AND Fixture	0	0

R05VAF05	**Integrated Information-Digital Information is integrated automatically**		
	Measuring & Test Device		
ST_567	"Integrate Information" AND "Measuring Device"	0	0
ST_568	Integrate Digital Information AND "Measuring Device"	0	0
ST_569	"Integrate Data" AND "Measuring Device"	0	0
ST_570	"Data Transmission" AND "Measuring Device"	0	0
ST_571	"Data Reception" AND "Measuring Device"	0	0
ST_572	MES AND "Measuring Device"	0	0
ST_573	"Integrate Information" AND "Test Device"	0	0
ST_574	Integrate Digital Information AND "Test Device"	0	0
ST_575	"Integrate Data" AND "Test Device"	0	0
ST_576	"Data Transmission" AND "Test Device"	0	0
ST_577	"Data Reception" AND "Test Device"	0	0
ST_578	MES AND "Test Device"	0	0
R05VAF10	**Integrated Information-Digital Information is integrated automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_579	"Integrate Information" AND "Conveying Device"	0	0
ST_580	Integrate Digital Information AND "Conveying Device"	0	0
ST_581	"Integrate Data" AND "Conveying Device"	0	0
ST_582	"Data Transmission" AND "Conveying Device"	0	0
ST_583	"Data Reception" AND "Conveying Device"	0	0
ST_584	MES AND "Conveying Device"	0	0
ST_585	"Integrate Information" AND "Discontinuous Conveyor"	0	0
ST_586	Integrate Digital Information AND "Discontinuous Conveyor"	0	0
ST_587	"Integrate Data" AND "Discontinuous Conveyor"	0	0
ST_588	"Data Transmission" AND "Discontinuous Conveyor"	0	0
ST_589	"Data Reception" AND "Discontinuous Conveyor"	0	0
ST_590	MES AND "Discontinuous Conveyor"	0	0
ST_591	Integrate Information AND "stacker crane"	0	0
ST_592	Integrate Information AND "industrial trucks"	0	0
ST_593	Integrate Information AND "Lift Truck"	0	0
ST_594	Integrate Information AND "Pallet Truck"	0	0
ST_595	Integrate Information AND "Automated Guided Vehicle"	0	0
ST_596	Integrate Information AND "material handling trucks"	0	0
ST_597	Integrate Information AND "Bridge Crane"	0	0
ST_598	Integrate Information AND monorail	0	0
R05VAF11	**Integrated Information-Digital Information is integrated automatically**		
	Conveying System (Continuous Conveyor)		
ST_599	"Integrate Information" AND "Conveying System"	0	0
ST_600	Integrate Digital Information AND "Conveying System"	0	0
ST_601	"Integrate Data" AND "Conveying System"	0	0
ST_602	"Data Transmission" AND "Conveying System"	0	0
ST_603	"Data Reception" AND "Conveying System"	0	0
ST_604	MES AND "Conveying System"	0	0
ST_605	"Integrate Information" AND "Continuous Conveyor"	0	0
ST_606	Integrate Digital Information AND "Continuous Conveyor"	0	0
ST_607	"Integrate Data" AND "Continuous Conveyor"	0	0

ST_608	"Data Transmission" AND "Continuous Conveyor"	0	0
ST_609	"Data Reception" AND "Continuous Conveyor"	0	0
ST_610	MES AND "Continuous Conveyor"	0	0
ST_611	"Integrate Information" AND Conveyor	0	0
ST_612	Integrate Digital Information AND Conveyor	0	0
ST_613	"Integrate Data" AND Conveyor	0	0
ST_614	"Data Transmission" AND Conveyor	3	1
ST_615	"Data Reception" AND Conveyor	0	0
ST_616	MES AND Conveyor	2	0
R05VAF14	**Integrated Information-Digital Information is integrated automatically**		
	Warehouse Facility (Shelfs, etc.)		
ST_617	"Integrate Information" AND Warehouse	0	0
ST_618	Integrate Digital Information AND Warehouse	6	0
ST_619	"Integrate Data" AND Warehouse	3	0
ST_620	"Data Transmission" AND Warehouse	2	0
ST_621	"Data Reception" AND Warehouse	0	0
ST_622	MES AND Warehouse	2	0
ST_623	"Integrate Information" AND Stock	1	0
ST_624	Integrate Digital Information AND Stock	3	0
ST_625	"Integrate Data" AND Stock	1	0
ST_626	"Data Transmission" AND Stock	0	0
ST_627	"Data Reception" AND Stock	0	0
ST_628	MES AND Stock	5	0
ST_629	"Integrate Information" AND Shelf	1	0
ST_630	Integrate Digital Information AND Shelf	3	0
ST_631	"Integrate Data" AND Shelf	0	0
ST_632	"Data Transmission" AND Shelf	4	0
ST_633	"Data Reception" AND Shelf	1	0
ST_634	MES AND Shelf	2	0
ST_635	"Integrate Information" AND Rack	0	0
ST_636	Integrate Digital Information AND Rack	0	0
ST_637	"Integrate Data" AND Rack	0	0
ST_638	"Data Transmission" AND Rack	1	0
ST_639	"Data Reception" AND Rack	0	0
ST_640	MES AND Rack	0	0
R05VAF16	**Integrated Information-Digital Information is integrated automatically**		
	Loading Aid		
ST_641	"Integrate Information" AND loading aid	0	0
ST_642	Integrate Digital Information AND loading aid	0	0
ST_643	"Integrate Data" AND loading aid	0	0
ST_644	"Data Transmission" AND loading aid	3	1
ST_645	"Data Reception" AND loading aid	0	0
ST_646	MES AND loading aid	1	0
ST_647	"Integrate Information" AND large carrier	0	0
ST_648	Integrate Digital Information AND large carrier	0	0
ST_649	"Integrate Data" AND large carrier	0	0
ST_650	"Data Transmission" AND large carrier	4	0
ST_651	"Data Reception" AND large carrier	0	0

ST_652	MES AND large carrier	1	0
ST_653	"Integrate Information" AND small load carrier	0	0
ST_654	Integrate Digital Information AND small load carrier	0	0
ST_655	"Integrate Data" AND small load carrier	0	0
ST_656	"Data Transmission" AND small load carrier	0	0
ST_657	"Data Reception" AND small load carrier	0	0
ST_658	MES AND small load carrier	0	0
ST_659	"Integrate Information" AND transport box	0	0
ST_660	Integrate Digital Information AND transport box	1	0
ST_661	"Integrate Data" AND transport box	0	0
ST_662	"Data Transmission" AND transport box	1	0
ST_663	"Data Reception" AND transport box	0	0
ST_664	MES AND transport box	0	0
ST_665	"Integrate Information" AND container	1	0
ST_666	Integrate Digital Information AND container	0	0
ST_667	"Integrate Data" AND container	0	0
ST_668	"Data Transmission" AND container	1	1
ST_669	"Data Reception" AND container	0	0
ST_670	MES AND container	1	0
ST_671	"Integrate Information" AND bin	0	0
ST_672	Integrate Digital Information AND bin	0	0
ST_673	"Integrate Data" AND bin	0	0
ST_674	"Data Transmission" AND bin	2	1
ST_675	"Data Reception" AND bin	0	0
ST_676	MES AND bin	6	1
R07VAF01	**Object Identification-Physical Objects are identified automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_677	Identification AND Production Worker	13	1
ST_678	Identifying AND Production Worker	62	0
ST_679	Recognition AND Production Worker	7	1
ST_680	Detection AND Production Worker	6	0
ST_681	Identification AND Logistics Worker	4	0
ST_682	Identifying AND Logistics Worker	4	0
ST_683	Recognition AND Logistics Worker	2	0
ST_684	Detection AND Logistics Worker	1	0
ST_685	Identification AND Warehouse Worker	0	0
ST_686	Identifying AND Warehouse Worker	7	0
ST_687	Recognition AND Warehouse Worker	0	0
ST_688	Detection AND Warehouse Worker	1	0
R07VAF02	**Object Identification-Physical Objects are identified automatically**		
	Machinery		
ST_689	"Machine Identification"	4	0
ST_690	"Machine Identifying"	0	0
ST_691	"Machine Recognition"	11	0
ST_692	"Machine Detection"	3	0
ST_693	RFID AND Machine	50	0
ST_694	Barcode AND Machine	6	0
ST_695	"IP Address" AND Machine	17	2

R07VAF03	**Object Identification-Physical Objects are identified automatically**		
	Tools		
ST_696	"Tool Identification"	2	0
ST_697	"Tool Identifying"	0	0
ST_698	"Tool Recognition"	0	0
ST_699	"Tool Detection"	3	0
ST_700	RFID AND Tools	68	4
ST_701	Barcode AND Tools	23	0
ST_702	"IP Address" AND Tools	21	0
R07VAF04	**Object Identification-Physical Objects are identified automatically**		
	Mounting Device		
ST_703	Identification AND "Mounting Device"	0	0
ST_704	Recognition AND "Mounting Device"	0	0
ST_705	Detection AND "Mounting Device"	1	0
ST_706	RFID AND Mounting Device	4	0
ST_707	Barcode AND Mounting Device	1	0
ST_708	"IP Address" AND Mounting Device	0	0
ST_709	Identification AND Holding Device	21	0
ST_710	Recognition AND "Holding Device"	0	0
ST_711	Detection AND "Holding Device"	0	0
ST_712	RFID AND Holding Device	4	0
ST_713	Barcode AND Holding Device	1	0
ST_714	"IP Address" AND Holding Device	1	0
ST_715	Identification AND Fixture	22	4
ST_716	Recognition AND Fixture	5	0
ST_717	Detection AND Fixture	29	1
ST_718	RFID AND Fixture	1	0
ST_719	Barcode AND Fixture	0	0
ST_720	"IP Address" AND Fixture	0	0
R07VAF05	**Object Identification-Physical Objects are identified automatically**		
	Measuring & Test Device		
ST_721	Identification AND "Measuring Device"	9	1
ST_722	Recognition AND "Measuring Device"	2	0
ST_723	Detection AND "Measuring Device"	12	0
ST_724	RFID AND "Measuring Device"	0	0
ST_725	Barcode AND "Measuring Device"	0	0
ST_726	"IP Address" AND "Measuring Device"	0	0
ST_727	Identification AND "Test Device"	11	2
ST_728	Recognition AND "Test Device"	0	0
ST_729	Detection AND "Test Device"	6	0
ST_730	RFID AND "Test Device"	0	0
ST_731	Barcode AND "Test Device"	0	0
ST_732	"IP Address" AND "Test Device"	0	0
R07VAF07	**Object Identification-Physical Objects are identified automatically**		
	Furniture		
ST_733	Identification AND Furniture	10	0
ST_734	Recognition AND Furniture	11	2
ST_735	Detection AND Furniture	18	0

ST_736	RFID AND Furniture	2	0
ST_737	Barcode AND Furniture	0	0
ST_738	"IP Address" AND Furniture	0	0
ST_739	Identification AND Fitment	0	0
ST_740	Recognition AND Fitment	0	0
ST_741	Detection AND Fitment	0	0
ST_742	RFID AND Fitment	0	0
ST_743	Barcode AND Fitment	0	0
ST_744	"IP Address" AND Fitment	0	0
R07VAF10	**Object Identification-Physical Objects are identified automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_745	Identification AND "Conveying Device"	0	0
ST_746	Recognition AND "Conveying Device"	0	0
ST_747	Detection AND "Conveying Device"	0	0
ST_748	RFID AND "Conveying Device"	0	0
ST_749	Barcode AND "Conveying Device"	0	0
ST_750	"IP Address" AND "Conveying Device"	0	0
ST_751	Identification AND "Discontinuous Conveyor"	0	0
ST_752	Recognition AND "Discontinuous Conveyor"	0	0
ST_753	Detection AND "Discontinuous Conveyor"	0	0
ST_754	RFID AND "Discontinuous Conveyor"	0	0
ST_755	Barcode AND "Discontinuous Conveyor"	0	0
ST_756	"IP Address" AND "Discontinuous Conveyor"	0	0
ST_757	Identification AND "stacker crane"	0	0
ST_758	Identification AND "industrial trucks"	0	0
ST_759	Identification AND "Lift Truck"	0	0
ST_760	Identification AND "Pallet Truck"	0	0
ST_761	Identification AND "Automated Guided Vehicle"	0	0
ST_762	Identification AND "material handling trucks"	0	0
ST_763	Identification AND "Bridge Crane"	0	0
ST_764	Identification AND monorail	0	0
R07VAF11	**Object Identification-Physical Objects are identified automatically**		
	Conveying System (Continuous Conveyor)		
ST_765	Identification AND "Conveying System"	0	0
ST_766	Recognition AND "Conveying System"	0	0
ST_767	Detection AND "Conveying System"	0	0
ST_768	RFID AND "Conveying System"	0	0
ST_769	Barcode AND "Conveying System"	0	0
ST_770	"IP Address" AND "Conveying System"	0	0
ST_771	Identification AND "Continuous Conveyor"	0	0
ST_772	Recognition AND "Continuous Conveyor"	0	0
ST_773	Detection AND "Continuous Conveyor"	0	0
ST_774	RFID AND "Continuous Conveyor"	0	0
ST_775	Barcode AND "Continuous Conveyor"	0	0
ST_776	"IP Address" AND "Continuous Conveyor"	0	0
ST_777	Identification AND Conveyor	1	0
ST_778	Recognition AND Conveyor	1	0
ST_779	Detection AND Conveyor	2	0

ST_780	RFID AND Conveyor	0	0
ST_781	Barcode AND Conveyor	0	0
ST_782	"IP Address" AND Conveyor	0	0
R07VAF14	**Object Identification-Physical Objects are identified automatically**		
	Warehouse Facility (Shelfs, etc.)		
ST_783	Identification AND Warehouse Facility	4	1
ST_784	Recognition AND Warehouse Facility	0	0
ST_785	Detection AND Warehouse Facility	0	0
ST_786	RFID AND Warehouse Facility	2	0
ST_787	Barcode AND Warehouse Facility	0	0
ST_788	"IP Address" AND Warehouse Facility	0	0
ST_789	Identification AND Warehouse Stock	7	1
ST_790	Recognition AND Warehouse Stock	2	0
ST_791	Detection AND Warehouse Stock	1	0
ST_792	RFID AND Warehouse Stock	5	0
ST_793	Barcode AND Warehouse Stock	1	0
ST_794	"IP Address" AND Warehouse Stock	0	0
ST_795	Identification AND Shelf	68	1
ST_796	Recognition AND Shelf	53	0
ST_797	Detection AND Warehouse Shelf	1	0
ST_798	RFID AND Shelf	23	0
ST_799	Barcode AND Shelf	0	0
ST_800	"IP Address" AND Shelf	1	0
ST_801	Identification AND Rack	8	0
ST_802	Recognition AND Rack	2	0
ST_803	Detection AND Rack	13	0
ST_804	RFID AND Rack	1	0
ST_805	Barcode AND Rack	0	0
ST_806	"IP Address" AND Rack	0	0
R07VAF16	**Object Identification-Physical Objects are identified automatically**		
	Loading Aid		
ST_807	Identification AND "loading aid"	0	0
ST_808	Recognition AND "loading aid"	0	0
ST_809	Detection AND "loading aid"	0	0
ST_810	RFID AND "loading aid"	0	0
ST_811	Barcode AND "loading aid"	0	0
ST_812	"IP Address" AND "loading aid"	0	0
ST_813	Identification AND large carrier	27	0
ST_814	Recognition AND large carrier	7	0
ST_815	Detection AND "large carrier"	1	0
ST_816	RFID AND large carrier	3	0
ST_817	Barcode AND large carrier	0	0
ST_818	"IP Address" AND large carrier	1	0
ST_819	Identification AND small load carrier	1	0
ST_820	Recognition AND small load carrier	0	0
ST_821	Detection AND small load carrier	3	0
ST_822	RFID AND small load carrier	0	0
ST_823	Barcode AND small load carrier	0	0

ST_824	"IP Address" AND small load carrier	0	0
ST_825	Identification AND transport box	6	0
ST_826	Recognition AND transport box	1	0
ST_827	Detection AND transport box	7	0
ST_828	RFID AND transport box	0	0
ST_829	Barcode AND transport box	0	0
ST_830	"IP Address" AND transport box	0	0
ST_831	Identification AND transport container	4	0
ST_832	Recognition AND transport container	1	0
ST_833	Detection AND transport container	2	0
ST_834	RFID AND transport container	3	0
ST_835	Barcode AND transport container	0	0
ST_836	"IP Address" AND transport container	0	0
ST_837	Identification AND bin	0	0
ST_838	Recognition AND bin	54	0
ST_839	Detection AND transport bin	2	0
ST_840	RFID AND bin	6	0
ST_841	Barcode AND bin	4	0
ST_842	"IP Address" AND bin	1	0
R08VAF01	**Object Tracking-Physical Objects are tracked automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_843	Tracking AND Production Worker	7	0
ST_844	Localization AND Production Worker	4	0
ST_845	Navigation AND Production Worker	3	1
ST_846	Positioning System AND Production Worker	9	0
ST_847	GPS AND Production Worker	0	0
ST_848	Tracking AND Logistics Worker	0	0
ST_849	Localization AND Logistics Worker	1	0
ST_850	Navigation AND Logistics Worker	0	0
ST_851	Positioning System AND Logistics Worker	5	1
ST_852	GPS AND Logistics Worker	0	0
ST_853	Tracking AND Warehouse Worker	1	0
ST_854	Localization AND Warehouse Worker	0	0
ST_855	Navigation AND Warehouse Worker	0	0
ST_856	Positioning System AND Warehouse Worker	1	0
ST_857	GPS AND Warehouse Worker	0	0
R08VAF03	**Object Tracking-Physical Objects are tracked automatically**		
	Tools		
ST_858	Tracking AND Production Tools	82	0
ST_859	Localization AND Production Tools	9	0
ST_860	Navigation AND Production Tools	17	0
ST_861	Positioning System AND Production Tools	82	1
ST_862	GPS AND Production Tools	8	0
R08VAF05	**Object Tracking-Physical Objects are tracked automatically**		
	Measuring & Test Device		
ST_863	Tracking AND "Measuring Device"	6	0
ST_864	Localization AND "Measuring Device"	1	0
ST_865	Navigation AND "Measuring Device"	0	0

ST_866	Positioning System AND "Measuring Device"	13	0
ST_867	GPS AND "Measuring Device"	0	0
ST_868	Tracking AND "Test Device"	2	0
ST_869	Localization AND "Test Device"	0	0
ST_870	Navigation AND "Test Device"	0	0
ST_871	Positioning System AND "Test Device"	1	0
ST_872	GPS AND "Test Device"	0	0
R08VAF10	**Object Tracking-Physical Objects are tracked automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_873	Tracking AND "Conveying Device"	0	0
ST_874	Localization AND "Conveying Device"	0	0
ST_875	Navigation AND "Conveying Device"	0	0
ST_876	Positioning System AND "Conveying Device"	0	0
ST_877	GPS AND "Conveying Device"	0	0
ST_878	Tracking AND "Discontinuous Conveyor"	0	0
ST_879	Localization AND "Discontinuous Conveyor"	0	0
ST_880	Navigation AND "Discontinuous Conveyor"	0	0
ST_881	Positioning System AND "Discontinuous Conveyor"	0	0
ST_882	GPS AND "Discontinuous Conveyor"	0	0
ST_883	Tracking AND "stacker crane"	1	0
ST_884	Tracking AND "industrial trucks"	0	0
ST_885	Tracking AND Forklift	7	2
ST_886	Tracking AND "Pallet Truck"	1	0
ST_887	Tracking AND "Automated Guided Vehicle"	11	6
ST_888	Indoor localization system	135	11
ST_889	Tracking AND Intralogistics	1	0
ST_890	Tracking AND Transport System	185	2
R08VAF16	**Object Tracking-Physical Objects are tracked automatically**		
	Loading Aid		
ST_891	Tracking AND loading aid	40	0
ST_892	Localization AND loading aid	11	0
ST_893	Navigation AND loading aid	8	0
ST_894	Positioning System AND loading aid	19	0
ST_895	GPS AND loading aid	0	0
ST_896	Tracking AND large carrier	39	0
ST_897	Localization AND large carrier	9	0
ST_898	Navigation AND large carrier	12	0
ST_899	Positioning System AND large carrier	21	0
ST_900	GPS AND large carrier	7	0
ST_901	Tracking AND small load carrier	3	0
ST_902	Localization AND small load carrier	0	0
ST_903	Indoor Navigation System	123	5
ST_904	Positioning System AND small load carrier	0	0
ST_905	GPS AND small load carrier	1	0
ST_906	Tracking AND transport box	3	0
ST_907	Localization AND transport box	2	0
ST_908	Navigation AND transport box	0	0
ST_909	Positioning System AND transport box	3	0

ST_910	GPS AND transport box	0	0
ST_911	Tracking AND transport container	7	0
ST_912	Localization AND transport container	2	0
ST_913	Navigation AND transport container	4	0
ST_914	Positioning System AND transport container	8	0
ST_915	GPS AND transport container	2	0
ST_916	Tracking AND bin	47	1
ST_917	Localization AND bin	11	1
ST_918	Navigation AND bin	7	0
ST_919	Positioning System AND bin	24	0
ST_920	GPS AND bin	12	0
R09VAF01	**Object Handling-Physical Objects are handled automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_921	Handle AND Production Worker	42	0
ST_922	Manipulate AND Production Worker	1	0
ST_923	Wield AND Production Worker	0	0
ST_924	Transport AND Production Worker	11	0
ST_925	Automation AND Production Worker	20	0
ST_926	Handle AND Logistics Worker	9	0
ST_927	Manipulate AND Logistics Worker	0	0
ST_928	Wield AND Logistics Worker	0	0
ST_929	Transport AND Logistics Worker	2	0
ST_930	Automation AND Logistics Worker	2	0
ST_931	Handle AND Warehouse Worker	6	0
ST_932	Manipulate AND Warehouse Worker	0	0
ST_933	Wield AND Warehouse Worker	0	0
ST_934	Transport AND Warehouse Worker	4	0
ST_935	Automation AND Warehouse Worker	0	0
R09VAF03	**Object Handling-Physical Objects are handled automatically**		
	Tools		
ST_933	Handle AND Production Tool	129	0
ST_934	Manipulate AND Production Tool	26	0
ST_935	Wield AND Tools	9	0
ST_936	Transport AND Production Tools	130	1
ST_937	Automation AND Production Tools	119	0
R09VAF04	**Object Handling-Physical Objects are handled automatically**		
	Mounting Device		
ST_938	Handle AND "Mounting Device"	1	0
ST_939	Manipulate AND "Mounting Device"	0	0
ST_940	Wield AND "Mounting Device"	0	0
ST_941	Transport AND "Mounting Device"	0	0
ST_942	Automation AND "Mounting Device"	0	0
ST_943	Handle AND "Holding Device"	0	0
ST_944	Manipulate AND "Holding Device"	0	0
ST_945	Wield AND "Holding Device"	0	0
ST_946	Transport AND "Holding Device"	0	0
ST_947	Automation AND "Holding Device"	0	0
ST_948	Handle AND Fixture	17	0

ST_949	Manipulate AND Fixture	3	0
ST_950	Wield AND Fixture	0	0
ST_951	Transport AND Fixture	2	1
ST_952	Automation AND Fixture	25	3
R09VAF06	**Object Handling-Physical Objects are handled automatically**		
	Consumables (Production VAF06, Packaging VAF18)		
ST_953	Handle AND Consumable	6	0
ST_954	Manipulate AND Consumable	0	0
ST_955	Wield AND Consumable	0	0
ST_956	Transport AND Consumable	8	0
ST_957	Automation AND Consumable	7	0
ST_958	Handle AND Expendable Items	0	0
ST_959	Manipulate AND Expendable Items	0	0
ST_960	Wield AND Expendable Items	0	0
ST_961	Transport AND Expendable Items	0	0
ST_962	Automation AND Expendable Items	0	0
R09VAF07	**Object Handling-Physical Objects are handled automatically**		
	Furniture		
ST_963	Handle AND Furniture	12	1
ST_964	Manipulate AND Furniture	2	0
ST_965	Wield AND Furniture	0	0
ST_966	Transport AND Furniture	7	0
ST_967	Automation AND Furniture	5	0
ST_968	Handle AND Fitment	0	0
ST_969	Manipulate AND Fitment	0	0
ST_970	Wield AND Fitment	0	0
ST_971	Transport AND Fitment	0	0
ST_972	Automation AND Fitment	0	0
R09VAF10	**Object Handling-Physical Objects are handled automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_973	Handle AND "Conveying Device"	0	0
ST_974	Manipulate AND "Conveying Device"	0	0
ST_975	Wield AND "Conveying Device"	0	0
ST_976	Transport AND "Conveying Device"	0	0
ST_977	Automation AND "Conveying Device"	0	0
ST_978	Handle AND "Discontinuous Conveyor"	0	0
ST_979	Manipulate AND "Discontinuous Conveyor"	0	0
ST_980	Wield AND "Discontinuous Conveyor"	0	0
ST_981	Transport AND "Discontinuous Conveyor"	0	0
ST_982	Automation AND "Discontinuous Conveyor"	0	0
ST_983	Handle AND "stacker crane"	2	0
ST_984	Handle AND "industrial trucks"	0	0
ST_985	Handle AND "Lift Truck"	2	0
ST_986	Handle AND "Pallet Truck"	1	0
ST_987	Handle AND "Automated Guided Vehicle"	26	0
ST_988	Handle AND "material handling trucks"	0	0
ST_989	Handle AND "Bridge Crane"	2	0
ST_990	Handle AND monorail	4	0

R09VAF16	**Object Handling-Physical Objects are handled automatically**		
	Loading Aid		
ST_991	Handle AND "loading aid"	0	0
ST_992	Manipulate AND "loading aid"	0	0
ST_993	Wield AND "loading aid"	0	0
ST_994	Transport AND "loading aid"	0	0
ST_995	Automation AND "loading aid"	0	0
ST_996	Handle AND "large carrier"	0	0
ST_997	Manipulate AND "large carrier"	0	0
ST_998	Wield AND "large carrier"	0	0
ST_999	Transport AND "large carrier"	3	0
ST_1000	Automation AND "large carrier"	0	0
ST_1001	Handle AND small load carrier	3	0
ST_1002	Manipulate AND small load carrier	0	0
ST_1003	Wield AND small load carrier	0	0
ST_1004	Transport AND small load carrier	9	0
ST_1005	Automation AND small load carrier	1	0
ST_1006	Handle AND transport box	8	0
ST_1007	Manipulate AND transport box	1	0
ST_1008	Wield AND transport box	0	0
ST_1009	Transport AND transport box	119	0
ST_1010	Automation AND transport box	1	0
ST_1011	Handle AND bin	60	0
ST_1012	Manipulate AND bin	8	0
ST_1013	Wield AND bin	0	0
ST_1014	Transport AND bin	22	0
ST_1015	Automation AND bin	9	0
R10VAF01	**Condition Detection-The physical object's condition is detected automatically**		
	Production Worker VAF01, Logistics Worker VAF09, Warehouse Worker VAF13		
ST_1016	Condition Detection AND Production Worker	3	0
ST_1017	Status Detection AND Production Worker	0	0
ST_1018	State Identification AND Production Worker	2	0
ST_1019	Condition Recognition AND Production Worker	2	0
ST_1020	Condition Detection AND Logistics Worker	0	0
ST_1021	Status Detection AND Logistics Worker	0	0
ST_1022	State Identification AND Logistics Worker	1	0
ST_1023	Condition Recognition AND Logistics Worker	0	0
ST_1024	Condition Detection AND Warehouse Worker	0	0
ST_1025	Status Detection AND Warehouse Worker	0	0
ST_1026	State Identification AND Warehouse Worker	0	0
ST_1027	Condition Recognition AND Warehouse Worker	0	0
R10VAF02	**Condition Detection-The physical object's condition is detected automatically**		
	Machinery		
ST_1028	"Condition Detection" AND Machine	4	1
ST_1029	Status Detection AND Machine	69	4
ST_1030	"State Identification" AND Machine	10	0
ST_1031	"Condition Recognition" AND Machine	4	0

R10VAF03	**Condition Detection-The physical object’s condition is detected automatically**		
	Tools		
ST_1032	"Condition Detection" AND Tools	4	1
ST_1033	"Status Detection" AND Tools	3	0
ST_1034	"State Identification" AND Tools	8	2
ST_1035	"Condition Recognition" AND Tools	1	0
R10VAF05	**Condition Detection-The physical object’s condition is detected automatically**		
	Measuring & Test Device		
ST_1036	Condition Detection AND "Measuring Device"	2	0
ST_1037	Status Detection AND "Measuring Device"	0	0
ST_1038	State Identification AND "Measuring Device"	2	0
ST_1039	Condition Recognition AND "Measuring Device"	1	0
ST_1040	Condition Detection AND "Test Device"	1	0
ST_1041	Status Detection AND "Test Device"	0	0
ST_1042	State Identification AND "Test Device"	3	0
ST_1043	Condition Recognition AND "Test Device"	0	0
R10VAF10	**Condition Detection-The physical object’s condition is detected automatically**		
	Conveying Device (Discontinuous Conveyor)		
ST_1044	Condition Detection AND "Conveying Device"	0	0
ST_1045	Status Detection AND "Conveying Device"	0	0
ST_1046	State Identification AND "Conveying Device"	0	0
ST_1047	Condition Recognition AND "Conveying Device"	0	0
ST_1048	Condition Detection AND "Discontinuous Conveyor"	0	0
ST_1049	Status Detection AND "Discontinuous Conveyor"	0	0
ST_1050	State Identification AND "Discontinuous Conveyor"	0	0
ST_1051	Condition Recognition AND "Discontinuous Conveyor"	0	0
ST_1052	Condition Detection AND "stacker crane"	0	0
ST_1053	Condition Detection AND "industrial truck"	0	0
ST_1054	Condition Detection AND "Lift Truck"	0	0
ST_1055	Condition Detection AND "Pallet Truck"	0	0
ST_1056	Condition Detection AND "Automated Guided Vehicle"	0	0
ST_1057	Condition Detection AND "material handling trucks"	0	0
ST_1058	Condition Detection AND "Bridge Crane"	0	0
ST_1059	Condition Detection AND monorail	0	0
R10VAF11	**Condition Detection-The physical object’s condition is detected automatically**		
	Conveying System (Continuous Conveyor)		
ST_1060	Condition Detection AND "Conveying System"	0	0
ST_1061	Status Detection AND "Conveying System"	0	0
ST_1062	State Identification AND "Conveying System"	0	0
ST_1063	Condition Recognition AND "Conveying System"	0	0
ST_1064	Condition Detection AND "Continuous Conveyor"	0	0
ST_1065	Status Detection AND "Continuous Conveyor"	0	0
ST_1066	State Identification AND "Continuous Conveyor"	0	0
ST_1067	Condition Recognition AND "Continuous Conveyor"	0	0
ST_1068	Condition Detection AND Conveyor	9	0
ST_1069	Status Detection AND Conveyor	0	0
ST_1070	State Identification AND Conveyor	2	0
ST_1071	Condition Recognition AND Conveyor	0	0

R10VAF14	Condition Detection-The physical object’s condition is detected automatically		
	Warehouse Facility (Shelfs, etc.)		
ST_1072	Condition Detection AND Warehouse Facility	0	0
ST_1073	Status Detection AND Warehouse Facility	0	0
ST_1074	State Identification AND Warehouse Facility	0	0
ST_1075	Condition Recognition AND Warehouse Facility	0	0
ST_1076	Condition Detection AND Warehouse Stock	0	0
ST_1077	Status Detection AND Warehouse Stock	0	0
ST_1078	State Identification AND Warehouse Stock	0	0
ST_1079	Condition Recognition AND Warehouse Stock	0	0
ST_1080	Condition Detection AND Shelf	27	0
ST_1081	Status Detection AND Shelf	5	0
ST_1082	State Identification AND Shelf	14	0
ST_1083	Condition Recognition AND Shelf	9	0
ST_1084	Condition Detection AND Rack	3	0
ST_1085	Status Detection AND Rack	2	0
ST_1086	State Identification AND Rack	2	0
ST_1087	Condition Recognition AND Rack	0	0
R10VAF16	**Condition Detection-The physical object’s condition is detected automatically**		
	Loading Aid		
ST_1088	Condition Detection AND "loading aid"	0	0
ST_1089	Status Detection AND "loading aid"	0	0
ST_1090	State Identification AND "loading aid"	0	0
ST_1091	Condition Recognition AND "loading aid"	0	0
ST_1092	Condition Detection AND large carrier	21	0
ST_1093	Status Detection AND large carrier	0	0
ST_1094	State Identification AND large carrier	3	0
ST_1095	Condition Recognition AND large carrier	4	0
ST_1096	Condition Detection AND small load carrier	0	0
ST_1097	Status Detection AND small load carrier	0	0
ST_1098	State Identification AND small load carrier	0	0
ST_1099	Condition Recognition AND small load carrier	0	0
ST_1100	Condition Detection AND transport box	2	0
ST_1101	Status Detection AND transport box	1	0
ST_1102	State Identification AND transport box	3	0
ST_1103	Condition Recognition AND transport box	0	0
ST_1104	Condition Detection AND transport container	1	0
ST_1105	Status Detection AND transport container	0	0
ST_1106	State Identification AND transport container	1	0
ST_1107	Condition Recognition AND transport container	1	0
ST_1108	Condition Detection AND bin	13	0
ST_1109	Status Detection AND bin	1	0
ST_1110	State Identification AND bin	7	0
ST_1111	Condition Recognition AND bin	5	0

Table 7: Full Results - Systematic literature review

6.2 Full Results – Pilot-Testing

In the following chapter the full results of the relation model applied on the pilot factory of the TU Wien are shown (see Table 8).

Nr. of Abstract Implementation Concept	**Matching Box ID: Description** Abstract Implementation Concepts	**Results of the Evaluation (Scale: 1-5)**
	R01VAF01: Digital Information – Production Worker	**5**
1.	Computer-based information	5
	R02VAF01: Collected Information – Production Worker	**4**
2.	Sensor-equipped Wearable Devices	3
3.	Motion Capture Systems	5
	R02VAF02: Collected Information – Machinery	**1,8**
4.	Sensor Integration	3
5.	Data Acquisition Card and Sensor Integration	2
6.	Data Acquisition Card, Sensor Integration and CNC/PLC Control System	1
7.	Sensor Integration with CNC and PLC Control System	1
8.	Data Acquisition from CNC and PLC System	2
	R02VAF03: Collected Information – Tools	**1,75**
9.	Sensor Integration	4
10.	Tool Condition Monitoring (TCM) by Sensor Integration & A/DConverter	1
11.	TCM by Sensor Integration and Data Acquisition Card	1
12.	Sensor Integration with CNC and PLC Control System	1
	R02VAF04: Collected Information – Mounting Device	**1**
13.	RFID-Technology	1
14.	Sensor Integration	1
15.	Sensor Integration and A/D Converter	1
	R02VAF05: Collected Information – Measuring & Test Device	**1,75**
16.	On-Machine 3D Touch Probing and CNC Control System	1
17.	Tool Setting Arm Probing and CNC Control System	1
18.	Laser-based Sensor Integration	4
19.	Scanning Probes	1
	R02VAF09: Collected Information – Logistics Worker	**-**
	(In Box Nr. R02VAF01)	-
	R02VAF10: Collected Information – Conveying Device	**5**
20.	Sensor Integration and Optical Measurement	5
21.	Optical Measurement System	5
22.	Sensor Integration	5
	R02VAF11: Collected Information – Conveying System	**Not implemented**
23.	Sensor Integration and RFID-Technology	Not implemented
	R02VAF13: Collected Information – Warehouse Worker	**-**
	(In Box Nr. R02VAF01)	-

	R02VAF14: Collected Information – Warehouse Facility	**2,5**
24.	Sensor Integration	1
25.	RFID-Technology	4
	R02VAF16: Collected Information – Loading Aid	**5**
26.	RFID-Technology	5
27.	Sensor Integration and RFID-Technology	5
28.	Barcode-based Inventory Management System	5
29.	Sensor Integration	5
	R03VAF01: Processed Information – Production Worker	**3**
30.	Digital Competence	5
31.	Training Systems to improve Digital Competence	1
	R03VAF02: Processed Information – Machinery	**3,33**
32.	Smart Device Applications	1
33.	Internet-based Prognostics and Operations Systems	4
34.	Machine-embedded Hardware	3
35.	Computer Hardware Integration and Cloud Data Management	4
36.	Computer Hardware Integration	4
37.	Processor Monitoring Systems	4
38.	Prognostics Software Systems	1
39.	CNC and PLC Control System Integration	5
40.	Embedded Cyber-Physical System	4
	R03VAF03: Processed Information – Tools	**4**
41.	Processor Monitoring System	1
42.	CNC and PLC Control System Integration	4
43.	Built-in Micro Computer Hardware	5
44.	Personal Computer Hardware Integration	5
45.	Network Platform	5
	R03VAF04: Processed Information – Mounting Device	**1,5**
46.	Built-in Micro Computer Hardware	2
47.	Personal Computer Hardware Integration	1
	R03VAF05: Processed Information – Measuring & Test Device	**1**
48.	Web-enabled Operation Systems	1
49.	Computer Hardware Integration and CNC Control System	1
50.	On-Machine 3D Touch Probing and CNC Control System	1
	R03VAF07: Processed Information – Furniture	**Nothing found**
	Nothing found	Nothing found
	R03VAF09: Processed Information – Logistics Worker	**-**
	(In Box Nr. R03VAF01)	-
	R03VAF10: Processed Information – Conveying Device	**5**
51.	Built-in Micro Computer Hardware	5
52.	Computer Hardware Integration	5
53.	PLC Control System Integration	5
	R03VAF11: Processed Information – Conveying System	**Not implemented**
54.	Computer Hardware Integration	Not implemented
55.	Programmable Logic Controllers (PLC)	Not implemented

	R03VAF13: Processed Information – Warehouse Worker	**-**
	(In Box Nr. R03VAF01)	-
	R03VAF14: Processed Information – Warehouse Facility	**Nothing found**
	Nothing found	Nothing found
	R03VAF16: Processed Information – Loading Aid	**3**
56.	Micro-Processor	3
	R04VAF01: Provided Information – Production Worker	**3**
57.	Mobile Devices – Screen	5
58.	Augmented Reality – See-trough Display	5
59.	Wearable Devices – Screen	5
60.	Visual Assistance Systems –Screen	5
61.	Visual Assistance System – Light Guidance	3
62.	Audio Assistance System – Voice Guidance	1
63.	Augmented Reality – Screen	1
64.	Virtual Assistance System – Projection Mapping	1
65.	Mobile Devices – Augmented Reality	1
	R04VAF02: Provided Information – Machinery	**3,8**
66.	Interfaces	5
67.	Interface Modules	5
68.	Digital Communication Protocols	3
69.	MTConnect Standard	2
70.	Interfaces and Digital Communication Protocols	4
	R04VAF03: Provided Information – Tools	**5**
71.	Interface Modules	5
	R04VAF04: Provided Information – Mounting Device	**1**
72.	RFID-Technology	1
73.	Sensor Equipped Fixture Systems	1
74.	MTConnect Standard	1
75.	Interfaces	1
	R04VAF05: Provided Information – Measuring & Test Device	**2**
76.	Interface Modules	3
77.	MTConnect Standard	1
	R04VAF09: Provided Information – Logistics Worker	**-**
	(In Box Nr. R04VAF01)	-
	R04VAF10: Provided Information – Conveying Device	**5**
78.	Digital Communication Protocols	5
79.	Interfaces and Digital Communication Protocols	5
	R04VAF11: Provided Information – Conveying System	**Not implemented**
80.	Digital Communication Protocols	Not implemented
	R04VAF13: Provided Information – Warehouse Worker	**-**
	(In Box Nr. R04VAF01)	-
	R04VAF14: Provided Information – Warehouse Facility	**Nothing found**
	Nothing found	Nothing found
	R04VAF16: Provided Information – Loading Aid	**5**
81.	Digital Communication Protocols	5

	R05VAF01: Integrated Information – Production Worker	**5**
82.	Wireless Local Area Network (WLAN)	5
83.	Not suitable for this Matching-Box	-
	R05VAF02: Integrated Information – Machinery	**4,71**
84.	MTConnect Adapter	1
85.	Cloud Environment	5
86.	Wireless Local Area Network (WLAN)	5
87.	Ethernet Connection	5
88.	LAN Connection	5
89.	Satellite-based Communication Connection	5
90.	BUS Connection	5
91.	NC-based Communication	5
92.	RS232 Communication	5
93.	Not suitable for this Matching-Box	5
94.	Gateways	5
95.	Zigbee Communication	5
96.	Bluetooth Communication	5
97.	Optical Data Transmission Systems	5
	R05VAF03: Integrated Information – Tools	**3,67**
98.	Wireless Local Area Network (WLAN)	5
99.	Optical Data Transmission Systems	1
100.	Wireless Data Transmission Systems	5
	R05VAF04: Integrated Information – Mounting Device	**1**
101.	Wireless Data Transmission System	1
	R05VAF05: Integrated Information – Measuring & Test Device	**1**
102.	Wireless Data Transmission System	1
103.	Hard-Wired Data Transmission System	1
104.	Internet Connection	1
	R05VAF07: Integrated Information – Furniture	**Nothing found**
	Nothing found	Nothing found
	R05VAF09: Integrated Information – Logistics Worker	**-**
	(In Box Nr. R05VAF01)	-
	R05VAF10: Integrated Information – Conveying Device	**5**
105.	Wireless Local Area Network (WLAN)	5
106.	BUS Connection	5
107.	Wireless Data Transmission System	5
	R05VAF11: Integrated Information – Conveying System	**Not implemented**
108.	Wireless Local Area Network (WLAN)	Not implemented
	R05VAF13: Integrated Information – Warehouse Worker	**-**
	(In Box Nr. R05VAF01)	-
	R05VAF14: Integrated Information – Warehouse Facility	**5**
109.	Wireless Local Area Network (WLAN)	5
	R05VAF16: Integrated Information – Loading Aid	**5**
110.	Cloud-based and Event-oriented Self-Execution System (SES)	5

	R07VAF01: Object Identification – Production Worker	**5**
111.	RFID- and QR-Technology	5
112.	Biometrical Data Identification Systems	5
113.	Not suitable for this Matching-Box	5
	R07VAF02: Object Identification – Machinery	**5**
114.	IP-Address	5
	R07VAF03: Object Identification – Tools	**5**
115.	RFID-Technology	5
	R07VAF04: Object Identification – Mounting Device	**1**
116.	RFID-Technology	1
117.	IP-Address	1
118.	Marker-Based QR-Code	1
119.	Not suitable for this Matching-Box	-
	R07VAF05: Object Identification – Measuring & Test Device	**5**
120.	IP-Address	5
	R07VAF07: Object Identification – Furniture	**1**
121.	IP-Address	1
122.	RFID-Technology	1
	R07VAF09: Object Identification – Logistics Worker	**-**
	(In Box Nr. R07VAF01)	-
	R07VAF10: Object Identification – Conveying Device	**5**
123.	IP-Address	5
124.	RFID-Technology	5
	R07VAF11: Object Identification – Conveying System	**Not Implemented**
125.	IP-Address	Not implemented
	R07VAF13: Object Identification – Warehouse Worker	**-**
	(In Box Nr. R07VAF01)	-
	R07VAF14: Object Identification – Warehouse Facility	**5**
126.	IP-Address	5
127.	RFID-Technology	5
128.	Not suitable for this Matching-Box	-
	R07VAF16: Object Identification – Loading Aid	**5**
129.	IP-Address	5
130.	RFID-Technology	5
131.	Optical Identification Systems	5
	R08VAF01: Object Tracking – Production Worker	**4,43**
132.	RFID-Technology	5
133.	Localization Sensor System	5
134.	Microphone-based motion tracking system	1
135.	Optical sensor-based motion tracking system	5
136.	Mobile and Wearable Devices	5
137.	Wireless Nearfield Localization	5
138.	Magnetic Field Tracking System	5
	R08VAF03: Object Tracking – Tools	**1**
139.	Wireless Nearfield Localization	1

	R08VAF05: Object Tracking – Measuring & Test Device	**Nothing found**
	Nothing found	Nothing found
	R08VAF09: Object Tracking – Logistics Worker	**-**
	(In Box Nr. R08VAF01)	-
	R08VAF10: Object Tracking – Conveying Device	**3,4**
140.	Wireless Sensor Network and Localization System	1
141.	Trajectory Tracking	5
142.	Magnet Spot Localization	5
143.	Optical Localization System	5
144.	RFID-Technology	1
145.	Not suitable for this Matching-Box	-
	R08VAF13: Object Tracking – Warehouse Worker	**-**
	(In Box Nr. R08VAF01)	-
	R08VAF16: Object Tracking – Loading Aid	**5**
146.	RFID-Technology and Wireless Sensor Networks	5
147.	RFID Technology and Mobile Devices	5
148.	RFID-Technology	5
	R09VAF01: Object Handling – Production Worker	**1**
149.	Exoskeleton Suits	1
	R09VAF03: Object Handling – Tools	**5**
150.	Collaborative Robots	5
	R09VAF04: Object Handling – Mounting Device	**1**
151.	Parallel Actuator Robots	1
	R09VAF06: Object Handling – Consumables Production	**Nothing found**
	Nothing found	Nothing found
	R09VAF07: Object Handling – Furniture	**Nothing found**
	Nothing found	Nothing found
	R09VAF10: Object Handling – Conveying Device	**Nothing found**
152.	Not suitable for this Matching-Box	-
	R09VAF16: Object Handling – Loading Aid	**1**
153.	Automated Guided Vehicles (AGVs)	1
	R09VAF18: Object Handling – Consumables Packaging	**Nothing found**
	Nothing found	Nothing found
	R10VAF01: Condition Detection – Production Worker	**3,67**
154.	Augmented Reality – See-trough Display	5
155.	Wearable Devices	1
156.	Motion Capture Systems	5
	R10VAF02: Condition Detection – Machinery	**2,25**
157.	Sensor Integration	3
158.	Sensor Integration and Control Software Systems	3
159.	Data Acquisition from CNC and PLC System	2
160.	Internet-based Prognostics and Operations Systems	1
	R10VAF03: Condition Detection – Tools	**2**
161.	Sensor Integration	2
162.	Sensor Integration with CNC and PLC Control System	2
163.	Sensor Integration and A/D Converter	2
164.	Sensor Integration and Data Acquisition Card	2

	R10VAF05: Condition Detection – Measuring & Test Device	**Nothing found**
	Nothing found	Nothing found
	R10VAF07: Condition Detection – Furniture	**Nothing found**
	Nothing found	Nothing found
	R10VAF09: Condition Detection – Logistics Worker	**-**
	(In Box Nr. R10VAF01)	-
	R10VAF10: Condition Detection – Conveying Device	**1**
165.	Sensor Integration	1
	R10VAF11: Condition Detection – Conveying System	**Not Implemented**
	Nothing found	Not Implemented
	R10VAF13: Condition Detection – Warehouse Worker	**-**
	(In Box Nr. R10VAF01)	-
	R10VAF14: Condition Detection – Warehouse Facility	**Nothing found**
	Nothing found	Nothing found
	R10VAF16: Condition Detection – Loading Aid	**Nothing found**
	Nothing found	Nothing found

Table 8: Full Evaluation Results - Pilot Testing

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8 List of Figures

9 List of Formulas

10 List of Tables

11 List of Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
6D	Six-Dimensional
A/D	Analog/Digital
AC	Adaptive Control
AE	Acoustic Emission
AGV	Automated Guided Vehicle
AJP	Automated Joining Process
AMCL	Adaptive Monte Carlo Localization
AMT	Association for Manufacturing Technology
AOE	Acousto-optic Emissions
API	Application Programming Interface
AR	Augmented Reality
ART	Affordable Reconfigurable Tooling
BIM	Building Information Modelling
BUS	Back Panel Unit Sockets
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAN	Controller Area Network
CBM	Condition-Based Maintenance
CCD	Charge-Coupled Device
CCF	Coordinate Control Fixture
CERAA	Ceit Ergonomics Analysis Application
CFRP	Carbon Fiber Reinforced Plastic
CM	Communication Medium
CMM	Coordinate Measuring System
CNC	Computer Numerical Control
CPS	Cyber-Physical System
CPU	Central Processing Unit
csv	comma separated value
D/A	Digital/Analog
DAQ	Data Acquisition
DAQF	Data Acquisition FFT Board
DAQT	Data Acquisition Temperature Board
DBMS	Database Management System
DC	Direct Current
DCN	Distributed Control Nodes
DDE	Dynamic Data Exchange
DOF	Degree Of Freedom
DSP	Digital Signal Processing
EPC	Electronic Product Code
EPM	Electrical Power Monitor Board
ERP	Enterprise Resource Planning

FAHF	Flexible Automated Holding Fixture
FFT	Fast Fourier Transformation
FT	Fourier Transformation
GPS	Global Positioning System
GUI	Graphical User Interface
HD	High Definition
HDD	Hard Drive Device
HMD	Head-Mounted Display
HMI	Human Machine Interface
HPPA	High-Precision Pull-down Arm
HPRA	High-Precision removable Arm
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
I/O	Input/Output
IC	Integrated Circuit
ICP	Iterative Closest Point
ICT	Information and Communication Technology
ID	Identification
IMM	Intelligent Machining Module
IMM	Inductive probe Module and machine tool Module
IMS	Intelligent Manufacturing System
IMUs	Inertial Measurement Units
IoT	Internet of Things
IP	Internet Protocol
IPC	Industrial Personal Computer
ISDN	Integrated Service Digital Network
IT	Information Technology
JSON	JavaScript Object Notation
LAN	Local Area Network
LDV	Laser Doppler Vibrometer
LED	Light Emitting Diode
LR RFID	Light-Responsive RFID
LZT	Lead Zirconate Titanate
M2M	Machine to Machine
MAA	Metrology Assisted Assembly
MAC	Multimodal Assembly Controller
MCL	Monte Carlo Localization
MCP	Monte Carlo Particle Filter
MCU	Micro Controller Unit
MEMS	Micro Electro Mechanical System
MES	Manufacturing Execution System
MI	Machine Interface
MPC	Machine Protection Control
MPU	Multi-Processing Unit
MQTT	Message Queue Telemetry Transport
MVC	Machine Vibration Control

NC	Numerical Control
NI	National Instrument
NIR	Near Infrared
OMM	Optical Machine Module
OPC	Object linking and embedding for Process Control
OPC UA	Object linking & embedding for Process Control Unified Architecture
OSC	Open Sound Control
PC	Personal Computer
PDA	Personal Digital Assistant
PKM	Parallel Kinematics Mechanism
PLC	Programmable Logic Controller
PNG	Portable Network Graphics
QMResults	Quality Measurement Results
QR	Quick Response
RFID	Radio Frequency Identification
RGB-D	Red Green Blue-Depth
R-LRMS	RFID- Logistics Resource Management System
RMI	Radio Machine Interface
RPP	Reconfigurable Prognostics Platform
RSSI	Received Signal Strength Indicator
SCADA	Supervisory Control and Data Acquisition
SD	Shaft Displacement
SDK	Standard Development Kit
SES	Self-Execution System
SKU	Stock Keeping Unit
SP	Server Provider
SQL	Structured Query Language
SR	Server Receiver
TCM	Tool Condition Monitoring
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
TMS	Tool Monitoring System
UDP	User Datagram Protocol
UHF	Ultra-High Frequency
UPnP	Universal Plug and Play
USB	Universal Serial bus
UV	Ultraviolet
VAF	Value-Adding-Factor
VR	Virtual Reality
WIFI	Wireless Fidelity
WIS	Worker Information System
WLAN	Wireless Local Area Network
WPC	Working Posture Controller
WSN	Wireless Sensor Network
XML	Extensible Markup Language