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Integrated consideration of product quality within factory automation systems

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Preface

This thesis has been created during my work at the Institute of Ergonomics, Manufacturing Systems and Automation (IAF) of the Otto-von-Guericke University Magdeburg and at Siemens Corporate Technology Erlangen.

I would like to thank Prof. Dr.-Ing. Arndt Lüder for his supervision, the positve discussions and for taking over the primary assessment. Furthermore, I thank Prof. Paulo Jorge Pinto Leitão, not only for his secondary assessment, but especially for the stimuli and fruitful Collaboration during the last three years.

Moreover, I would like to thank Dr. Ulrich Löwen and Thomas Schäffler, who, in their position as Research Group Heads at Siemens Corporate Technology, have made this work possible at all and who have continuously supported it.

For their numerous critical stimuli, discussions and improvement suggestions during the review of this thesis, I'd like to thank Stephanie Schmidt and Mario Eichler.

In addition, I would like thank all employees and colleagues of the chair of Factory Operations and Manufacturing Systems and of Siemens Corporate Technology, Systems Engineering, Engineering Methods and Tools, especially Prof. Dr.-Ing. Herman Kühnle, Tobias Jäger, Michael Gepp and Dr. Stefan Horn.

Furthermore, I thank all members of the GRACE consortium, whose stimuli and collaboration have influenced wide parts of this thesis. Especially I would like to thank Claudio Turrin, Arnaldo Pagani, Prof. Nicola Paone, Dr. Cristina Cristalli and Nelson Rodrigues.

Besides I thank my whole family, especially my parents, grandparents and my fiancée Constanze Meinecke, who have always been at my side and gave me the strength and support needed to complete this task.

In the end I would like to thank Dr. Thomas Wagner. His human and professional assistance have shaped this work like no one else. I dedicate this thesis to him.

Magdeburg, 28.06.2013 Matthias Foehr

Vorwort

Diese Arbeit entstand während meiner Tätigkeit am Institut für Arbeitswissenschaft, Fabrikautomatisierung und Fabrikbetrieb (IAF) der Otto-von-Guericke Universität Magdeburg und der Siemens Corporate Technology Erlangen.

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Zudem möchte ich mich bei meiner gesamten Familie, insbesondere meinen Eltern, Großeltern und meiner Verlobten Constanze Meinecke bedanken, die mir während der gesamten Zeit dieses Projektes stets zur Seite gestanden haben und mir die benötigte Kraft und Unterstützung zu Teil kommen ließen.

Zu guter Letzt möchte ich mich bei Dr. Thomas Wagner bedanken. Mit seinem menschlichen und fachlichen Beistand hat er diese Arbeit geprägt wie kein anderer. Ihm widme ich diese Arbeit.

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Abstract

The assurance of high quality of manufactured products has been a focus of research and industry for the last decades. In parallel, the pressure on plant operators to provide more flexible and efficient plants at reduced cost and during ever shorter cycle times is continually rising.

This thesis presents a methodology, allowing to systematically capture the cause-effect-chains between production processes and products, as well as their respective engineering processes and their control. The underlying model is based on four elements: product materials, production processes, product functions and product quality features.

The first part of this thesis makes basic considerations about engineering processes of products and production systems, definitions and perspectives on product quality, as well as quality management and quality assurance approaches. Here, it is especially pointed out how these methods are missing in an effort to support a consistent exchange of knowledge and information along the product lifecycle.

In the subsequent part the so-called MPFQ-model is introduced, which represents an approach for integrated consideration of product quality in discrete production systems. Withal, basic elements of the model and their correlations are explained. In the concluding part it will be shown how it is possible to use this model not only to support product design and plant engineering, but also to support production control in discrete production systems. The benefits of the proposed solution are shown based on a prototypical implementation at a real production line for washing machines.

Kurzfassung

Die Sicherstellung einer hohen Qualität von gefertigten Produkten ist seit Jahrzehnten im Fokus von Forschung und Industrie. Parallel dazu steigt der Druck auf Anlagenbetreiber, flexiblere und effizientere Anlagen zu immer geringeren Kosten und in immer kürzeren Zeitabständen zu erstellen.

Diese Arbeit stellt eine Methodik vor, welche es erlaubt, die Wirkzusammenhänge zwischen Produktionsprozess und Produkt sowie deren jeweiligen Engineering-Prozessen und deren Steuerung systematisch zu erfassen. Das zu Grunde liegende Modell stützt sich dabei auf vier Elemente: Produktkomponenten, Fertigungsprozesse, Produktfunktionen und Qualitätsmerkmale des Produktes.

Der erste Teil dieser Arbeit befasst sich mit grundlegenden Betrachtungen zu den Themen Engineering-Prozesse von Produkten und Produktionssystemen, Definitionen und Sichtweisen von Produktqualität, sowie mit Qualitätsmanagement- und Qualitätssicherungsmethoden. Dabei wird insbesondere herausgearbeitet, inwiefern es diesen Methoden an einer Unterstützung des durchgängigen Austauschs von Wissen und Informationen entlang des Produktlebenszyklus fehlt.

Im darauf folgenden Teil wird das sogenannte MPFQ-Model eingeführt, welches einen Lösungsansatz für die integrierte Betrachtung von Produktqualität in diskreten Fertigungssystemen darstellt. Dabei werden die zu Grunde liegenden Modellelemente und deren Abhängigkeiten erläutern. Im abschließenden letzten Teil werden Möglichkeiten aufgezeigt, wie das Modell über die Unterstützung des reinen Produktdesign und Anlagenengineering hinaus ebenso zur Unterstützung und Steuerung des Fertigungsprozesses genutzt werden kann. Die Vorteile der entwickelten Methodik werden an Hand einer prototypischen Implementierung an einer realen Fertigungsstrecke für Waschmaschinen dargelegt.

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Abbreviations

ABS	Anti-lock Braking System
BoM	Bill of Material
BoO	Bill of Operation
BS	British Standards
CAD	Computer Aided Design
CQF	Comprehensive Quality Function
DeCoDe	Demand Compliant Design
DIN	"Deutsches Institut für Normung" (German Institute for Standardization)
DoE	Design of Experiments
DPMO	Defects Per Million Opportunities
EN	"Europäische Norm" (European Standard)
ERP	Enterprise-Resource-Planning
ESP	Electronic Stability Program
FMEA	Failure Mode and Effect Analysis
FPGA	Field Programmable Gate Array
GRACE	"inteGration of pRocess and quAlity Control using multi-agEnt technologies" (European Research Project under FP7 Framework)
HMI	Human-Machine Interface
IEC	International Electrotechnical Commission
IMA	Independent Meta Agent
ISO	International Organization for Standardization
MA	Machine Agent
MAS	Multi-Agent System
MES	Manufacturing Execution System

MOT	Ministry of Transport test (comparable to German TÜV)
MPFQ	Material-Process-Function-Quality-model
OEM	Original Equipment Manufacturer
PA	Product Agent
PLC	Programmable Logic Controller
PPR	Product-Process-Resource
PTA	Product Type Agent
QCA	Quality Control Agent
QFD	Quality Function Deployment
RA	Resource Agent
RPN	Risk Priority Number
SPC	Statistical Process Control
TPS	Toyota Production System
TQM	Total Quality Management
VDI	"Verein Deutscher Ingenieure" (Association of German engineers)

Glossary

NOTE: *In order to keep definitions of terms consistent, most terms are defined according to* DIN EN ISO 9000.

Characteristic	*"distinguishing feature"* [DIN EN ISO 9000]
Engineering	*"creative application of scientific principles to design or develop structures, machines, apparatus or manufacturing processes or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behaviour under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property."* [TEC41], [Enc11]
Engineering Process	*"a sequence of activities of creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes; all as respects an intended function, economic and safe operation."* [LHF11]
Manufacturing	*"make (something) on a large scale using machinery"* [Oxf13a]
Process	*"A process comprises the totality of actions effecting each other in a system in which matter, energy, or information are converted, transported or stored"* [IEC 60050] *"set of interrelated or interacting activities which transforms inputs into outputs"* [DIN EN ISO 9000]
Process Control	*"Activities involved in ensuring a process is predictable, stable, and consistently operating at the target level of performance with only normal variation."* [Bus13]. Within this thesis process controls mainly refers to control of production processes.
Product	*"result of a process"* [DIN EN ISO 9000]
Product Quality	following definition of quality: *"[…] degree to which a set of inherent [product] characteristics fulfills requirements."* [DIN EN ISO 9000]
Production	*"the action of making or manufacturing from components or raw materials or the process of being so manufactured"* [Oxf13b] - The difference between "Production" and "Manufacturing" within this work, is that production includes manufacturing and other processes like quality control, transportation, etc.

Quality	*“degree to which a set of inherent characteristics fulfills requirements.”* [DIN EN ISO 9000]
Quality Assurance	*"part of quality management focused on providing confidence that quality requirements will be fulfilled"* [DIN EN ISO 9000]
Quality Control	*"part of quality management focused on fulfilling quality requirements"* [DIN EN ISO 9000]
Quality Improvement	*"part of quality management focused on increasing the ability to fulfil quality requirements"* [DIN EN ISO 9000]
Quality Management	*"coordinated activities to direct and control an organization with regard to quality"* [DIN EN ISO 9000]
Requirement	*"need or expectation that is stated, generally implied or obligatory"* [DIN EN ISO 9000]

1 Quality within Engineering

1.1 Motivation

Product Quality has been proven to be one of the key factors within competition among OEMs [HeS06]. But plant operators are facing tough challenges on global markets, as pressure rises to produce high quality products [Cro79], [Fri94]. In parallel, production lines should be engineered to be more flexible and efficient in order to face pressure on cost and time [Die08]. As shown in [Art03], 70% of the non-conformance cost in the domain of discrete manufacturing can be ascribed to inconsistent and incomplete information, as well as unknown relationships within products and between products and their production lines. These deficits are significantly influenced by high pressure on time and cost. Thus, this pressure leads to a decreasing quality of products produced on the production line. With an amount of 55%, automation engineering and implementation contributes most to the overall engineering costs of new plants [Dra10]. Thus, it seems promising to provide concepts integrating quality management and process control in order to face these problems.

Within [Art03] it is shown, that discrete manufacturing yields highest improvement potentials when compared to other domains. Together with the high non-conformance cost due to unknown relationships within and between products and production lines, this leads to the conclusion that product quality has to be considered also within production line engineering. There are numerous approaches to deal with product quality within production line engineering e.g. Quality is free [Cro79], Lean [Aki13], Total Quality Management [BS 7850-1] and Six-Sigma [DBM03]. But although most of them have been applied for at least 20 years, problems still remain. One reason for this might be the approach taken to define quality. Following Crosby [Cro79], most concepts describe quality as the fulfillment of requirements. But as pointed out in [Art03], incomplete information and unknown relations lead to incomplete and also inconsistent requirements. But if the basis for quality considerations is already inconsistent, how should high quality be achieved?

One solution to this is knowledge management. Following [Art03] and [Foe13] one key point is that knowledge is only implicitly available by few experts but not explicitly documented. Thus, missing knowledge, respectively knowledge availability, leads to inconsistent requirements. Within [Ger04] it is shown, that knowledge is transferred easiest if it is unambiguous and explicitly codified. This can be achieved by using models for knowledge preservation.

Considering the above mentioned challenges, it is obvious that systematic approaches are needed to preserve knowledge about the interrelations within and between products and production lines, which have to be consistently usable not only within product design but also beyond. [Hun12] points out the importance of consistent and seamless data exchange throughout all phases of a product and plant lifecycle.

Based on these prerequisites, the following section 1.2 will provide three research questions as a basis for further considerations within this thesis.

1.2 Research Questions

The research area of product quality, as described within the previous chapter, touches many different domains. Consequently, the focus of this work should be defined before research questions are identified.

The term quality is related to different domains, e.g. product quality, process quality, service quality, etc. Products may be produced in two different ways, discrete production or process-oriented production. Within this thesis the product quality of discrete products like cars, washing machines, etc. will be focused, as [Art03] showed high improvement potentials within this area. Applicability of a derived solution to process-oriented production is appreciated but out of scope.

The proposed solution should explicate knowledge about the dependencies between products and production systems and within both of them in order to overcome previously described hurdles. Additionally, the solution should be applicable throughout the whole product lifecycle starting from product design, over plant design right to production (especially production process control) and use. In this way, cost and time constraints should be met, as knowledge defined and stored within early phases is automatically usable and can be enriched later on.

To reach this goal, the following three research questions shall be answered:

Research question 1:

Which measures can be taken on the product and/or its production system in order to manage and/or improve predefined quality features?

This question focuses on the identification of measures suitable to influence product quality in order to improve specific product quality features, eliminate product quality problems or provide multiple solutions for quality problems. In order to select a feasible measure, different perspectives might be considered (e.g. technical, economical, legal organizational and scheduling [Ove07]). This thesis will focus on technical considerations. Other perspectives might only be considered indirectly. To support the selection of suitable measures, research question 2 is introduced.

Research question 2:

Which is the (technical) influence of identified quality measures and where does it have additional effects on?

By answering this research question, it is not only possible to analyze suitability, but it should also be able to identify if other features originally not in focus of the selected quality measure, might be positively or negatively influenced as well.

Finally, it was pointed out in section 1.1 that consistent use of information along the product lifecycle is a key factor in order to improve cost and time as well as reducing error-proneness of engineering results. Thus, all information gathered within the phases of a product lifecycle should be usable in subsequent phases as well as in similar engineering projects.

Research question 3:

How can information about product quality be used in an integrated manner along all lifecycle stages in order to assure, manage and/or improve product quality?

By providing one integrated solution to answer these three research questions it should be possible to improve product quality and quality management. This has to be proven by a pilot implementation of the solution.

In the end the approach provided within this thesis shall enable the improvement of product quality throughout all lifecycles of a product and corresponding production system. The research questions 1 and 2 are mainly focusing the proactive improvement and assurance of product quality by specifically improving product design and plant engineering, while research question 3 focuses on product quality improvements and assurance during the production by directly influencing production processes.

1.3 Thesis Structure

In order to handle the research questions, this thesis is divided into three main sections. The first section, entitled “state of the art”, deals with currently available processes, methodologies and tools available in the area of product quality. It shows how products and production systems are engineered in order to provide insights how product quality is achieved within product design and plant engineering processes. Afterwards, the term quality is analyzed and a definition is derived to be used within this work. Subsequently currently available approaches for quality management and improvement are analyzed. These approaches are analyzed also with regard to their applicability within different phases of the product lifecycle.

The second main section “solution concept” will address the basic approach to deal with the research questions mentioned above. Here, a model based approach will be presented, integrating different aspects of crucial product quality influence.

The last section will show how this solution concept can be used within different application cases. Therefore, the theoretical application of the solution will be shown as well as a practical implementation within a washing unit production line. Finally results are analyzed in order to validate the proposed solution. The structure of this thesis is shown in Figure 1-1.

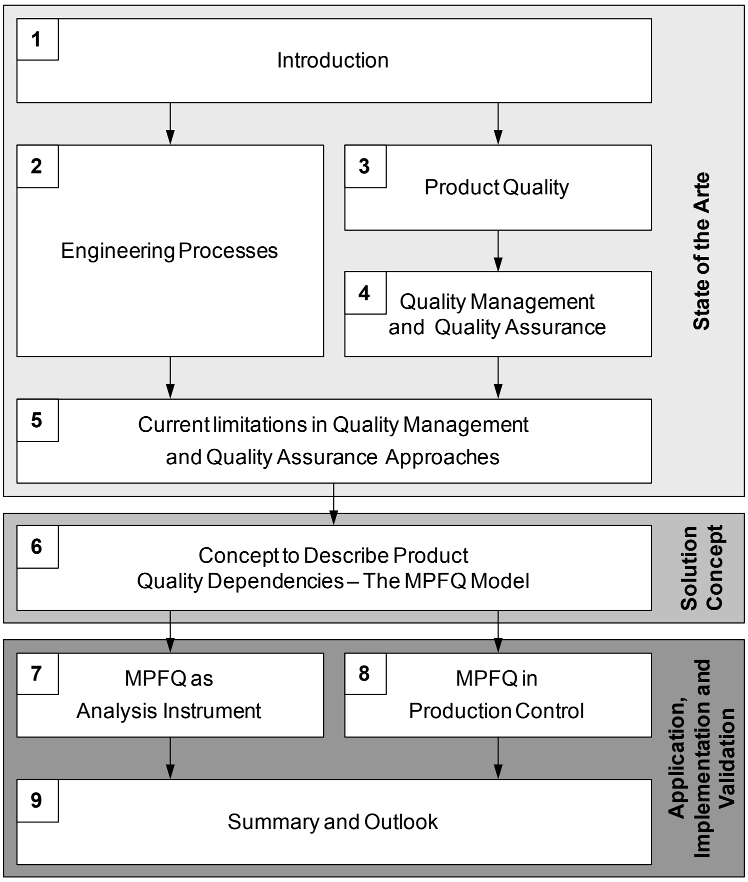

Figure 1-1: Thesis structure

The different chapters will deal with the following core themes.

Chapter 2 will deal with engineering processes. First selected engineering processes for product design are shown. All processes shown originate from standards. Afterwards the same will be done for plant engineering processes. Together both domains will give a clue which phases a product will pass during its lifecycle, respectively which phases are needed before a product can be produced. This chapter will conclude with an aggregated engineering process showing a basic phase model for both product design and plant engineering.

The next chapter aims to define the term “product quality” within this work. First of all, different concepts of product quality are analyzed in order to show how difficult a straight definition might be as understanding differs, depending on the individual viewpoint. Afterwards, types of product quality are discussed. These types give a kind of classification approach. Again they are depending on individual viewpoints, e.g. the application domain and should, therefore, show which directions can be taken to classify product quality features. Finally, the term product quality will be defined as it is used within this thesis considering the dissociations above.

The fourth chapter will deal with quality management and assurance approaches. Three major management approaches will be described. In addition, four main quality measures will be analyzed in order to provide insight into tools that may be used to improve and assure product quality. The final part of this chapter will describe additional quality measures. These measures are typically used supporting the main quality measures.

Chapter 5 will complete the state of the art section. Here, all quality measures and management approaches are correlated with the phases of the aggregated engineering process for product design and plant engineering. It will be shown that there is still a gap currently not covered by available approaches especially considering the consistent use of quality tools throughout all product and plant lifecycle phases.

Within the sixth chapter, the solution concept will be described. Therefore, the chapter will start by pointing out the importance of production for the final product quality perceived by a customer. As a model-based approach is used for the solution, its four main elements are defined within this chapter. Afterwards it is discussed how these elements can be integrated and correlated. A lifecycle model for setting up the proposed solution model is described and a modeling example is presented. Both are intended to ease the understanding of the solution concept.

The application and implementation of the solution model will be discussed in chapters 7 and 8. Chapter 7 will show the benefits originating from the integrative approach. Additionally, proactive and reactive measures will be described suitable to manage and improve product quality within product design and plant engineering. Chapter 8 subsequently shows how the model used for quality consideration in planning phases can also be applied to a production control system. The prototypical implementation will be described and, finally, results derived from this implementation are used to evaluate the suitability and applicability of the presented solution.

Finally, chapter 9 will conclude this thesis by answering the research questions, summarizing the results achieved and giving an outlook to future work.

2 Engineering Processes

The Engineers' Council for Professional Development [TEC41] defines engineering as the *"creative application of scientific principles to design or develop structures, machines, apparatus or manufacturing processes or works utilizing them singly or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behaviour under specific operating conditions; all as respects an intended function, economics of operation and safety to life and property."* [Enc11]. Following this definition, the term engineering process shall be defined as follows within this thesis.

*An **engineering process** is a sequence of activities of creative application of scientific principles to design or develop structures, machines, apparatus or manufacturing processes with respect to their intended function and economic and safe operation.*

In the literature, engineering processes are often divided according to the business model they are applied to. In [LFH11] different engineering processes have been analyzed and categorized as product business, component business, solution business or a free combination of the previous ones. This categorization depends on the point of view, as products might serve as a component for other products in their future. A typical example is a manufacturer of motors and drives who is manufacturing his products on a production line. From his point of view he is acting as a product developer and, therefore, product engineering processes have to be applied. From the point of view of a washing machine provider or a plant engineer, the motors and drives purchased from the manufacturer are used as components in their washing machines (products) or manufacturing stations (plants) and, therefore, have to be regarded as component business. To overcome this obstacle, only two types of businesses shall be regarded within this thesis.

First, the product business addresses the development of products usable within several production systems and/or other products of different domains. The engineering processes based on product business shall be called product design further on. More information on product design can be found in [UIE08] and [ScS 2005]. Second, the solution business addresses the engineering of production systems used to produce specific products. The engineering processes based on solution business shall be called plant engineering within the context of this thesis. Additional information on solution business can be found in [WHE10].

The next two sub-chapters will depict some selected processes from product design and plant engineering. As there are multiple process descriptions within literature, focus will be set on engineering processes described within normative documents. Finally section 2.3 will derive an aggregated engineering process.

2.1 Product Design

2.1.1 VDI 2221 – Systematic Approach to the Development and Design of Technical Systems and Products

The VDI 2221 "Systematic approach to the development and design of technical systems and products" [VDI 2221] deals with common, domain-independent essentials of product development and design. It focuses on system-oriented problem solving cycles and decomposition of overall problems to partial-problems and single-problems in order to derive bottom-up single solutions, partial-solutions and overall solutions.

VDI 2221 [VDI 2221] proposes an iterative product development and design process which is separated into seven general procedure steps with seven related results. Each step can be processed completely at once, partially or iteratively. Thus, an iterative evolution of the results is supported.

The first step is dedicated to the clarification of customer and product development requirements. Here, all available information is gathered, information gaps are identified and the requirements are enriched with external requirements (e.g. legal requirements) and company specific internal requirements. The result of this step is a requirement specification which builds the basic information platform for all subsequent working steps. This requirement specification is changed, updated and defined more precisely over time as new customer requirements or changed product development decisions arrive. For practical reasons, the requirements specification is frozen at a certain time in order to avoid permanent product design changes.

The second step is the determination of functions and their structures. Here, the overall function of the system and the main functions creating the overall function are defined. Depending on the product complexity, these functions are further decomposed. Especially for complex products, the single and partial functions are combined into functional structures as a basis for future solution search. The results of this step are one or more functional structures.

Within the third step, a search for solution principals is conducted based on the functional structures of the previous step. In order to do that, physical, chemical and other effects are selected and proper active structures are designed. The result of this step is the principle solution including also auxiliary functions needed for their realization. The principle solution depicts the active structure needed to fulfill specific product functions or functional structures.

The next step is the division of the principle solution into realizable modules. Goal and result of this step is a modular structure depicting real components, assembly groups and the connections among them. At this point the product design is often separated into the design of specific modules like basic modules, modules for variants, maintenance modules etc.

The fifth step is the design of key modules. This step is often called conceptual design. Geometrical, material and software related determinations are done on a level where the identification and selection of design optima is possible but determinations themselves are rarely concrete. Results of this step are preliminary designs like rough full-scale drawings.

These preliminary designs are then enriched by details, additional elements and assemblies, and all parts and assemblies are linked. This detailed design results in a complete design of the product containing all relevant design characteristics.

The last step is the preparation of operating and application instructions. The resulting product documentation includes all usage information like bill of material, manufacturing-, assembly-, test- and transport-instructions and user/operator manuals.

The product design process according to VDI 2221 is depicted in Figure 2-1. Further information and detailed instructions on product planning, methodic development of solution principles and systematic embodiment design of technical products can be found in [VDI 2220], [VDI 2222-1] and [VDI 2422].

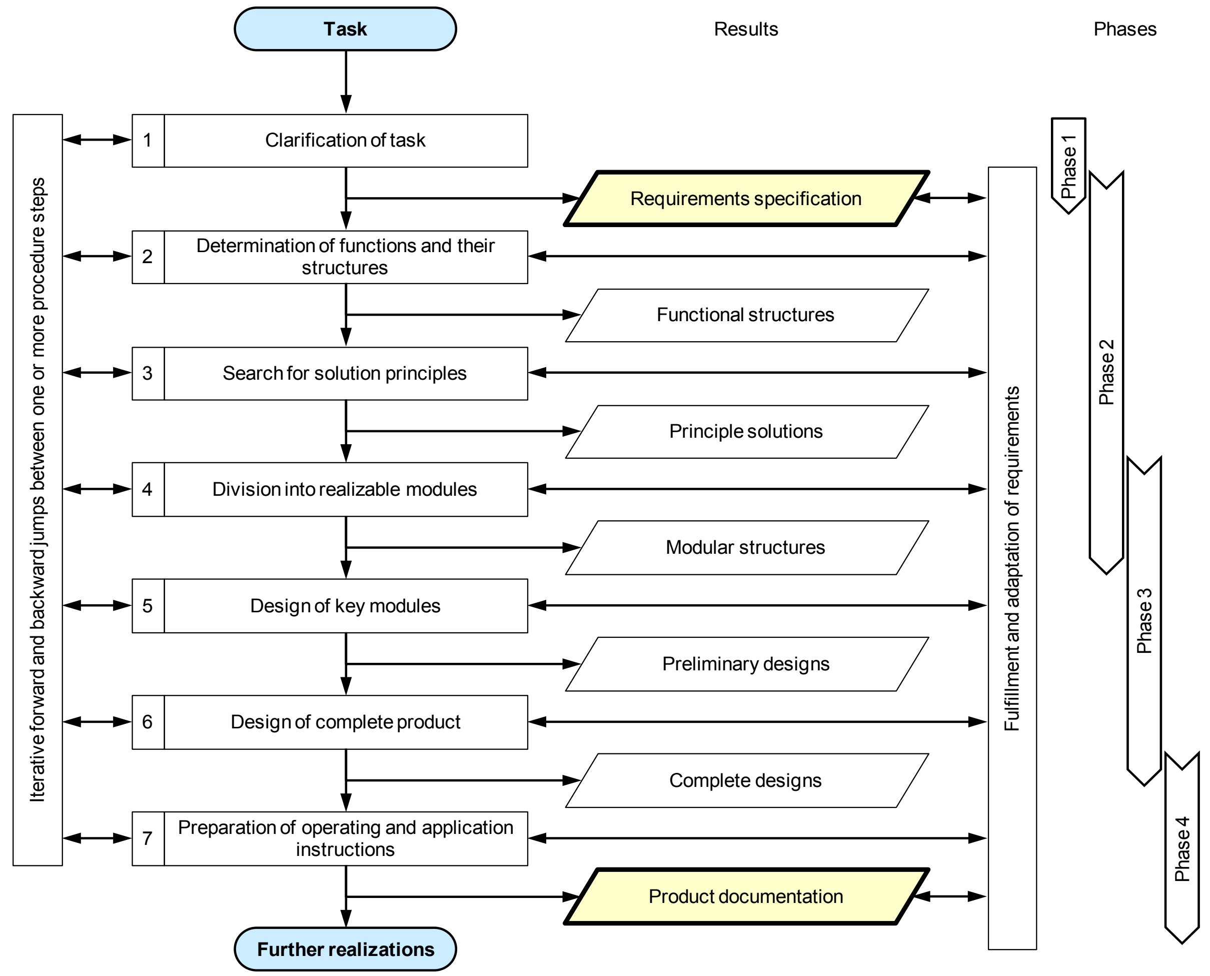

Figure 2-1: Product design process according to [VDI 2221]

2.1.2 VDI 2422 – Systematical Development of Devices Controlled by Microelectronics

The VDI 2422 "Systematical development of devices controlled by microelectronics" [VDI 2422] was first released in February 1994, nearly one year after the first release of VDI 2221. VDI 2422 takes into consideration the rising importance of micro-electronic controllers for product design. Therefore, special focus was set on functional device structures, description of information flows between user interface, controller and process interface and device types.

Within VDI 2422 a slightly changed procedure for product development is proposed. In a first step the development task is clarified based on the product requirements of the customer, market, etc. The requirements specification is thereby seen as frozen from the beginning and the iterative clarification of requirements like done in the VDI 2221 is discarded.

Based on the development task, a product concept is elaborated. Herein, all information about functionalities of the product and service specification is given and the kind of control device (analog, digital or micro-controller) is chosen. The following design and development phases are divided into three domains: software engineering, circuit engineering and electro-mechanical engineering.

The software design is defining interfaces between user and controller and designs a rough functional structure. To support design decisions, problem analysis of the functional product structure and economic feasibility studies are conducted. Additionally data structures are defined and the functional structure is modularized in a top-down approach. In the subsequent software development phase, these modules are implemented on a microcontroller. Suitable programming languages are selected, especially focusing on allocated memory. Afterwards, the software is loaded to the controller, product functions are tested and software documentation is being prepared.

The circuit design starts with the technology selection. Circuit diagrams, impulse diagrams, etc. are drawn and analyzed. Additionally, input and output data is defined, transfer functions are elaborated and power supply and interface groups are defined. The circuit design phase ends with a design of independent, testable building blocks and electromagnetic compatibility analysis. In the following circuit development phase, the wiring of devices is designed and assemblies are decomposed and detailed. For the documentation, test instructions are created and information about automatic failure detection is given.

The electro-mechanical design starts with a preliminary design. Here, geometrics, kinematics, materials characteristics and measurements for fault tolerances are defined. In parallel, ergonomic studies are conducted in order to optimize the human-machine interface (HMI). In cooperation with the circuit design, an electromagnetic compatibility analysis is conducted. Subsequently, the mechanical development is defining geometrics, kinematics, fault tolerances and selects proper materials. Production documents, operating manuals, assembly-, adjustment- and testing instructions are created and added to the product documentation.

After all three domains are finished, the product is tested. In this phase, VDI 2422 introduces little of the iterative development cycle of the VDI 2221 as laboratory prototypes, working models, prototypes and pilot series are created and evaluated. Especially for complex products, different implementations are needed in order to improve the product and reach required quality standards. Within this phase, the product documentation needs to be updated multiple times. After a successful pilot production, the product is released for serial production.

The product design process according to VDI 2422 [VDI 2422] is depicted in Figure 2-2.

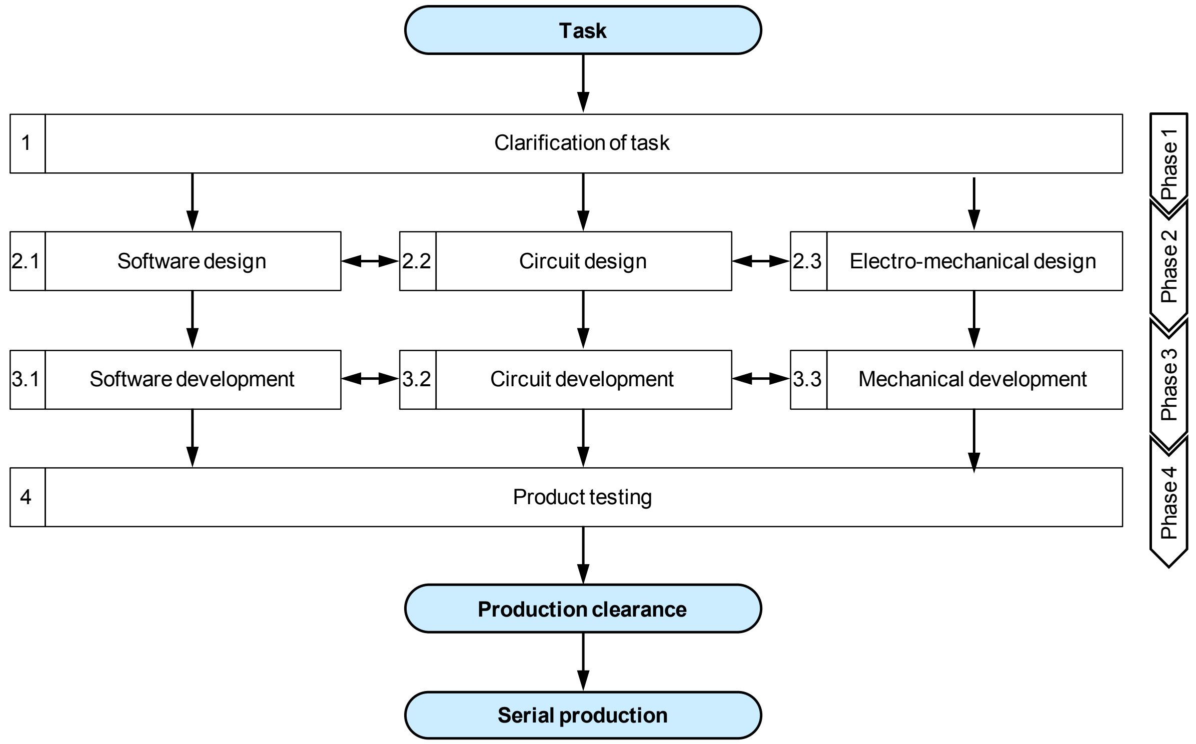

Figure 2-2: Product design process according to [VDI 2422]

2.1.3 VDI 2206 – Design Methodology for Mechatronic Systems

The VDI 2206 "Design methodology for mechatronic systems" was written as a practical guideline for the systematic development of innovative products, requiring an interdisciplinary combination of mechanical engineering, electrical engineering and information technology [VDI 2206]. This was needed as the VDI 2221 is very focused on the mechanical domain and a shape-oriented view, while the VDI 2422 focuses the domain of micro-electronics and is missing a detailed device concept as well as parallel, but separated development [Möh03].

The procedure to develop mechatronic products is based on three basic elements; the general problem-solving cycle on micro level, the V-model on macro level and on predefined process modules for handling of recurrent working steps [VDI 2206].

The problem-solving cycle as a micro cycle originates from the systems engineering and is supposed to help product developers solving singular tasks/problems and partial tasks/problems in a systematic way, although they might be unforeseen. As the term "micro cycle" indicates, this problem solving cycle is not designed to deal with all problems at once, instead each cycle is processed to solve one specific problem. In this way it is possible to maintain flexibility and respect process peculiarities. Each problem-solving cycle starts either with a situation analysis (as-is analysis) or a goal adoption (to-be analysis). Then, alternative solutions are developed in the analysis and synthesis step. Subsequently, these solutions are re-analyzed and assessed in order to decide for one or more solutions for the future planning. Each problem-solving cycle is terminated with the planning of further procedures and learning. In case the achieved result is not satisfactory, further steps are planned and new problem-solving cycles are processed. The analysis of pros and cons of the respective cycle leads to the generation of new knowledge. Further information on the problem-solving cycle can be found in [HaD97].

The V-model [VDI 2206], as macro cycle, describes a generic approach for the design of complex interdisciplinary systems. Starting point for each cycle are the requirements derived from a development order. Requirements are of crucial importance as they are the measure against which the product will be assessed. Thus, improper requirements can lead to good product assessments but bad perceived product quality by customers as requirements derived from product orders might not be aligned with general customer requirements. After requirements are precisely described, the system design phase starts. The goal of this phase is to establish a domain crossing solution concept describing the main physical and logical characteristics of a product. As soon as these characteristics are defined, the domain specific design phase starts. Here, all involved domains, such as mechanical, electrical, automation, hydraulical etc. are starting with further concretization of the solution based on the common solution concept. These parallel developments are joined in the system integration phase, where all individual solutions are integrated into the overall system. The system design, domain specific design and system integration phases are accompanied by modeling and model analysis activities and the assurance of properties. All design decisions are continuously checked and measured against the solution concepts and product requirements.

The V-model takes up the iterative approaches of VDI 2422 and VDI 2221, as the V-model is not uniquely processed, instead there are several iterations, each one resulting in a more detailed solution. Thus the first iteration might result in a laboratory prototype which is further detailed within the next iteration to become a first working model. Depending on product complexity, multiple iterations are needed to come up with the final product ready for serial production. The V-model, as macro cycle, is shown in Figure 2-3.

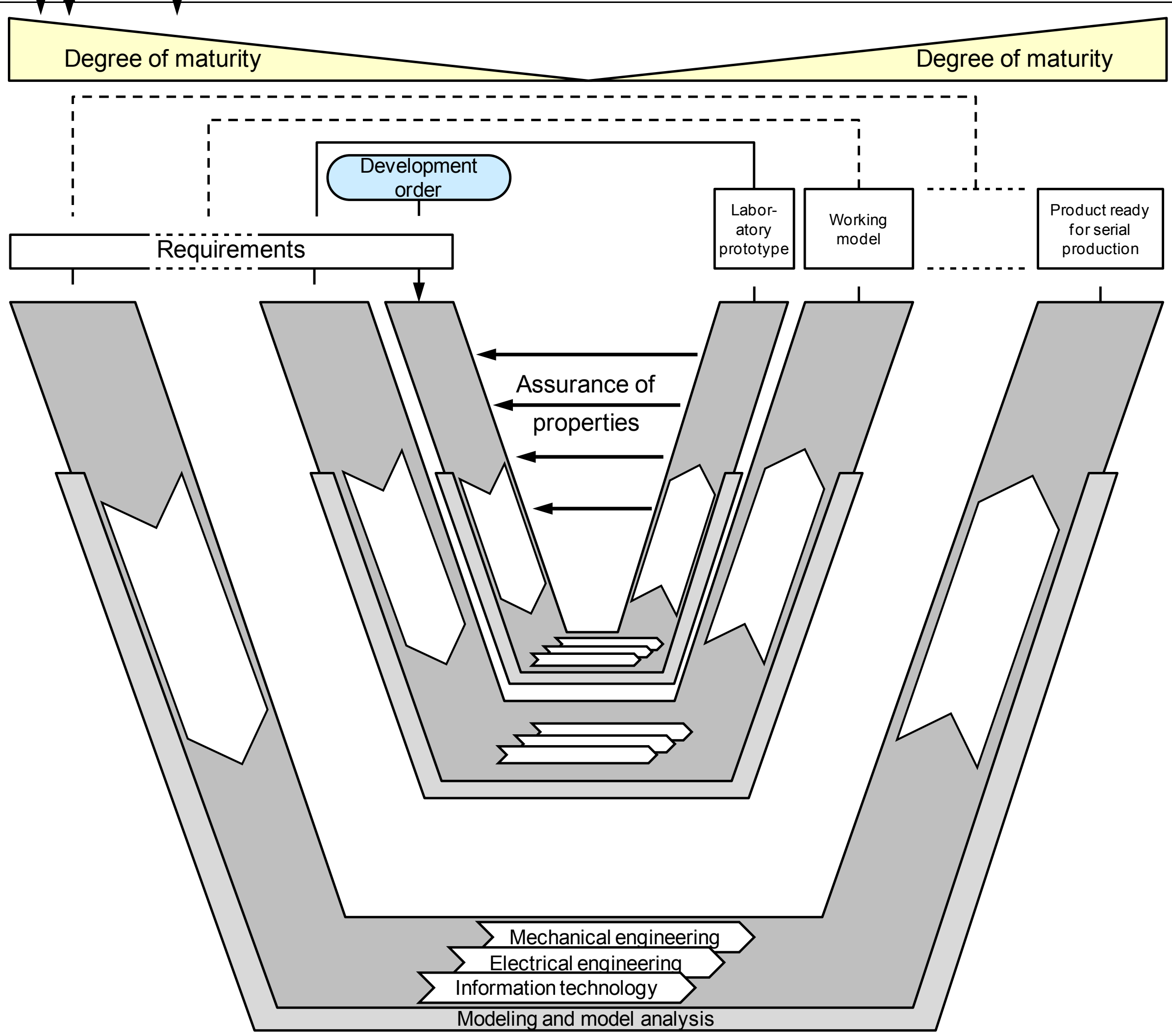

Figure 2-3: V-model as macro cycle as iterative approach for product design processes according to [VDI 2206]

The third element of the VDI 2206 procedure to develop mechatronic products are the process modules for recurrent working steps. These process modules define an amount of specific activities needed to reach a specific intermediate goal. Besides the activities, each process module contains a description of input and output information, classification criteria and additional information like supported methods or required competences to support working with these process modules [Hun12]. The VDI 2206 [VDI 2206] defines several process modules for the system design, domain specific design, system integration, modeling and model analysis and the assurance of properties.

2.2 Plant Engineering

2.2.1 VDI 4499 – Digital Factory

The VDI 4499 “Digital factory” [VDI 5600-1], [VDI 4499-2], addresses the challenges of globalized markets and shortening of development cycles for new and customized products. The idea behind VDI 4499 is to introduce the digital factory to support an early parallelization of product development and plant engineering. One main claim is to digitalize both processes as early as possible, use an integrated data management for both processes and to shorten development cycles by parallelization of planning phases and early virtual start-up and operation [VDI 5600-1]. The first part of VDI 4499 is classifying the different phases of the digital factory lifecycle, starting from market requirements, over product development, product prototyping, assembly and production planning, production process and system engineering right to serial production and service & maintenance of the production line.

Especially the second part of VDI 4499 deals with the application of the digital factory concept within the plant lifecycle. The first step of the plant lifecycle is an assembly and production process planning. Here, suitable processes, technologies and tools are chosen in order to realize the production of the specified product. Afterwards, the production system is engineered. This is one major part where parallelization takes place. After a rough layout planning the mechanical, electrical, fluidics and software parts are engineered. Within the concept of a digital factory this is done based on a common data management, meaning all domains are engineered on the same data basis. In parallel to software engineering, virtual commissioning starts. Both steps are finalized during the assembly and commissioning of the production system. Afterwards, the production system planning ends with a start-up of serial production. An important last step is the feedback of information from the serial production to the models of the digital factory. This is done to ensure consistency of digital models (e.g. simulation models) and is often related to as the “digital shadow” of a system. How this feedback may be processed is shown also in [VDI 5600-1]. The whole engineering process is accompanied by a consistent data management. The plant engineering process according to [VDI 4499-1] and [VDI 4499-2] is shown in Figure 2-4.

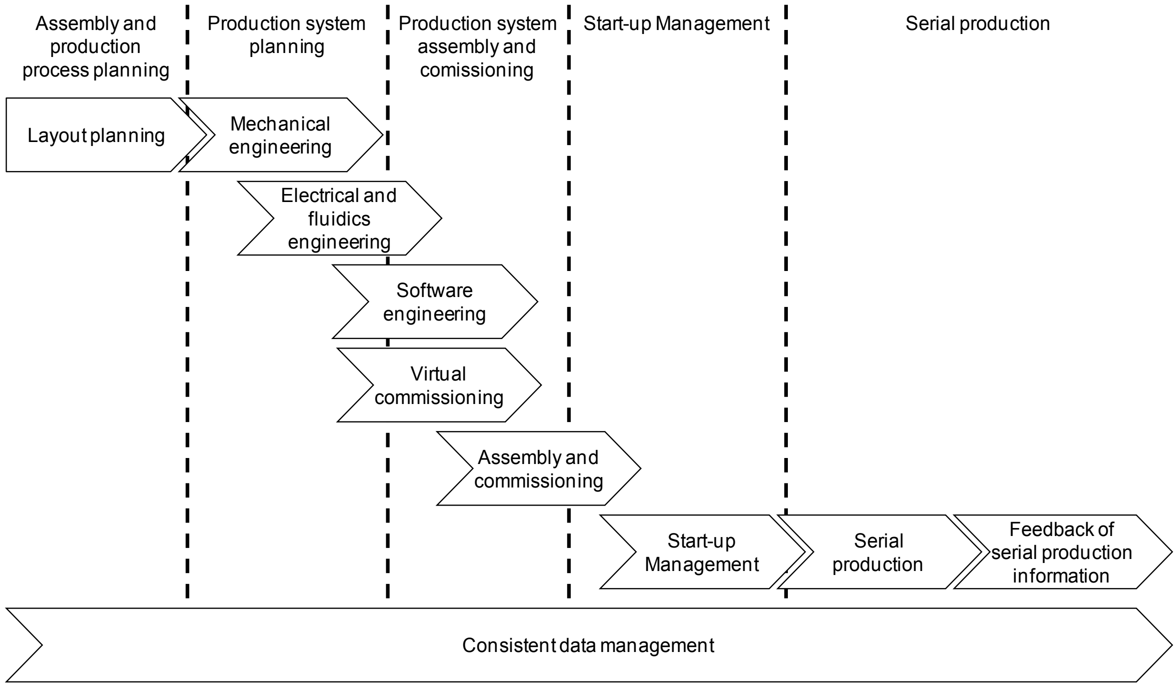

Figure 2-4: Plant engineering process according to [VDI 4499-1] and [VDI 4499-2]

2.2.2 VDI 5200 – Factory Planning – Planning Procedures

The VDI 5200 “Factory planning - Planning procedures” [DIN 69901-5] was published in 2009 as a reaction to the fact that scientific knowledge about factory planning was based on results created in the 1960s and 1970s. Thus, trends like globalization of markets, shortening of product and technology cycles were missing. The goal was to support *“[…] a factory planning approach appropriate to the present time […]”* [DIN 69901-5].

The presented planning procedure focuses on the development planning (green-field) and re-planning (brow-field) scenarios. It is divided into seven phases and accompanied by project management activities. The first phase of the plant engineering process is the setting of objectives. In a first step, corporate objectives and general constraints like market planning etc. are analyzed in order to roughly describe the task to be fulfilled. In a second step, the factory and project objectives are set. The goal is to obtain key data for factory operation (e.g. production of X units per hour) and project objectives (e.g. date for start of production). The last two steps are the itemization of evaluation criteria and the definition of work packages, providing cost requirements and weighted project evaluation criteria as well as a project plan with specified work packages.

The second phase is the founding of a project basis. This includes the acquisition and evaluation of all necessary information for the subsequent planning phases. After completing this information acquisition, the concept design phase starts. This phase is again divided into four steps. First, the structure planning is done, resulting in a functional schema of the plant and a communication concept. Afterwards, the dimensioning is carried out. This includes dimensioning of resources, space assignments and a logistics concept. The last two steps are the ideal and real planning. Here, at first an ideal layout of the plant is designed. This is then discussed and customized according to spacious, financial, quantative, qualitative and practicability restrictions. The results of both steps are evaluated ideal variants and the decision for some preferred variants, resulting in a rough plant layout.

The fourth phase is called detailed planning. Here, the detailed planning and preparation of approval applications is done. Goal of this phase is to obtain detailed plant layouts, building plans and corresponding cost calculations, as well as approval applications required by the corresponding legal provisions. Additionally, within this phase, the specifications of services are prepared. They include functional and detailed specifications needed for further engineering proceeding and for subcontracting.

The next phase includes all steps needed for the preparation of the realization. Here, procurement is done by selecting suitable suppliers from a bidders list. Offers are technically and financially analyzed in order to select and commission suppliers. Subsequently, the detailed design planning is monitored by approving final plans. Accompanied by these three steps, the implementation planning is carried out, resulting in a changeover concept, construction site preparation plan, relocation plan and personnel expense plan.

The sixth phase is the monitoring of the implementation. For this purpose the realization is coordinated, monitored and documented and the final documentation is prepared. The objective is to ensure that all agreed services are completed at the right quality and that real costs stick to the predefined budget. The last technical phase includes start-up and ramp-up support and a final factory evaluation. The objective is to ensure that the plant is producing the predefined amount of products in stable processes at the predefined performance level.

All of these phases can be processed iteratively if needed. The accompanying project management should be done based on [DIN 69901-1] and [DIN 69901-5] and ends with the project close out. Here, the project performance is evaluated in terms of time, cost and quality. Additionally knowledge management is carried out in order to preserve created knowledge for future projects. The plant engineering process according to VDI 5200 is depicted in Figure 2-5.

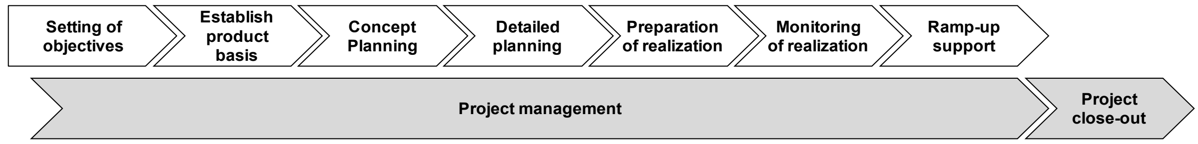

Figure 2-5: Plant engineering process according to [VDI 5200-1]

2.2.3 VDI 3695 – Engineering of Industrial Plants - Evaluation and Optimization

The guideline series VDI 3695 "Engineering of industrial plants - Evaluation and Optimization" [VDI 3695-1], [VDI 3695-2], [VDI 3695-3], [VDI 3695-4] was released in 2010 in order to provide guidance to engineering organizations planning, developing and/or commissioning industrial plants. The VDI 3695 is, thereby, presenting an approach to plant engineering which is consciously separating the project of engineering an industrial plant from other accompanying activities and especially pointing out the project independent development of reusable artifacts or standards.

The first part of VDI 3695 [VDI 3695-1] presents the phases of the plant engineering process related to the engineering project. Therefore, NA 035 [NA 035] is referred to for detailed phase description. Each project starts with the acquisition phase. Here, all basics and information needed to engineer the plant are determined. The second phase is the planning of the industrial plant which includes preliminary engineering, concept design and detailed planning. During the following realization phase, the plant is constructed. The final commissioning phase is dedicated to ramp-up activities. Each project is ended by a project closure phase which also includes knowledge management and feedback to the project independent development which is described in more detail within [VDI 3695-2].

The project independent activities describe all activities taken to support daily project business by pre-developed tasks and methods. Typical project independent activities include the development of a common data model as a basis for engineering tools (see [VDI 3695-4] for detailed description), specification of common description languages, reusable artifacts, reference models and technological plant structures (all according to [VDI 3695-3]). This project independent development process is also divided into four tasks. In the first phase, the market, customer as well as external requirements and inputs are analyzed. Additionally, actual and previous projects are taken into consideration. Based on this analysis, reusable artifacts and standards are developed in the planning phase and realized in the realization phase. Finally the artifacts are tested for functionality and accurateness and standards are approved. The result of this independent sub-process of project independent development are reusable artifacts and standards, available for current and future projects within the engineering organization and may be applied within all phases of the project related plant engineering sub-process.

In addition to the project independent activities, there are also other management activities accompanying the project development. These activities. such as supply chain management, quality assurance, configuration management, risk management, change management, customer relationship management and knowledge management, are interacting with the different project related engineering processes in order to give support, guidance and to control them. The plant engineering process according to VDI 3695 is shown in Figure 2-6.

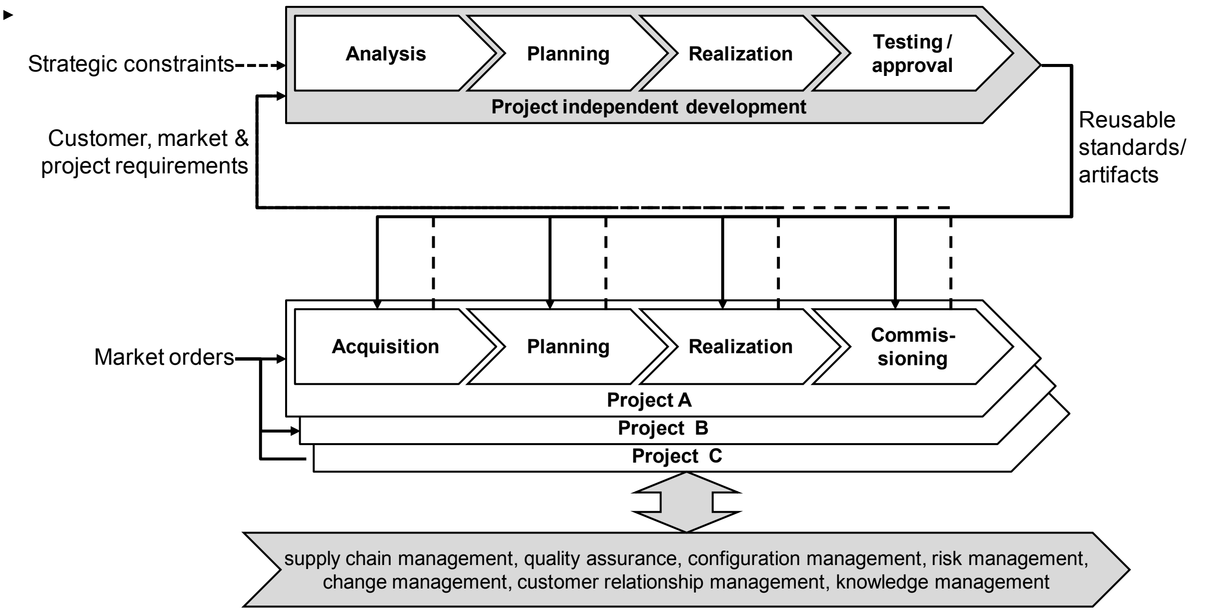

Figure 2-6: Plant engineering process according to VDI 3695 following [VDI 3695-2]

2.3 Aggregated Engineering Process

This section uses the previously presented engineering processes for product development and plant engineering in order to derive a kind of meta-engineering process. Besides these standardized engineering processes there are also many others which are also taken into consideration:

- Aquimo Engineering Process (plant engineering domain) [AQU10a], [AQU10b]
- AutomationML reference process (plant engineering domain) [Aut10], [Dra10], [HLP08]
- Engineering process for decentralized factory automation systems [WHE10]
- Engineering process in the plant engineering and solution business domain [JMG10]
- Engineering process according to Kiefer (automotive domain) [Kie07], [KBB06], [KBR10]
- Engineering process according to Schnieder (automation & control domain) [Sch99]
- GRACE reference engineering process (factory automation / MAS domain) [GRA11b], [GRA12b], [GRA11c], [GRA12b], [GRA11a]
- Medeia engineering process (automation & control domain) [MED10], [SRE08]
- The “Münchener Vorgehensmodell” following Lindemann (mechatronical systems) [Lin09]
- PABADIS’PROMISE engineering process (automation & control/MAS domain) [WHE10], [PAB08]

The list of these reference processes may be easily extended. The additional information gathered by extending this list might still be negligible, as there are many commonalities between the different engineering processes.

As the research of Bahill and Gissing made evident, all kind of processes may follow the same basic schema; what they called the SIMILAR Process [BaG98]. According to them, each process starts with some customer needs as an input. Based on these requirements, the problem is stated, alternatives are investigated and the system is modeled. After all different modules of the system are modeled, they are integrated and the overall system is launched. The last phase is a performance assessment of the system's outputs. The process itself is highly iterative, because after each phase, results are taken in order to re-evaluate results from previous phases. Figure 2-7 depicts the SIMILAR process.

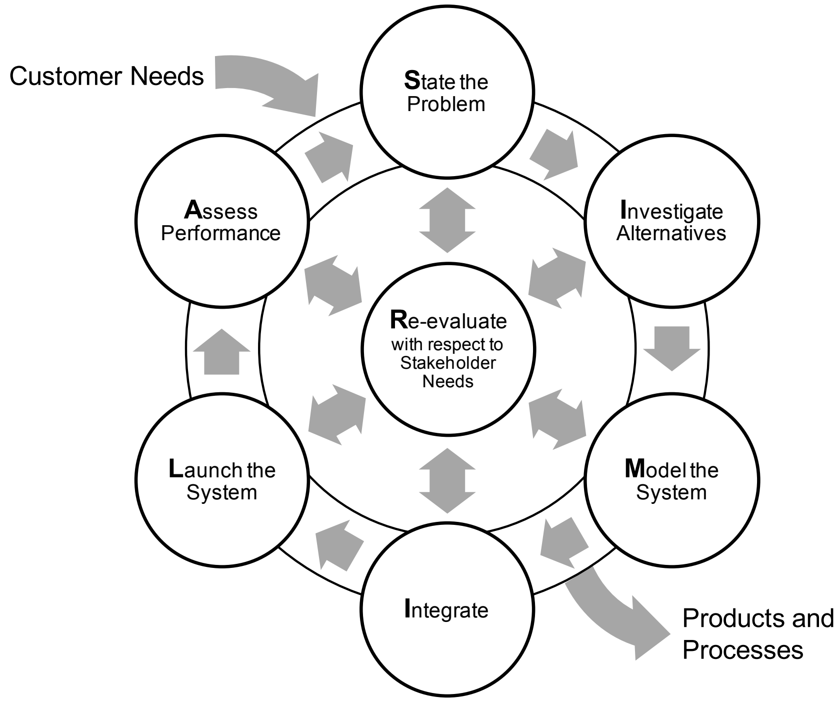

Figure 2-7: The SIMILAR Process following [Bah10]

Following the idea of the similar process it is possible to aggregate an meta-engineering process which is applicable for both, product design and plant engineering. This aggregated process is the synthesis of the commonalities between the previously presented processes. Analyzing them, it becomes evident that the starting point for each process is indeed some kind of external requirements. These requirements might refer to a production order, a sold product or other external conditions like market needs, legal requirements, etc. These requirements are then analyzed within a first phase in order to specify them and also to check them for completeness and consistency. This also includes the acquisition of all information needed in order to design the product or plant later on.

The second phase is the concept and basic design. Within this phase, different solution principles are sketched and analyzed for their applicability. This phase results in a basic solution concept to be further detailed in the detailed design phase. This third phase is dedicated to the development of the technical solution, thus transferring functional structures into realizable technical modules. The detailed design also includes the integration of technical solutions developed separately into one overall technical solution.

This overall solution is physically realized in the installation & commissioning phase. Here, all procurements are done and the real technical system is constructed. This also includes ramp-up activities. Finally, the technical system is used and during its use further measures may be taken in order to optimize the system.

All of these phases are processed iteratively so that design decision once taken might be fed back to earlier phases, resulting in optimizations and design changes if needed. Additional management activities, e.g. procurement, quality assurance etc. might accompany the engineering process in order to derive economical, efficient technical solutions. The aggregated engineering process is shown in Figure 2-8.

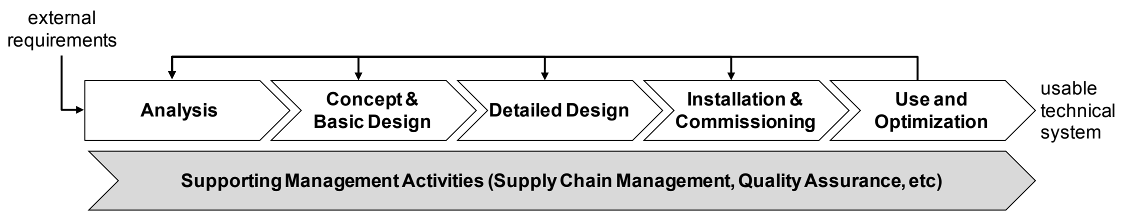

Figure 2-8: Aggregated engineering process

Utilizing this aggregated engineering process, products may be designed and manufactured. Within the following chapter the term product quality shall be examined in order to understand the prerequisites for “good” product quality.

3 Product Quality

Within this thesis the term “quality” is used equivalent to “product quality”. Going beyond this thesis there are also concepts of quality used within other domains like process quality, service quality etc. Within [Bah10] it is stated that product quality is a direct result of good process performance (resp. process quality). Hence, it should be clear that none of these domains can be fully understood without at least noticing the impact of other domains. Nevertheless, an analysis focusing on one domain is possible as long as interactions are taken into account. The aim of this chapter is to define the term “quality” within this thesis and to give a categorization of types of product qualities. Therefore, the first section 3.1 will give an overview of definition approaches in the literature. Afterwards, section 3.2 will provide some categorization schemas for quality. Based on these considerations the term quality and its use within this thesis will be described.

3.1 Conceptions of Product Quality

Quality is a term which is widely used within scientific and also non-scientific language. Thus, its meaning is quite hard to define as various concepts of the term “quality” exist. In the non-scientific language the term is often used in an evaluative manner to describe the excellence of a specific good or service. The term itself is, therefore, often attributed with other terms like “good” or “bad”. But how can a good or bad quality perceived by a customer be translated into the scientific language?

Garvin has analyzed different perspectives on product quality, especially taking into consideration viewpoint conflicts resulting from different domain backgrounds. Within [Gar84] he identified five different concepts to define product quality.

The transcendent view [Gar84] on quality is very familiar with the colloquial concept of quality. It describes quality as an inherent product or service characteristic which cannot be defined exactly and is perceived by humans based on experience. As product quality is not exactly defined, it is also not analyzable, which is one of the reasons this concept has minor importance for scientific approaches. Garvin also points out that the transcendent view on product quality *“borrows heavily from Plato’s discussion on beauty”* [Gar84]. In this context Pirsig defines quality as *“the result of care”* [Pir09] or Weinberg as the *“value to some person”* [Wei92]. Other typical examples for the transcendent view on product quality can be found in [Tuc80].

The second view according to [Gar84] is the product-based definition. In this view, product quality is precisely measurable as a sum of inherent product characteristics. A typical example according to Garvin is the durability of a product: *“[…] durable goods provide a stream of services over time, increased durability implies a longer stream of services”*. Within this concept, product quality can be measured by (a) the attributes a product inherits and (b) the quantity in which these attributes are present, leading to simple mathematical calculability of quality. Hence, this approach leads to a more objective assessment of product quality as it is measurable and not only dependant on personal experience like the transcendent approach. At the same time this approach is depending on the prerequisite that specific attributes are considered preferable or avoidable by nearly all customers. Examples for the product-based view can be found in [Abb73], [GrB71] and [Lan71].

The user-based view [Gar84] on product quality highlights the subjectivity of quality. Here it is assumed that each customer has his own needs (requirements) and will judge those products with good quality which fit his demands best. Thus, it partly contradicts the product-based view as quality is still measurable but not applicable for a product in general. Instead, product quality emerges from a product – customer pairing, leading to the fact that the same product may be assessed as desirable for one customer and as non-desirable for another. This subjectivity is one main concern of the Kano model [KST84] which will be described in more detail within section 3.2. Additionally, a subjective product quality will lead to the fact that individual requirements are highly varying. This is a minor problem if the product to be sold is a one-of-a-kind product, such as e.g. in the plant business, rail business (trains) or aviation business. Here, the products are customized to customer demands and produced in relatively low numbers (sometimes only one time). For mass products, the subjective user-based view causes many problems as in most cases customizing a product for each customer is economically not feasible. In most of these cases it is assumed that high quality products meet the demands of the majority of customers. For more complex and expensive products like in the automotive industry this problem is faced by allowing the customer to choose between multiple basic variants (model types) and additional options. These examples show that the user-based view on product quality is objectively measureable only if the individual customer needs are considered. A general quality assessment of the product is not possible. Ducker describes this dilemma perfectly in [Dru85]: *“Quality in a product or service is not what the supplier puts in. It is what the customer gets out and is willing to pay for.”* As one can see there is a separation of business and customer interest. Typical examples of the user-based view can be found in [JuG88], [May76] and [KuD62]

The fourth view according to Garvin is the manufacturing-based view on product quality [Gar84]. This view emphasizes the deviation of a product from predefined requirements. Crosby, as one of the main representatives, defines quality as *"conformance to requirements"* [Cro79]. This definition leads to an objectively measurable product quality as product characteristics can be measured and compared to predefined values. The degree of conformance then defines the quality of the product. This also leads to the definition of Crosby that quality can be measured by the cost of non-conformance. Within the manufacturing-based view, an internal focus, which in some cases might lead to dismissal of customer needs, is set. It is assumed that customer needs are reflected by product requirements. Nevertheless, this assumption is not confirmed by any of the manufacturing-based approaches. This is also one of the main conflict potentials when product quality is discussed between representatives of the user-based and manufacturing-based views. Garvin also points out that the manufacturing-based approach leads to the fact that *"a well-made Mercedes is a high-quality automobile, as is a well-made Chevette."* When only considering the conformance of both with their requirements, this may be true. In our empirical world, customers may nevertheless define one as more qualitative than the other. A very technical concept is defined within the six-sigma approach. Here, product quality can be defined as the number of defects per million opportunities (DPMO) [Mot06]. The six-sigma quality level is reached if less than 3.4 DPMO occur or in other words 99.99966% or more of all products are produced without any defect. Other typical examples of the manufacturing-based view can be found in [Cro79] and [Gil74].

Within the value-based view [Gar84] the excellence dimension of quality is enriched by the value dimension as product quality is defined as performance at an acceptable cost. Garvin argues that under this view *"a $ 500 running shoe, no matter how well constructed, could not be a quality product, for it would find few buyers."* [Gar84]. This statement, although applicable in most cases, is not always true as can be seen by looking at sales figures of Apple products over the last years [Mac13]. Examples for the value-based approach can be found in [Fei91] and [Bro82].

As can be seen from the previous described views, there are multiple concepts to define product quality which are obviously, at least partially, in conflict within each other. Each view is focusing different aspects and lifecycle phases of a product. Thus, considering all different views is crucial for a comprehensive approach to quality as the product and its quality definition may change over the lifetime. Especially, there is a need to shift from user-based views when identifying user needs to a product-based approach during product design to a manufacturing-based approach within the production of the product.

An overview to the five different quality perspectives of Garvin is given in Figure 3-1.

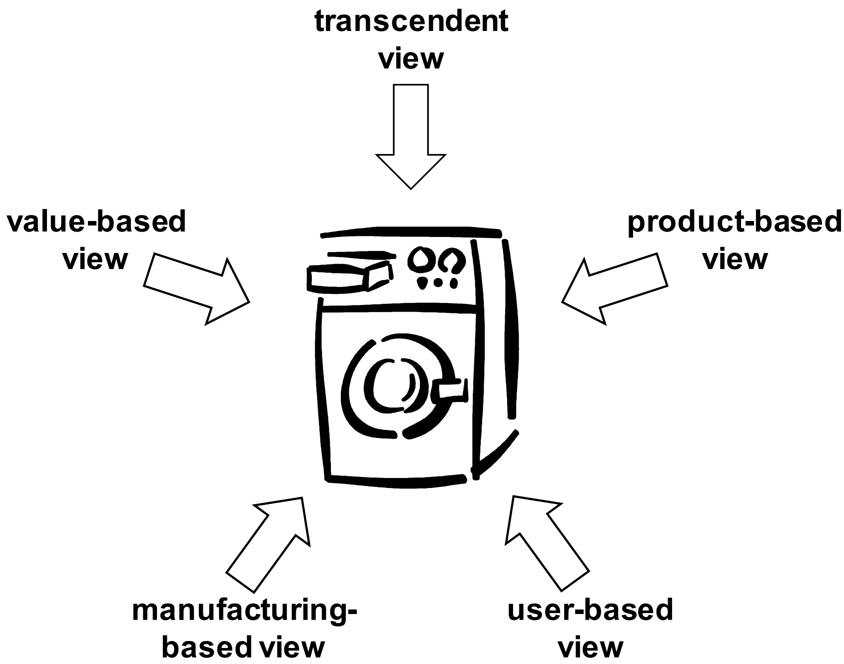

Figure 3-1: Product quality perspectives according to [Gar84]

3.2 Types of Quality

After the different views on product quality have been described above, this section provides some approaches to the categorization of product quality features in order to identify which kind of product quality features have to be analyzed.

3.2.1 Kano model

In 1984 Kano presented an approach to distinguish quality features of a product with respect to their importance to the customer. Since then, the Kano model has been developed to one of the most important measures for strategic product design.

The Kano model [KST84] separates five different quality types. The must-be quality attributes describe features that are generally taken for granted. They have to be fulfilled in any case, although their fulfillment does not lead to customer satisfaction whereas their non-fulfillment leads to high dissatisfaction. Typical examples for these quality features are the safety of a washing machine and its durability and reliability during the period of warranty. Each customer expects that a washing machine can be used without threatening e.g. the user or children in the household, as well as each kind of product should serve at least throughout the period of warranty and, optimally, also beyond. But if someone is harmed when using the washing machine (e.g. by sharp edges of metal parts or by electrical injuries of any kind) or the product breaks down within the first usage cycles the customer is dissatisfied. Although fulfillment of must-be quality features is crucial, their improvement leads to nearly no additional satisfaction of the customer and thus, it does not yield competitive advantage. Therefore, most companies must look for basic assurances of these features but do not further invest in their improvement.

The second types of product quality [KST84] is the one dimensional quality feature. These features lead to satisfaction if they are fulfilled and to dissatisfaction if not implemented or performing poorly. Typical examples for one-dimensional quality features are energy and water consumption and the maximum spinning rate of a washing machine. If a washing machine reaches an "A++" rating in energy and water consumption, this leads to satisfaction of the customer. An rating of "B" is typically taken for granted and leads to no satisfaction or dissatisfaction, while an energy and water consumption rating of "D" is taken as an indication for poor quality products and leads to dissatisfaction [DRL13]. Same applies in an analogue way to the dry spinning speed. One-dimensional quality features are often used within marketing for strategic product placement. Although an investment in improvement of performance of these quality features generally leads to higher customer satisfaction, an endless improvement is in most cases neither reasonable nor feasible. The energy consumption may be reduced but a washing machine will never generate energy as this would obviously lead to a perpetuum mobile. At the same time, every improvement also needs investments which, in the end, need to be paid for by the customer. Thus, it is crucial to determine how much a customer is willing to pay for an improvement and if investing in this improvement is therefore economically reasonable.

The third kinds of qualities are the attractive quality features [KST84]. These quality features are typically not expected by the customer. Thus, if they are not implemented they do not lead to any dissatisfaction. In turn, their implementation mostly leads to an additional usage of the product and thus to customer satisfaction. Typical examples are special washing programs or automatic soap dispensers of a washing machine. In first place, the customers do not ask for these features, but they provide additional functionalities which the customer will find nice and useful. Attractive quality features are one of the main elements for customer satisfaction beyond their basic needs and yield high potential for distinguishing own products from the ones of market competitors. Introducing these kinds of quality features in most cases needs a kind of product innovation and can be very cost intensive. Additionally, these quality features may become very important to the customers and turn into one-dimensional quality features over time (things the customers never wanted, but once they have gotten them, they are not willing to let them go again).

This changing of quality features over time is not only given for attractive quality features but for all of them. As time goes by, product features that once were innovative and new turn into more basic features which are asked and will be judged with respect to their performance. When washing machines became more and more available for everybody in the 1960s and 1970s, no one thought about their energy consumption. Over the time, the awareness for energy consumption grew and energy labels have been defined. In their first appearance they rated products from "A" to "G" and the first washing machines earning an "A" label were providing additional value in the eyes of the customer. But with technical advances in research and development, washing machines became even more efficient. In turn energy labels "A+" to "A+++" have been added. Nowadays customers expect at least an "A" rating and are only satisfied if these ratings are exceeded. The energy consumption has turned from an attractive quality feature into and one dimensional quality feature. With further advances in technology washing machines will one day reach a certain minimum amount of energy consumed, which will become a must-be quality feature. Every machine consuming more than this minimal amount will be regarded as a poor quality product, which will lead to dissatisfaction. Same can be seen for safety features in the automotive industry like airbags, ABS and ESP. From their first introduction until today, they turned from attractive quality features into must-be quality features.

These first three quality features and their degrading over time is shown in Figure 3-2.

Kano also describes two additional types of quality: the indifferent quality features and the reverse quality features [KST84]. Indifferent quality features do not lead to any satisfaction or dissatisfaction weather they are implemented or not. This can be seen especially for supplementary equipment. The equipment of a car with a panorama glass roof, for instance, may for some customers be not important (especially when buying a used car). The reverse quality features are those which lead to dissatisfaction when implemented, but do not lead to satisfaction when not implemented. An example for this is an expired Ministry of Transport (MOT) certificate when buying a used car.

One important fact for the Kano model is that all quality features are subject to the individual customers. As quality features can degrade over time, they are also subjective for each customer. An automatic transmission is regarded as must-be feature for most car drivers in the USA. In Germany, this feature may be seen as attractive, indifferent or even as a reverse quality feature. Thus Kano’s model is able to give a kind of categorization for quality features which in any case is subjective and dependant on the individual customer or customer groups. Other similar categorizations can be also found in [HMS73], [Bra88] and [CaT89].

Figure 3-2: Kano model following [KST84]

3.2.2 Eight Dimensions of Product Quality

In the late 1980s, Garvin analyzed multiple quality concepts. Besides the five views on product quality (see section 3.1), he also identified eight dimensions of product quality [Gar87]. The first quality feature he identified was the performance of a product which is describing its primary operating characteristics. For a washing machine these kinds of features might be the washing performance (i.e., its ability to clean clothes), the dry-spin performance or the noise emitted during a washing cycle. According to Garvin, performance attributes are usually measurable. Therefore, products of different brands might be compared very easily on their basic performance level. Nevertheless, a detailed look is needed as products might still differ in technical specifications. E.g., a washing machine with 4,5 kg maximum load and one with 8 kg maximum load might both perform identically with respect to washing performance etc. Still the first might be more suitable for single households while the second would be preferred by families. Garvin also points out that products might be separated into performance classes in order to match them to corresponding target customers.

The second type of quality dimensions are the features of a product [Gar87]. Features might be seen as *"secondary aspect of performance"* and can distinguish products with similar performance. Both are sometimes hardly separated as they represent a kind of product functionality and are measurable objectively in an attributive manner. Typical features for a washing machine are special purpose washing programs or indicator lamps for the lint filter and water supply. According to Garvin, features contribute to the overall product quality by their total number (giving customers the feeling of possessing an all-round-product) or by customization (giving the customer the feeling of a tailored product).

The dimension of reliability is one of the traditional dimensions used in quality control [Gar87]. Reliability describes the probability to which a product is working properly over a specified time period. Malfunctions, downtimes and under-performance lower the reliability. Although it is an important dimension, it is especially meaningful for durable products used over a long time period. Shortly used products or disposals are not designed for multiple use-cycles. Therefore, reliability is no meaningful dimension for these kind of products. Garvin also points out that reliability is especially important where downtimes are relatively more expensive to the customer. Therefore, a washing machine used for industrial purpose has to be more reliable than one for private persons, as any downtime may result in high economic losses for the customer.

The fourth dimension of quality is conformance [Gar87]. This dimension is tightly bound to the manufacturing-based quality view. Conformance means the degree to which the final product meets standards and specifications defined earlier, e.g. in the product design phase. In the traditional approaches, this conformances is mostly regarded in an mechanical manner where predefined tolerances have to be met. One problem pointed out by Garvin is the stacking of tolerances. As specifications are designed for a certain interval, all product parts that are within the interval are regarded as "good" quality. This problem becomes obvious if one part has to be pressed into another. A bearing ranking at lower tolerance limits that is inserted into a seat ranking at upper limit will provide less extraction force than a bearing and a seat exactly matching the tolerance medium. Although mechanical tolerances can be defined in a way that these problems become negligibly, similar tolerance stacking problems especially in today’s complex mechatronic products may appear and are easily overseen.

The next quality dimension is the durability of a product [Gar87], which describes in an economic and technical way how long a product can be used or which use the customer gets out of a product before it breaks down or is replaced due to lower maintenance cost for newer products. In a first step, the technical aspect is dominating as the product has to be operating preferably for a long period. But following the definition of Garvin, durability goes beyond downtimes. It also takes into account if repairing the product is preferable to replacement. Thus, a product which never breaks is for sure durable. But also, a product with high acquisition cost and low maintenance and repair cost might be durable although it breaks down from time to time. Which might sound weird in the first place is still a good definition for durability as the time a product is used by a customer until replacement is economically preferred. This also leads to the fact that durability and reliability are closely linked, as reliable products cause less repair cost and thus replacement of the product is unlikely. Under these circumstances, durability is one area of quality differentiation for products with an long lifetime expectation. Especially in markets with short innovation cycles like cell phones, durability might be less interesting. As [Sta12] shows the expected lifetime by customers of cell phones in 2012 ranges between 6 and 24 months. Thus, a durability beyond this timeframe is only requested by, 15-20% of the customers and will be economically less meaningful for cell phone manufacturers.

Serviceability is the sixth quality dimension [Gar87]. This dimension is linked with the reliability and durability. As soon as a product breaks down it needs to be repaired. The time it takes to repair a product, the ease of repair, the required competence of service personal (also on customer hotlines), but also the complaint handling define the serviceability. Serviceability is one of the quality dimensions which are not only objectively measureable, as it also depends on the personal expectations of the customer. As markets shift to service economies [ScY03] this quality dimension gets more and more important with respect to the classical dimensions of reliability, durability and conformance.

The last two dimensions of quality are aesthetics and perceived quality [Gar87]. Both of them are highly subjective. Aesthetics describe all information a customer gets from a product using his senses (look, feel, hear, taste and smell). How the customer translates this received information into a quality impression is in most cases unforeseeable. Some customers might judge colored washing machines superior to the standard white colored washing machines, other might judge them inferior. Therefore, aesthetics provide a good field to find own market niches. The perceived quality subsumes information and experiences we connect in some way with the product. The reputation of a company to provide durable and reliable products might be a selling argument, although a given customer might have never bought a product of this company before. This reputation is based on the expectation that the product a customer wants to buy is made of the same quality than previous products [Gar87]. This is also one of the reasons companies invest an essential amount of money for advertising and marketing.

All of these eight dimensions are somehow connected to each other and should therefore always be regarded as a whole. Focusing on specific quality dimensions might be useful in order to occupy market niches, but that requires a complete analysis of the own product strengths and weaknesses. If only some of these features are focused and the others are completely discarded, high risks on failing customer expectations arise [Gar87]. The eight dimensions of product quality according to Garvin are shown in Figure 3-3.

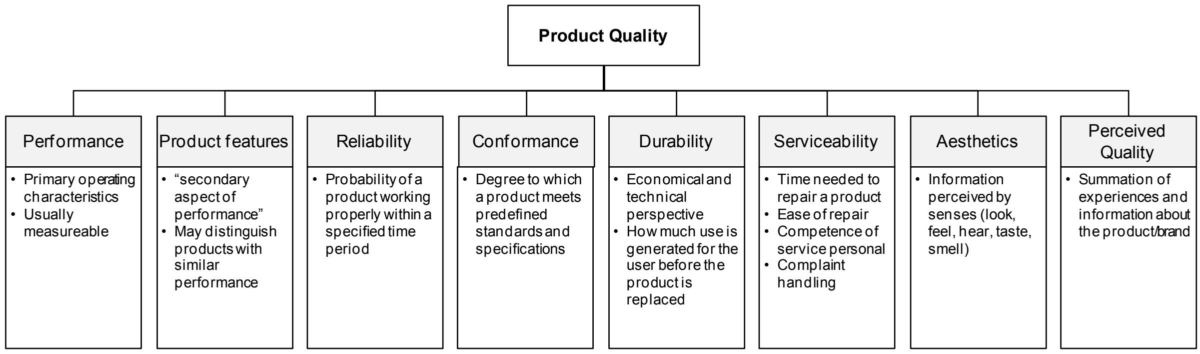

Figure 3-3: Eight dimensions of product quality according to [Gar87]

3.2.3 ISO 25010 – Systems and Software Engineering – Systems and Software Quality Models

In 2011, the ISO/IEC 25010 "Systems and software engineering – Systems and software Quality Requirements and Evaluation (SQuaRE) – Systems and software quality models" [ISO/IEC 25010] revised the ISO/IEC 9126 "Software engineering – Product quality – Part 1: Quality model" [ISO/IEC 9126-1]. In that way, the software focus was broadened to a system view. Within this update, a product quality model has been defined containing eight quality characteristics and 31 sub-characteristics. The scope of this product quality model is intended to be used to provide static and dynamic properties of a software and computer systems. Nevertheless, the provided models may be *"relevant to wider systems and services"* [ISO/IEC 25010].

The first quality characteristic is the functional suitability of a product [ISO/IEC 25010], describing how well the functions provided by the system fulfill explicitly stated and implicitly assumed requirements by the customer. This characteristic includes the degree to which predefined tasks and objectives can be processed / achieved, as well as the correctness to which these objectives are achieved (degree of precision) and the appropriateness to which a task is fulfilled (fulfilling it only using necessary steps and no unnecessary ones).

Another product quality characteristic is the performance efficiency [ISO/IEC 25010], taking into account the amount of resources acquired to fulfill a given task. This efficiency can be further distinguished into the time behavior of the system (input, processing and response times, as well as overall cycle times of a system when performing different tasks), resources utilized in order to complete a task (including human resources) and the capacity of the system (threshold of the system before it is limited in providing additional functionalities or running several tasks in parallel, due to system limitations).

The third characteristic is the compatibility of a system [ISO/IEC 25010], describing the capability of a product to exchange information with its environment and maintain its functionality while sharing its hardware/software environment with other products. This obviously includes the co-existence with other systems in the environment using the same resources without impacting each other's proper function execution and the interoperability between two or more systems to exchange and understand information, services, etc.

The usability of a system according to [ISO/IEC 25010] describes the effectiveness, efficiency and satisfaction to which a user is able to achieve predefined goals by using the product. It can be measured by the following sub-characteristics or as a subset of measures of quality in use (see [ISO/IEC 25010]). The usability can be further divided into the degree of appropriateness of the product recognized by the user (including initial impressions, demonstrations, tutorials, documentation, etc., provided together with the product); the effort to be spend in order to learn to use the product effectively, efficient, risk-free and with satisfaction; the easiness to operate and control the product (including operator fault tolerance and conformity to user expectations); the degree to which users are protected against making errors; the aesthetics of the user interface; and the accessibility of the product especially for people with disabilities.

The fifth product quality characteristic according to [ISO/IEC 25010] is the reliability of the product. The reliability describes the conformance of the system performance under specified conditions over a specified time period. This includes the conformance under normal conditions (maturity); the tolerance of the product to hardware and software faults; and the ability of the system to recover after interruption or failure into the desired execution mode.

Security is another main product quality characteristic following [ISO/IEC 25010]. This is a mainly software focused characteristics which describes the ability of the system to provide different types of authorization; to provide data and information only according to these authorizations (confidentiality) and to protect it from unauthorized access (integrity). This also includes the unconfined traceability of events or actions right to the entity that caused the action or event and the ability to authenticate the identity of a subject or resource.

Maintainability as a product quality characteristic describes the effectiveness and efficiency of modifications on the product or system [ISO/IEC 25010]. This can be achieved by a modular system design in which exchanging one module leads to minimal or no changes and disturbances in the other modules; the reusability of those modules (i.e., the ability to be used also in different systems; by granting easy analysis (in terms of effectiveness and efficiency) of product change impact, product failure or product modifications; the effectiveness and efficiency to which a product may be modified without introducing new failures; and the testability of a product.

The last important product quality characteristic according to [ISO/IEC 25010] is the portability, describing the effectiveness and efficiency to which a product may be ported from one operating environment (e.g. hardware, software, etc.) to another. This includes the ability of the system to adapt to evolving environments, as well as the ability of the system to be installed and uninstalled in different environments, as well as the ability to be replaced by another product within the same environment serving the same purpose.

These eight main characteristics and their sub-characteristics are shown in Figure 3-4 following [ISO/IEC 25010].

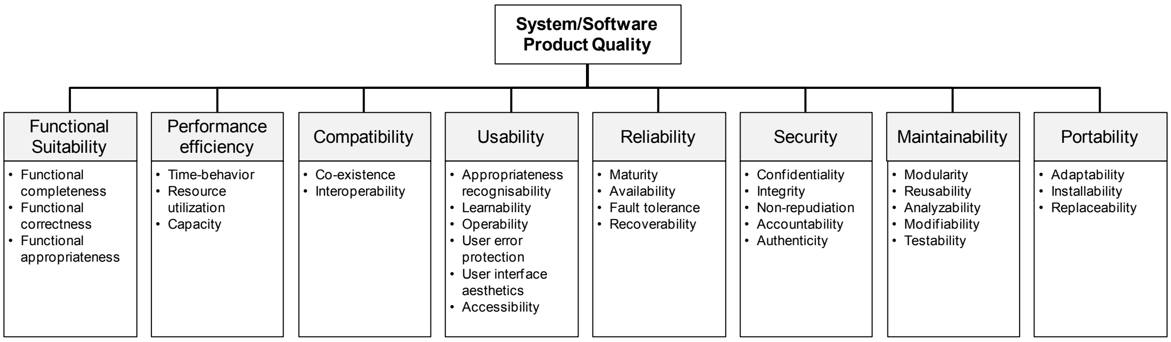

Figure 3-4: Product quality model following [ISO/IEC 25010]

3.3 Product Quality within this Thesis

After presenting the concepts of product quality and some of its characterization approaches, this chapter gives a definition of the term quality and describes how it will be used within this thesis.

As shown in section 3.1, one approach which is very common among all quality conceptions is the idea that quality is the fulfillment of customer expectations (also called requirements) by product characteristics. In the ISO 9000 [DIN EN ISO 9000] quality is defined as the *"[…] degree to which a set of inherent [product] characteristics fulfills requirements."* By requirements the ISO 9000 does not only mean customer requirements, but instead all kind of requirements influencing the product, from the first idea over design, production, sale, use, right until disposal are covered. Hence, although the ISO 9000 at the first view shows many commonalities to the manufacturing-based view, it is not limited to it and also includes all other views by reflecting them in the product requirements. Therefore, the requirements identification and analysis is crucial for any measure to quality improvements. Within the rest of this thesis, the term product quality will be defined according to the ISO 9000 [DIN EN ISO 9000] under the condition that the term requirements is including all influences on the product and not only its manufacturing related requirements.

Section 3.2 has shown that there are many ways to characterize or categorize product quality features. As this thesis will deal with quality under a technical perspective and with the question how it can be improved and ensured during engineering and production phases, the categorization following the Kano-model would be too much focused on the customer perspective. The approach of ISO 25010 in turn is too much focused on software systems in a hardware environment. While typical mechanical products may be classified by this schema, most of the product quality features are only implicitly defined there. The work of Garvin [Gar84], [Gar87] is technically focusing on the product quality without cutting off the subjective perspective of the customer and will be used as a basis for this thesis. This is also done with respect to the application examples from the home appliance domain further down in this thesis. Nevertheless, when applying the methodology of this thesis presented in chapters 6 to 8 within different domains, another categorization might be favored, without impacting the strategic approach presented.

Finally, it should be mentioned that product quality is not the only main driver within product and plant business. When these businesses are analyzed, all measures have to be weighted with respect to their influence on cost, time and quality [HrA93], [VDI 2870-1]. These three main drivers build up the so called magic triangle (see Figure 3-5). For optimizing product and plant business, a suitable balance between optimizing product quality, reducing costs (e.g. for product design, production planning, production) and reducing time (e.g. production time, time to market, etc.) has to be found. Therefore, any measures taken to improve one of these main drivers should be also analyzed with respect to its influence on the other two.

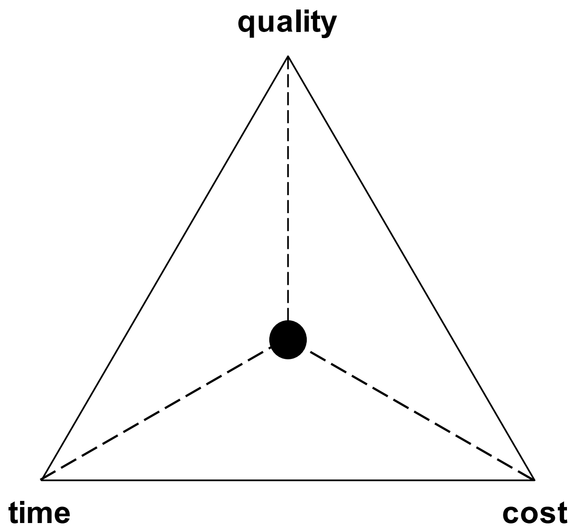

Figure 3-5: Magic triangle of cost, time and quality

4 Quality Management and Quality Assurance Approaches

After the basic characteristics of product quality have been depicted in the previous chapter, it shall now be shown how this quality is managed and assured during product design and plant engineering. There are numerous different quality management techniques, measures and dependency models described in literature. Within [VDI 2870-2], [IBH03] and [Lin09] most important approaches are named.

This chapter is structured as follows: First, section 4.1 gives an overview about important quality management approaches. Section 4.2 will subsequently show main quality measures from literature which are used within these management approaches in order to assure and improve quality of product and processes. Finally, section 4.3 will show additional quality measures used but in a comprehended manner. The goal is to give a slight overview about practically applied methods and measures and the ideas behind but not to give a complete overview about all approaches available. All measures and models described are sorted alphabetically within this section, without presuming their practical relevance.

4.1 Quality Management Approaches

The following sub-sections describe important quality management approaches applied in industry and research. Although described separately, there are some works trying to integrate these singular management approaches, e.g. lean or Six-Sigma. The presented approaches raise no claim to completeness, but are intended to give an overview about approaches practically used.

4.1.1 Lean Manufacturing Approach

The lean manufacturing approach emerged in the 1990 when the Toyota Production System (TPS) was generalized to other than the automotive domain. Since then, "Lean" has become one of the leading principles in production. The Toyota Production System was developed between 1948 and 1975 after World War 2 when resources for the Japanese industry were very restricted. In this environment, Toyota Motor Corporation developed an approach focusing on reduction of all kinds of waste within production [Ohn88]. The Toyota Production System itself, as well as lean, are less a method which can be applied to a production system in order to improve efficiency, instead both provide a kind of framework and basic principles to follow in order to accomplish improvements.

There are three types of waste defined within the Toyota Production System: mura (inconsistencies), muri (overburden) and muda (waste). These kinds of waste are dealt with during different phases of the plant engineering process. First of all, muri is regarded during the plant design. It includes all kind of work which is unreasonable, thus leading to overburden of workers, processes or production systems. The goal is to avoid these during plant design as, otherwise, they will lead to shortcuts, modified decisions and thus to decreased quality or production breakdown. Mura focuses on the implementation of the planned production system. The goal here is to design the system as close as possible to the ideal one, reducing fluctuations of the operational characteristics like quality of produced products or production volume. Muda is focusing on the production phase and can be examined only at the running plant or production line. Muda can be identified through variations between the real output of the production and the originally planned one. Both muda and mura should be fed back to muri in order to improve future projects.

When talking about lean production, mostly running production lines are focused, thus reducing the waste with focus only on muda. There are seven different kinds of muda-waste to be taken care of [WJR90]:

- waste of making defect products (including efforts to inspect or fix defects)
- waste of movement (people and equipment moving more than required to perform a process)
- waste of over production (producing more products of a type than demanded by the customers)
- waste of processing (over processing due to poor tool or product design)
- waste of stock at hand (components, work in progress, finished product not currently processed)
- waste of waiting (a product waiting for the next production step)
- waste of transportation (moving product or product components which are not actually required to be processed)

Although the Toyota Production System and the lean approach share many commonalities, there are some minor differences to be observed. First of all, the overall goal of Toyota was to improve profit of the company. As profit may be described as the price when selling the product minus the cost for making the product, waste reduction is one of the main aims in order to decrease costs. The implementations of lean approaches are also considering that part of waste reduction, but are more focused on the question of quality of products. Thus, they tend to emphasize a little more on measures for quality improvements. This can be seen also by [WoJ03] defining an eighth waste of manufactured products not meeting the customer requirements.

Second, many lean programs tend to rely on tools only. There are various typical lean tools like Single-Minute Exchange of Die (fast way of changing the manufacturing process from the current product to the next), Value Stream Mapping (analyze and design material and information flows, 5S (effective and efficient organization of workspace), Kanban (logistical scheduling system), Poka-Yoke (mechanisms to support operators in avoiding mistakes), etc. When relying only on these tool results, there is a threat to trust too much in these results. It should always be clear that all these methods have their boundaries. Thus, relying on one or few techniques for the implementation of lean, there might be blind spots left which lead to the fact that not all waste is reduced.

In order to achieve lean production systems, three steps are needed [Aki13]. First of all manufacturing systems should be designed in a simple way, decreasing cycle times and inventory and increasing productivity and equipment utilization. In the second step, improvement potentials should be realized. This includes manufacturing system improvement by improving manufacturing processes and operators (e.g. training). Value adding activities and non-value adding activities should be identified. Then, especially non-value adding activities should be simplified, reduced, integrated or eliminated. The third and most crucial step is establishing a mindset of continuous improvement throughout the howl company.

More information on the development of the lean approach can be found in [WJR90] and [Hol07].

4.1.2 Six-Sigma (6σ)

The Six-Sigma approach was, like many other quality approaches, based on Japanese developments in the 1970s. Its first dissemination was done by Motorola in 1985 [Ten01]. The final breakthrough of the approach came with its application at General Electric in 1995, when yields of multiple million US$ have been announced due to application of Six-Sigma [DBM03], [Mot94]. The basic idea behind Six-Sigma is to describe, measure, analyze, improve and control processes with statistical tools. The approach itself focuses a lot on economic verification and validation of measures that have been taken.

The term Six-sigma originates from the statistical process assessment of normally distributed process outcomes, where sigma ("σ") describes the standard variation of a process around its medium value. The term of Six-Sigma thus indicates a process with a variation of ±6σ around the process medium. Within [Ten01] it is shown that, based on practical experience, processes behave differently from short term perspective when analyzed in long term. In fact it is observed that medium values of processes drift about 1,5σ over time. Thus, the real medium value might be not 6σ but only 4,5σ distant from the originally defined tolerance threshold. This refers to a defect rate of 3,4 Defects Per Million Opportunities (DPMO), meaning that e.g. 3,4 of overall one million produced pieces are defective. Although mathematically incorrect, it is commonly agreed that the 6σ-level refers to exactly these 3,4 DPMO (or in other words: 6σ including a ±1,5σ shift). Note that not every Six Sigma program is necessarily aiming for a 6σ level. Instead the level of acceptable process deviation is defined individually for each project and might be also below 6σ. The effect of the 1,5σ shift with a 6σ acceptance level is shown in Figure 4-1.

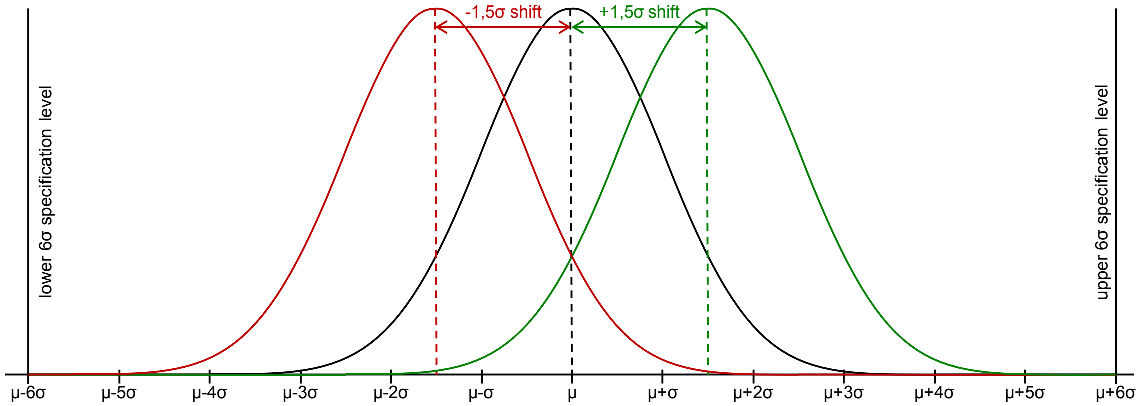

Figure 4-1: Normal distribution with 6σ specification limits and 1,5σ shift

Six-Sigma is implemented as management method in order to improve different processes. It also introduces a role system of "champions", "black belts", "green belts", etc. in order to create an infrastructure of project improvement experts within the company [MKB04].

In order to systematically improve process quality within different projects, multiple project methodologies are defined in the context of six-sigma. The two most popular methodologies are DMAIC, primarily designed for business processes [DBM03]; and Design for Six Sigma (DfSS), also known as DMADV, design for product design. The acronym DMADV stands for the five phases of the project, namely "define", "measure", "analyze", "design" and verify. The main difference to the classical DMAIC approach, is that DfSS does not need a process to be installed and running. Instead it is used to identify and improve customer and business needs and deriving a solution [Lee06].

The DMADV development cycle is shown in Figure 4-2. Further information on Six-Sigma can be found in [Mot06], [Ten01], [DBM03] and [MKB04].

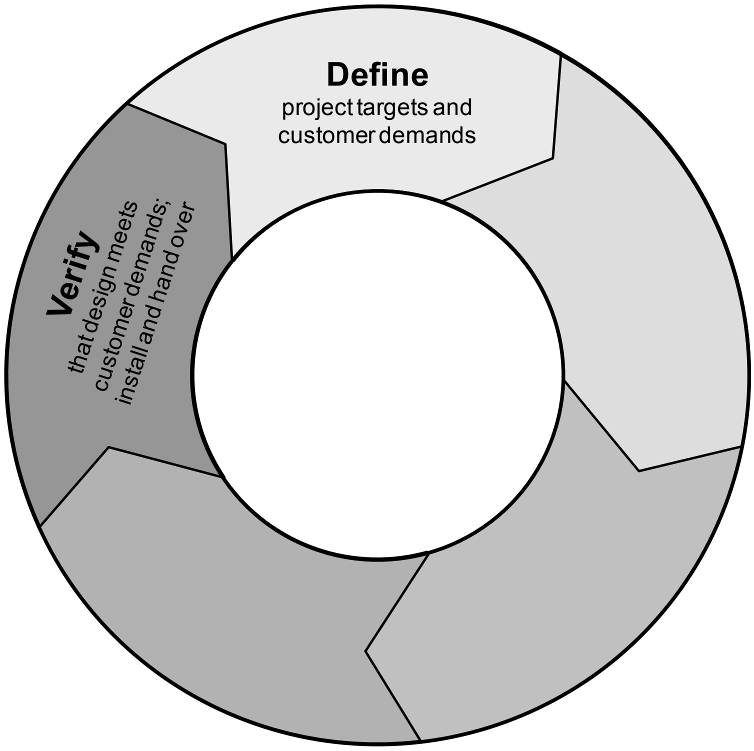

Figure 4-2: DMADV development cycle

4.1.3 Total Quality Management (TQM)

Total Quality Management (TQM) is a management approach with the goal to improve product and process quality. The main idea behind TQM is that every single employee is involved in and responsible for quality and has to take product and/or process quality as the superior goal. Thus, not only product designers and plant operators are influencing product quality, but also management, supplier and customers are involved. One of the first people researching in the field of TQM was Deming in the 1940s. But only after moving from USA to Japan, TQM became recognized. In [Dem00] he described 14 key principles which, although not naming TQM, are credited to be the first dissemination of the TQM ideas.

The British Standard 7850 - Part 1 [BS 7850-1] defines Total Quality Management as "*management philosophy and company practices that aim to harness the human and material resources of an organization in the most effective way to achieve the objectives of the organization.*" Within TQM, quality is always customer oriented and is achieved by all employees regardless of their department or position within the company. To ensure quality, active acting is needed from everyone especially focusing the processes to create results (e.g. products, services, etc.).

The definition of quality within TQM is aligned with the contemporaneous approach of Crosby, who defined quality as the fulfillment of customer requirements [Cro79]. Thus, quality can not only be defined based on producing something in the right way, compliant to some requirements like tolerances etc; instead quality is defined within the interaction of a company and its customer and results from a product, service or process compliant to customer needs. Hence, it is the customer who determines whether the efforts spent by the company in order to improve and ensure quality are worthwhile or not. This key assumption also explains the strict customer focus of TQM.

In order to monitor and manage quality, Total Quality Management focuses on a process view. Each result is created in a sequence of steps using internal and/or external inputs and creating internal and/or external outputs. Every single step can be measured and thus, process performance can be assessed. If outcomes vary unexpectedly, suitable measures may be identified by analyzing the processes which lead to the outcome. This analysis is not only done within the one process creating the outcome, but also by analyzing parallel and upstream processes which may have had an influence. This integrated system view shows up on multiple places within TQM. Pushing everyone to take responsibility for quality is just another example for this, as everyone might contribute to product quality although it might not be obvious in the first place.

TQM is deliberately involving company management level into quality management. They are supposed to define long term strategies and visions integrating product, process and service quality as a key factor. Additionally continuous improvements are needed which are practically achievable only if management commitment and support is granted. This also includes communicating needs for changes.

4.2 Main Quality Measures

The following sections describes main quality measures to describe product, product quality and production dependencies. None of them are used as standalone measures, but instead they are supported by each other or by additional quality measures. The presented measures raise no claim to completeness, but should give an overview about measures practically used.

4.2.1 Demand Compliant Design (DeCoDe)

The Demand Compliant Design (DeCoDe) is a model for the systematic analysis of technical systems [ScW09]. It was developed in order to support the product design of technical systems and is focusing on pure technical influences without considering human interaction or socio-technical aspects. The main aim of DeCoDe is fault prevention due to a product design which is oriented on requirement satisfaction. The application area is focused especially on complex mechatronical products where the high demand for interaction between different domains complicates the development of a common picture of the overall system [ScW09].

Following [VDI 2221] and [VDI 2206], requirements are the starting point for product development. These requirements are the first element of the DeCoDe model and are defined following [DIN EN ISO 9000] as *"need or expectation that is stated, generally implied or obligatory."* Based on the product requirements, functions and components can be derived. These functions are describing the system inputs and their resulting outputs in order to accomplish a specific task. The product components may be physical parts or assemblies as well as logical parts like software. These three model elements are completed by the processes which the product passes through its lifecycle. They are modeled in order to describe the interactions during product design [ScW09].

The basic schema of the DeCoDe model is based on correlation matrices which are also known from the Quality Function Deployment (see section 4.2.4). This basic schema is depicted in Figure 4-3.

The main matrices of the model are the requirements matrices A, A_F, A_C and A_P. They depict the correlations between requirements and the product components, functions and processes. Thus it can be seen which element contributes to the fulfillment of product requirements. Within Matrix A all requirements on the product are collected and their mutual influences are depicted. Thus, requirements can be prioritized, systematized or eliminated (e.g. if they appear multiple times).

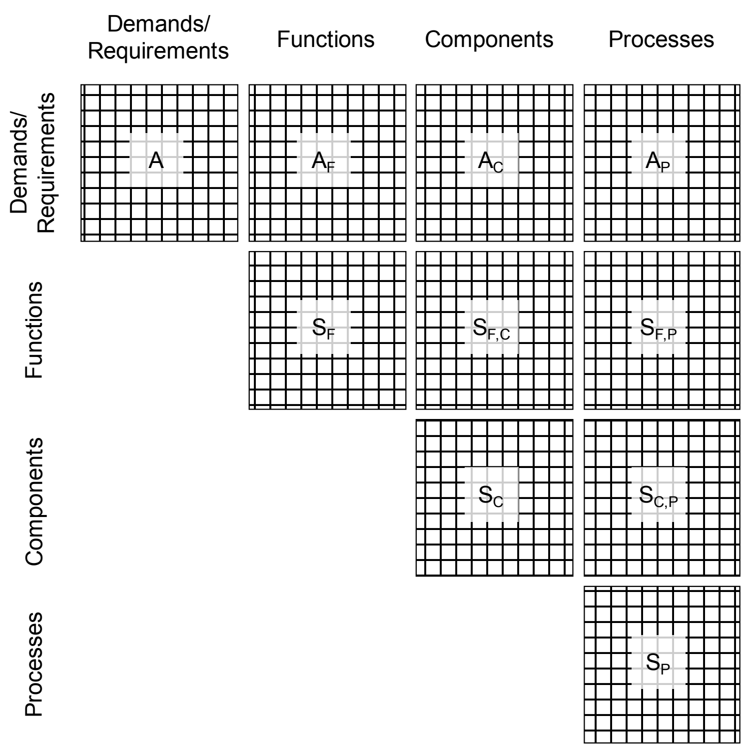

Figure 4-3: DeCoDe basic schema following [ScW09]

The matrices A_F, A_C and A_P are describing the influence of requirements on functions, components and processes vice versa. Thus, they show which function, component orprocess is fulfilling which requirement. At the same time, new requirements may be derived from the functions, components and processes. The matrices S_F, S_C and S_P describe the influences amongst functions, components and processes. They may be used to describe correlations on function-, component- or process-level. The other matrices $S_{F,C}$, $S_{F,P}$ and $S_{C,P}$ are used to describe which components and processes are needed to accomplish a specific function and which components are needed to execute a specific process. They may be also used to describe conflicts among these elements [ScW09].

Within [SiW11] different application examples of DeCoDe are shown. Within Figure 4-4, the direct application of DeCoDe is depicted. Based on the product environment specification the requirements/demands are analyzed and formulated. Based on these requirements, necessary product functions are identified and related to the requirements. At the same time, requirements may be evaluated and additional requirements may be formulated derived from new product functions. Based on the list of product functions required components are identified. Again by identifying these components additional function might show up and are added. When all functions and components are related, the influence of components on the fulfillment of requirements may be analyzed. Afterwards all processes required are identified and analyzed. Again new processes might lead to additional required components, functions and finally requirements. After all these feedback loops are stabilized and no new requirements, functions, components or processes show up, the processes can be related to the requirements. In the next step, requirements are ranked against each other in order to identify conflicts and distinguish crucial requirements from those desirable or even unimportant requirements. Based on this ranking, the weighted sum of degree of requirements fulfillment, named Comprehensive Quality Function (CQF) can be evaluated and influence matrices can be built. If the CQF value is low, this corresponds to a product which is only little and insufficiently fulfilling its requirements. Thus the design process might be iteratively repeated until CQF value reaches a satisfactory threshold [SiW11].

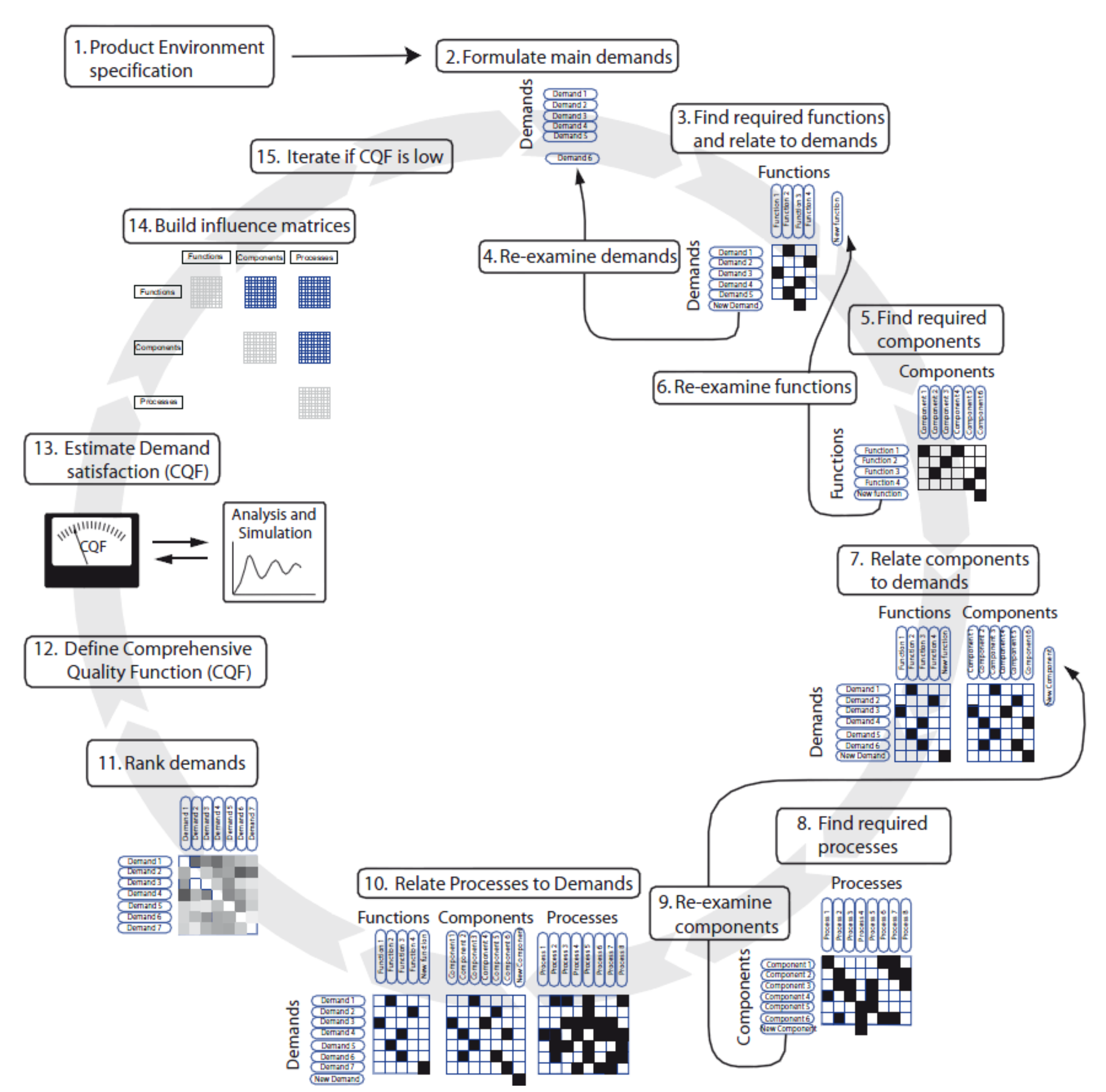

Figure 4-4: DeCoDe method following [SiW11]

4.2.2 Failure Mode and Effect Analysis (FMEA)

The Failure Mode and Effect Analysis (FMEA) is a systematic approach to analyze system failures, their causes and effects. The analysis method has been standardized within DIN EN 60812 [DIN EN 60812]. Formally [DIN EN 60812] differentiates between FMEA and FMECA, which adds a criticality analysis to the normal FMEA. Nevertheless, both techniques are commonly used and referred to as “FMEA”.

There are different types of analysis and depending on the system under inspection they are differentiated as Design-FMEA, System-FMEA, Hardware-FMEA, Software-FMEA, Process-FMEA, etc. The goal of each analysis is to identify failures, which are interfering with the system function or significantly decrease system performance. This is done in order to ensure the fulfillment of customer requirements, security and safety requirements as well as to improve maintainability of the system [DIN EN 60812].

The core of each FMEA is to identify system failures and their causes, document them on a working sheet and derive appropriate measures. The basic assumption for each analysis is that a failure is always only caused by one reason. Therefore, the scale of FMEAs might become very big as system complexity grows. Hence, it is recommended to reuse FMEAs from system components already assessed and only reassess them if operating conditions changed significantly.

As FMEA has a proactive character, it is expedient to start analysis as soon as possible within the design process, as failure elimination costs rise over time [VDI 2235], [Per92]. Nevertheless, FMEA is not suitable for the analysis phase and should start with concept design earliest, as the definition of system function blocks is a crucial prerequisite for conducting the analysis. The process of conducting a Failure Mode and Effect Analysis can be separated into the following tasks. First of all the, basic rules for the FMEA should be set, including scheduling and acquiring knowledge and experts. Afterwards, the FMEA should be conducted and documented on worksheets or other diagrams like Fault-Tree-Analysis [IEC 60300-3-1]. Based on the analysis and the documentation, conclusions can be drawn and measures can be identified. The last step is the continuation of the FMEA, as each design change might also influence the causes, effects and failures identified within an analysis, the FMEA should be constantly reevaluated. The typical procedure of an FMEA is depicted in Figure 4-5.

As described above, most FMEAs are usually conducted as FMECAs. The “C” shows, that the analysis also includes importance analysis. The criticality gives information about the importance of a failure mode and about the extent it has to be treated or its effects should at least be softened. Within FMECA, some numerical calculations are made in order to assess criticality and priority of risks. Therefore the severity (S) of a failure effect is weighted (usually using a scale from 1 to 10) giving estimation about how much the system or user would be influenced by this failure mode. Another value to be weighted will be the occurrence (O) which is estimating the likelihood of the cause producing the failure mode and thus the negative effect. The product of severity and occurrence is called risk or criticality.

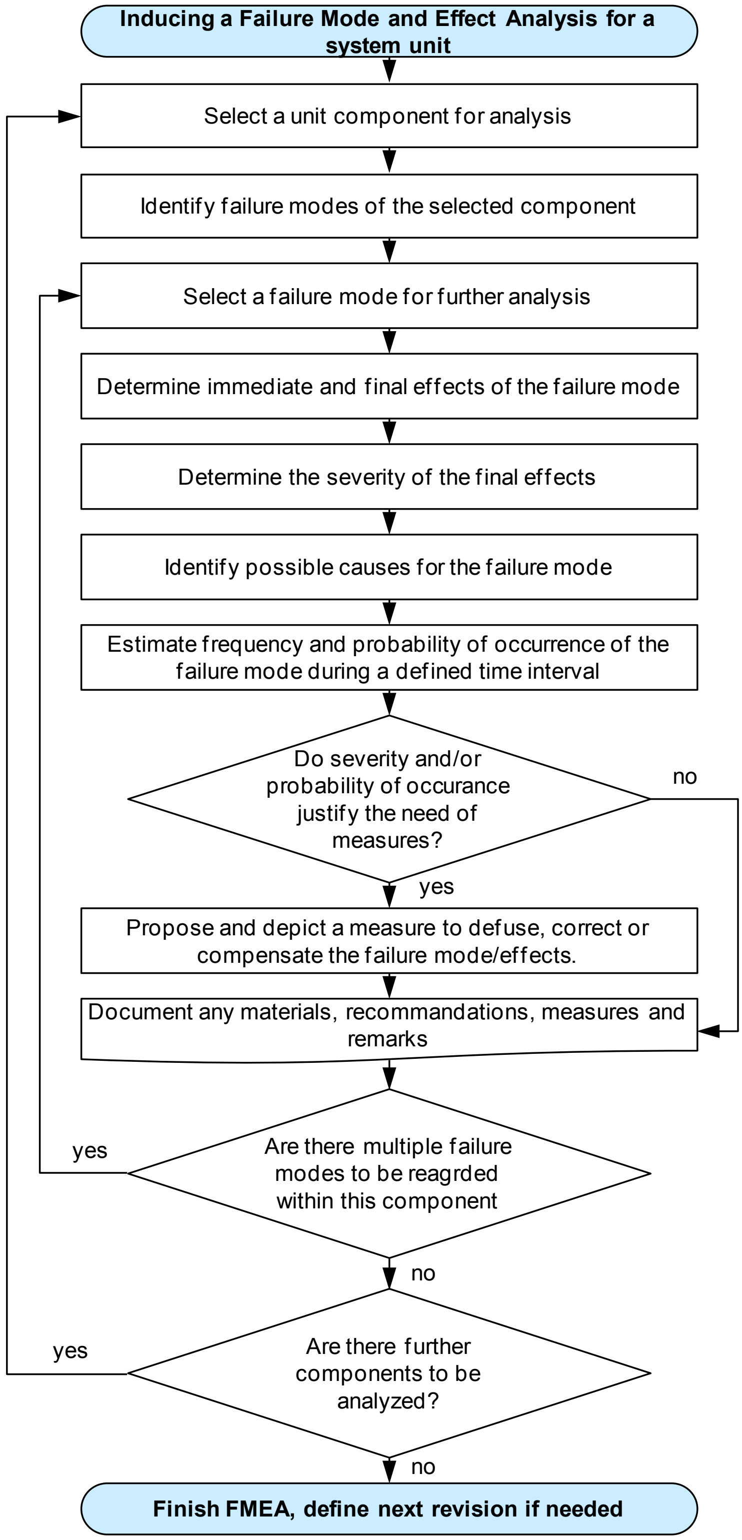

Figure 4-5: FMEA procedure following [DIN EN 60812]

A last value to be assessed in the FMECA is the detection (D) of a failure mode, which gives an estimate about the effectiveness to control or prevent the failure. From these three values mentioned above a Risk-Priority-Number (RPN) can be calculated.

$$RPN = S \cdot O \cdot D$$

This RPN can be used to define a priority for the measures on failure prevention. Nevertheless, RPN should never be the only prioritization characteristic. Every failure with a high severity is likely to have unacceptable effects and, therefore, has to be analyzed. At the same time, failures with a high criticality (S*O) are likely to occur often or at least have severe effects. Thus, also criticality has to be regarded. It is easy to show that numerical combinations can be build where the RPN of some failure is high while the most severe or critical failures have a relatively low RPN due to low detection effectiveness. Hence, RPN should never be the only characteristic for prioritization and severe and/or critical failures should always be checked.

Finally Figure 4-6 shows the head of a typical working sheet for FMEA and FMECA for documentation of failure modes, causes, effects, measures, criticality and RPN. For further information on FME(C)A it is referred to [DIN EN 60812] and [Sta03].

Unit/Function			Failure Mode	effects		Severity (S)	possible causes	detailed cause	Occurance (O)	Criticality (S*O)	Actual monitoring mechanism, preventive	actual monitoring mechanism, detection	Detection (O)	RPN (S*O*D)	recommended measure	resposible/ date	Result of measure				
Sub-System	Assembly	Component		lokal effects	final effects												description	Severity (S)	Occurance (O)	Detection (D)	RPN

Figure 4-6: Typical worksheet for FME(C)A following [DIN EN 60812]

4.2.3 Product-Process-Resource Approach (PPR)

The Product-Process-Resource approach originates from the Product-Data-Management domain. The idea is to integrate information about the product and its components, the production processes and the production resources in order to cope with actual challenges like globalization, product quality assurance and improvement, customer demands, diversity of variants, reduction of development times, time to market, cost reduction and shortening of product cycle times [Kat05].

The approach aims at a consistent, integrated use of planning data within the product development process. All data about the product, processes and resources should be available and up-to-date at any time, also including the consistency of the digital plant with the real one in order to enable virtual commissioning and feed back of real production data into the planning phases for further improvements [Sch07].

One idea to improve this integration is to change the construction kit oriented product structure into a connection oriented product structure. Thus, each product component can be described and multiple components may be connected via connector positions. These connector positions are enriched by additional data. Thus, it can be described which product components are assembled to which sub-assembly within which production processes using which production resources [Kat05]. To built up these models, first a product structure is defined. Within this structure, all product components are connected via connector positions. Within a feature based product design these connectors are enriched with additional data. Thus, it can be described which surfaces of the product components should be connected and how this is done (e.g. gluing, screwing, welding, etc.). Subsequently, a process model can be defined, enriching the connector positions with process information like sequences and parameters. After suitable production technologies are selected and final process model is depicted, the corresponding production resources are selected, again enriching connector position information [Kat05].

In order to enable this data integration, multiple different data and information have to be integrated into one single data backbone. This includes CAD data, 3D-product models, process operations, process structures, ergonomic data, production resource data, time analysis, tact timings, logistic data, 2D and 3D factory layout data, facility planning, etc [Hor02]. One approach to ensure data semantics among these different models is the use of an ontology. Such an ontology was developed within the OZONE abstract domain model [BeS07]. The OZONE ontology consists of five concepts which are product, demand, constraint, activity and resource. These five concepts and their interrelations are depicted in Figure 4-7. To map these ontology concepts to the product-process-resource approach, products and resources might be mapped one-to-one, while processes correspond to activities.

Further efforts have been taken by ISO Technical Committee 184 / Sub-Committee 4 - Industrial Data (ISO/TC 184/SC4). It has proposed a standard for a product-process-resource based approach for managing modularity in production management. The ISO 15531 MANDATE [CYM07] defines a series of standards for exchanging industrial manufacturing management data. For further information on this standardization refer to [ISO 15531-1], [ISO 15531-31], [ISO 15531-32], [ISO 15531-42], [ISO 15531-43] and [ISO 15531-44].

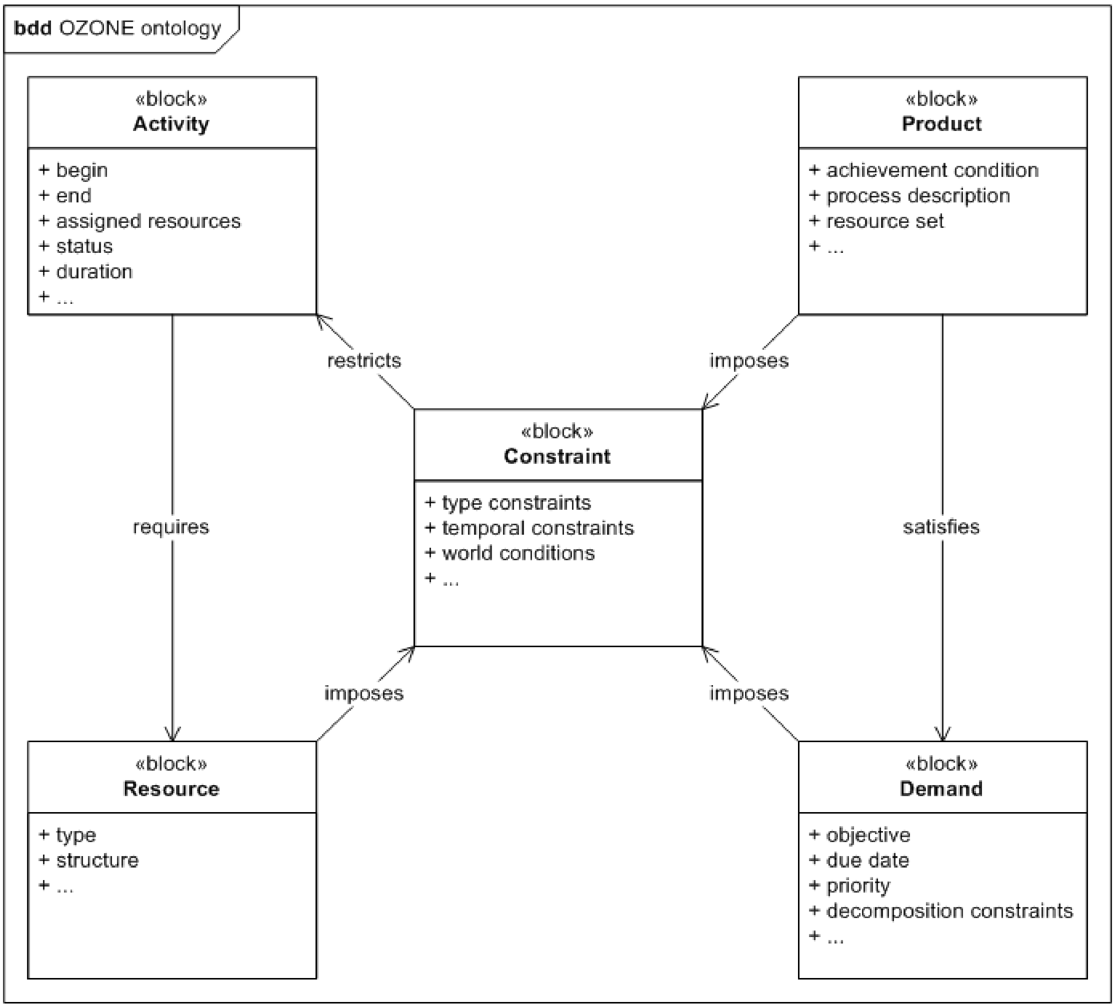

Figure 4-7: OZONE ontology, following [BeS07]

4.2.4 Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a method of quality assurance. Its goal is to design, develop and sell only products which are desired by the customer. The first concept of QFD was developed in 1966 by Yoji Akao [Aka90]. The QFD method is a team based approach trying to correlate customer delights with technical characteristics of the product and production processes, involving cross functional teams in the product development process. The QFD approach can be separated into four different phases which are translating customer needs to production control finally. QFD thereby builds on a quite simple, in its easiest way binary, correlation of development aspects.

Within the first phase, the product planning, the customer needs and technical product characteristics are correlated. This is mostly done by marketing departments and also known as "House of Quality". The House of Quality is a well known tool from Quality Function

Deployment. In many cases it is also the only tool used as subsequent tasks are often processed with traditional engineering methods.

Within the House of Quality, customer demands and technical requirements are systematically assessed [Ham11]. First of all, customer requirements are identified using market analysis or customer surveys. Ideally, the customer weights the requirements in parallel in order to differentiate between unimportant and crucial requirements. This is mostly done using a simple rating scale. In a second step, these customer needs are compared to competitors. Normally the top two or three competitors are taken as references. For each customer requirement, the customers are asked to weight their fulfillment for the different products. In this way, it is possible to derive in which categories/requirements the own product is leading and where competitors are superior.

In the next step, technical characteristics of the product are identified. These characteristics should always be measurable in order to be able to verify their fulfillment or, respectively, to define a specific peculiarity of the characteristic. Within the fourth step, the optimization direction of the technical characteristics is defined. Here, it is defined if a certain characteristic should be maximized, minimized or if it should reach a predefined value. In the fifth step, the correlations between technical characteristics are analyzed. It should be evaluated if there is no correlation, minor correlation or even a strong correlation, as well as if the correlation is positive or negative.

The next step is the filling of the main correlation matrix. Here, a correlation between a given technical characteristic and its fulfillment of customer requirements is established. This correlation is weighted in a way that a differentiation between strong fulfillment or contribution to fulfillment, medium influence or minor influence become visible.

In the seventh step, the technical realization of the technical characteristics is analyzed. First of all, the difficulty of the technical realization is estimated. This can be done using a numbered scale in order to depict the effort needed in order to realize a specific technical characteristic. Subsequently, reference values for the technical characteristics are defined. Here again, it becomes visible, that defining measurable technical characteristics is important. Otherwise, a definition of reference values would not be possible. Finally, a comparison with competitors can be done. This comparison is different from the one in step two as there are two main differences. First, the comparison is done by own engineers, second, the comparison is not based on a subjective assessment but instead on comparing the previously defined reference values with objectively measured values from the competitors products. In this way it should be ensured, that a technical improvement is reached.

Finally, in order to complete the House of Quality, an assessment of the technical importance or technical characteristics is performed. In order to do this, the subjective customer importance of customer requirements is multiplied with the influence of the technical characteristics on the customer requirements (from the main matrix). These can be summed up for each technical characteristic. The resulting values are giving an objective evidence of the overall technical importance of a technical characteristic. Thus, technical characteristics with a high technical importance are also very important for the fulfillment of customer requirements and should be treated carefully in the subsequent product development phases. The House of Quality and its rooms, respectively the steps to build it up, are depicted in Figure 4-8

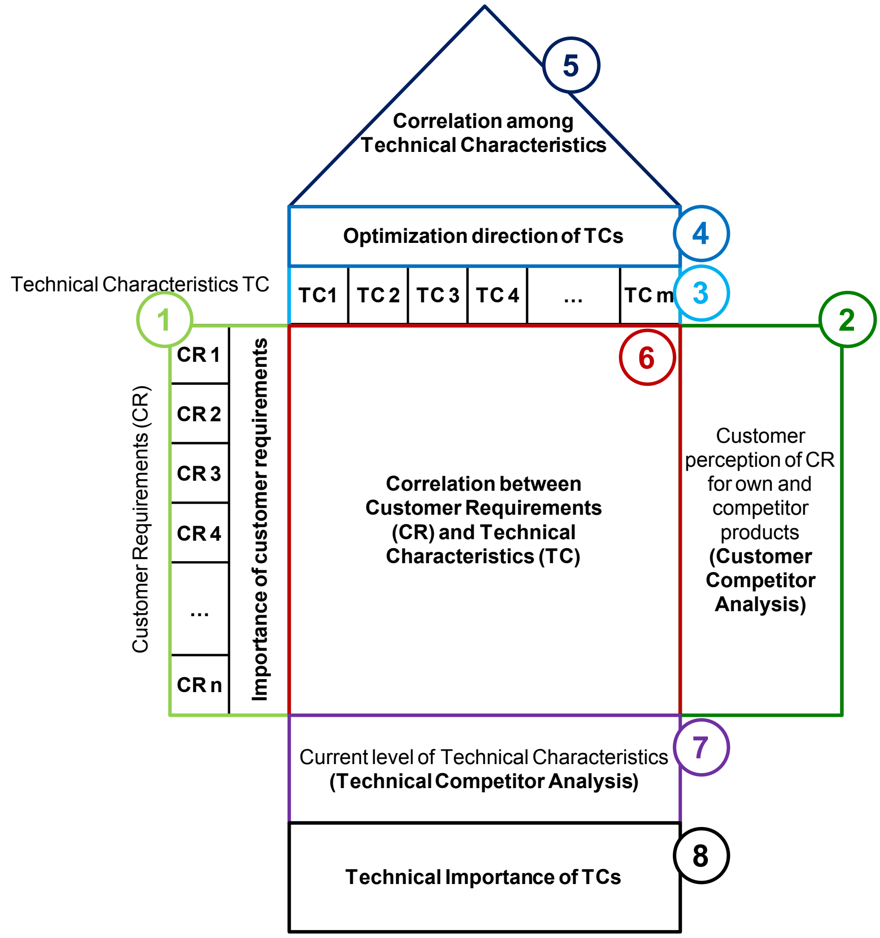

Figure 4-8: House of Quality following [Ham11]

The same way the House of Quality is used within the product planning phase, there are additional correlation matrices used within QFD. The product design can be typically supported by building up a correlation between the technical characteristics of the product and its components. This way it can be assessed which product components are needed to fulfill certain technical characteristics. In the process design phase, these product components are again taken as input in order to derive a correlation matrix to the production processes. Here, a correlation is established between processes and their creation, assembling or influencing of product component. The final phase of QFD is the process control, where the process design matrix is taken as input and processes are assessed based on their conformance to the predefined process parameters and outputs.

For further information on QFD as well as on extension of QFD it is referred to [Aka90] and [Kin89].

4.3 Additional Quality Measures

This sub-chapter presents some additional quality measures. Most of them are widely used as a supporting tool for each other or for more complex quality measures as presented in sub-chapter 4.2. The presented measures raise no claim to completeness, but should give an overview about measures practically used.

4.3.1 5S

The 5S method is designed to create safe, clean and clear working environments. It is thereby a crucial element of the lean approach. The name 5S is derived from the 5 words of the Japanese original terms for the steps, all beginning with an “S”. First step (“seiri”) is sorting things out which are unnecessary at the working place. Second step (“seiton”) is to systematize things and set them in an order to flow. This means that all things left after sorting should be put in a fixed, ergonomically reasonable and labeled place. Afterwards, the task (“seiso”) is to systematically clean the place and to keep it clean. The fourth step (“seiketsu”) is to define standards and to practice the first three steps in predefined intervals. Standardization is also a goal in order to enable interchangeability of working places and humans working there. The final step (“shitsuke”) is to practice self-discipline and to comply to the defined standards as well as to further improve working place organization by continuous improvement and replacing outdated standards. Further information can be found in [WJR90], [Ohn88] and [EPA07].

4.3.2 Balanced Score Card

The Balanced Score Card (BSC) is a tool to measure, document and control quality improvement activities. It is therefore not a quality measure in itself but helps to identify what has to be measured or measures to chose for improvement programs and to assess the performance of these improvement programs. The Balanced Score Card concept is widely used [Kur97]. The concept of Balanced Score Cards has been driven by Kaplan and Norton in the early 1990s, who defined four perspectives of the BSC. First the financial perspective includes typical performance indicators like revenue and costs and helps to identify financial measures. The customer perspective is less oriented on short term yields but focuses on customer orientation and long term customer satisfaction in order to improve long term revenue. The internal business process perspective focuses on delivered quality as a result of good process quality and also on process cycle times. The last perspective "learning and growth" focuses on performance indicators for the long term development of the company like improvement, value creation, innovations and staffing. For more information on the Balanced Score Card it is referred to [Kur97], [KaN91], [KaN97] and [Hub07].

4.3.3 Design of Experiments

Design of Experiments is used to develop and improve products or processes. The basic idea is to use systematic experimental setups in order to derive cause-effect relations between system inputs and outputs or in a more general manner independent and dependent variables. Thereby, the number of investigated influence factors, the type of influence factors (qualitative or quantitative), available information and required reliability and accurateness of the experiment are considered. There are three different types of experimental designs. The full factorial design allows the investigation of all possible factorial combinations between inputs and outputs. As resources are usually rare, first a screening methodology is used in order to analyze the influence of numerous factors at a time and derive significant factors within only few experiments. Afterwards, response surface methodology is used to analyze correlations between significant factors and dependent variables in detail. In this way it is possible to derive detailed analysis within few experiments utilizing as few resources as possible. Further information on Design of Experiments can be found in [BHH05], [CoC57] and [MMA09].

4.3.4 Poka-Yoke

Poka-Yoke was developed in the 1960s by Shigeo Shingo as one method used within the Toyota Production System. Its main aim is to prevent errors from occurring, instead of identifying errors [Shi86]. The basic idea is to provide additional process modifications and techniques to eliminate failures. Three types of Poka-Yoke techniques can be distinguished. First of all, the contact method allows to test physical attributes like size and shape of products and to use these in order to prevent errors. A typical example are telephone TAE plugs which are designed as "F" and "N" plug [DIN 41715-1]. Both are shaped in a way that they only match their corresponding connection even eliminating the possibility of plugging them in the wrong way round. The second technique is the fixed value method where errors are identified by the number of movements done. If there are too many or too less movements than designed, a failure has likely happened. The last method is the motion step ensuring that all predefined steps of a process have been executed. In Poka-Yoke these failures are either identified and reported to the operator in order to prevent follow-up defects or they are even prevented by the above mentioned techniques. For more information on Poka-Yoke it is referred to [Shi86], [Shi89] and [Shi08].

4.3.5 Statistical Process Control

The Statistical Process Control (SPC) was developed by Shewhart in the 1920s and first published in 1931 [She80]. The basic idea is that product quality is mainly depending on the variation of technical characteristics of its components. Shewhart identified two possible types for this variation. First, there are common sources of variation which include natural stochastically deviations from the mean value of a process like noise. The second type are special sources of variation, including failures in materials, machines, processes, etc. Based on his observations of natural and technical variations, Shewhart developed control charts in order to monitor and control production processes. The goal of Statistical Process Control is not to improve quality itself, instead a predefined quality should be ensured by using a reasonable amount of resources. A typical goal for SPC is to reach a $\pm 3\sigma$ area (corresponding to a $4{,}5\sigma$ level in the Six Sigma approach and to 99,73% of products without defects). By using control charts it is also possible to identify stable processes which may be further analyzed within process capability analysis to ensure that they produce conform products also in the future. If processes with excessive variations are identified, additional tools like Design of Experiments may be used to identify causes for these variations. Further information on Statistical Process Control can be found in [She80], [Dem86], [Whe00] and [DiS05].

4.3.6 SWOT-Analysis

SWOT-Analysis has been developed in the 1960s at Harvard Business School. The acronym stands for "Strengths", "Weaknesses", "Opportunities" and "Threats" and is used to strategically develop an organization [KBB10]. The idea of systematically identifying these four elements is to either match them (e.g. matching strengths to opportunities) or to convert them (e.g. converting threats into strengths or opportunities) or if both is not possible, try to minimize or avoid threats and weaknesses. The analysis is done by identifying internal factors of the organization (strengths/weaknesses) and external factors (opportunities/threats). The basis for every SWOT-Analysis is that the target is well defined, as the categorization of the four elements is highly depending on the target state. When the SWOT-Matrix is build up it is the goal to maximize strengths and opportunities and to decrease weaknesses and threats by combining them. This way, strengths and opportunities are combined to increase the likelihood of realizing the chance; strengths and risks are combined in order to utilize strengths to prevent risks from happening or lessen their effects; weaknesses and opportunities are combined to convert weaknesses to opportunities or even to strengths; and weaknesses are combined with risks in order to identify which are the main weaknesses and to identify measures to protect the organization from damage. This strategic orientation can be used to align the organization with customer demands and to highlight where demands are not fulfilled. Thus quality of the products, processes and services provided by the company might be enhanced. More information on SWOT-Analysis can be found in [KBB10] and [MBA99].

5 Current Limitations in Quality Management and Quality Assurance Approaches

This chapter points out limitations of quality management approaches and quality measurements currently available with respect to the research questions described in chapter 1.2. These limitations are shown only exemplarily for the approaches described in chapter 4, as it is practically impossible to analyze every quality measure or management approach that's ever been made.

Looking back at the research questions 1 and 2, they have already been answered within chapter 4, where it is described which measure is working in which way and how it is influencing product quality. So the key factor left to analyze is consistency along the product lifecycle chain. This can be done by correlating the different quality measures and management approaches to the phases of the aggregated engineering process from chapter 2.3 and by analyzing which measure can be used within which phase for product design and plant engineering. Such a correlation is done in Table 5-1. Here, the correlation is done in a simple way; “x” indicates that the approach or measure is directly managing or improving product quality within this phase; “o” indicates that the approach or measure is supporting the management and improvement of product quality; and finally “-“ indicates that there is no influence of the approach or measure on product quality within this phase. With respect to the analysis carried out in chapter 4 the following observations can be made.

The Lean approach is primarily focusing on waste reduction during the production. It is based on the observations of a running production line, so it is mainly performed within the use & optimization phase of the plant engineering. Taking into consideration other types of waste (muri and mura) as well, which are typically not part of implemented Lean programs, the Lean approach is also supporting planning and implementation phases of the production system.

Six-Sigma is applied in the domain of plant engineering and focuses on reduction of process variances. Typically it is applied during the installation & commissioning or the use & optimization phase as real processes are needed to compare real process output with predefined outputs. Nevertheless, Six-Sigma is also supporting the planning of production lines when used as a predictive tool.

When it comes to Total Quality Management, direct influences on product quality are rare. TQM is more a kind of mindset implemented at a company which is indeed working towards improving product quality based on the awareness of everyone. Nevertheless, it is not TQM itself, but indeed the measures taken with a TQM background that are directly managing or improving product quality. Still, TQM integrates both domains of product design and plant engineering as everyone within the company is responsible for quality.

The Demand Compliant Design approach is used to design products in accordance with their requirements. Thus, it is applied in the product design phase. Except from the production phase (installation & commissioning), it is directly planning and optimizing of products and thus the product quality defined within these phases.

Due to the numerous variations of FMEA, it is applicable for both domains of product design and plant engineering. Since FMEA is started based on – at least – rough functional structures of the system, it is not applicable in the analysis phase, but only after the functional structure is defined in the concept & basic design phase. The main focus of FMEA is set on the planning phases, where it is used to directly manage system quality. Within the installation & commissioning and the use & optimization phases the method may still be used as a supportive tool. Although different types of FMEA make the method applicable in both domains, it is not correlating both domains as different types of FMEA are conducted separately from each other. Thus the method does not contribute to a consistent integration and use of quality related information along the product lifecycle.

The Product-Process-Resource approach is applied in the domain of plant engineering. Although it is not focusing on product quality, its integrated approach leads to a direct influence on quality during the early planning phases. It might also be used to support plant optimization.

Quality Function Deployment is mainly used in the domain of product design. By correlating customer demands and technical product characteristics it is directly influencing the product quality in the planning phases. In practice QFD is applied using only the correlations between customer demands and technical characteristics. But the original approach is also including further correlations to the production processes. Thus, QFD could be (in general) supportively used within analysis, concept and basic design phase of the production line.

By its general character, the 5S method can be used in every phase of both domains. Nevertheless, 5S is not directly focusing the management or improvement of specific quality features. Instead it is reducing failures within the design activities by supporting humans within their workplaces. Hence, there is also no integrative character of 5S as it is not contributing to the consistent information chain along the product lifecycle.

The Balanced Score Card method is acting similarly to TQM. The method itself is not directly managing or improving any quality features. Instead, it is used to select and asses quality measures which in turn directly influence quality. Thus, Balanced Score Card might be applied within all phases of both domains as a supportive tool.

Design of Experiments might be used within the concept and basic design phase in order to support feasibility studies and technology selection within both domains. Additionally, DoE is used to identify and analyze key influences on quality features of the final system. Although applied in both domains, Design of Experiments is conducted separately, thus not integrating domains and information within.

Poka-Yoke is used to prevent errors or to instantly recognize them in order to prevent subsequent failures. The method is mainly applied in the installation & commissioning phase of products and plants. It might be also used supportively to maintain system quality within the use and optimization phase, by preventing (user) errors which otherwise could lead to system breakdown. Like other approaches before, Poka-Yoke is not integrating neither product design nor plant engineering.

The Statistical Process Control can be applied to production processes but also to processes within a product. Thus SPC might be applied within both domains, where it can directly manage and improve process variances and thus product quality. This is done without integrating both domains or exchanging information and knowledge between applications within different domains. As SPC controls real processes, it is applied in the installation & commissioning phase and especially in the use & optimization phase only.

SWOT-Analysis is a strategic planning tool to evaluate development alternatives. Thus it is applied primarily in the analysis phases of product design and plant engineering. Its results might also be used to support concept design. Again, both domains are not integrated by SWOT-Analysis.

When looking at Table 5-1, it becomes obvious that there are certainly many methods and tools managing and improving product quality. Nevertheless, they are not integrating product design and plant engineering. This is in alignment with observations made by [IBH03] where it is pointed out that there is a scarcity of research on influencing product quality during production system design. This gap automatically leads to an non-consistent information and knowledge exchange with respect to product quality along the product lifecycle.

This inconsistency contradicts the ideas of systems and system of systems engineering [HaD97] which generate synergies out of the fact that not only small parts of the system are considered, but instead the overall system and the interaction of its sub-systems is the key consideration point. By focusing on small encapsulated quality considerations, the chance is thrown away to improve overall quality and to find additional measures for quality improvements as emerging behavior and also emerging quality aspects are overseen. Hence, a new systematic approach is needed enabling a consistent knowledge and information exchange along the product lifecycle. Within the following chapters the concept of such an approach is proposed, the application and implementation is shown and quality improvements based on the results of a prototypical implementation are depicted.

	short Description	Product Design					Plant Engineering					Remarks
		Analysis	Concept & Basic Design	Detailed Design	Installation & Commissioning	Use and Optimization	Analysis	Concept & Basic Design	Detailed Design	Installation & Commissioning	Use and Optimization	
Lean Approach	quality management approach aiming to raise customer value by reducing waste	-	-	-	-	-	o	o	o	o	X	most implemented lean programs only focus waste reduction & production optimization (muda), while origins from TPS also consider planning (muri) and implementation (mura)
Six-Sigma	quality management program focused on reduction of process variance	-	-	-	-	-	o	o	o	X	X	six-sigma is applied in the domain of plant engineering; focus is set on reducing process outcome variance (running processes)
Total Quality Management	quality management approach in which everyone within the organizatiuontakes responsibility for quality	o	o	o	o	o	o	o	o	o	o	TQM is invloving everone in quality improvement actions; proper measures are defined on individual basis; by involving everyone, TQM connects product design and plant engineering
Demand Compliant Design	quality measure for designing products according to requirements	X	X	X	-	X	-	-	-	-	-	DeCoDe focuses on product design only without considering production of products.
Failure Mode and Effect Analysis	quality measue focusing on system analysis for preventive failure avoidance	-	X	X	o	o	-	X	X	o	o	Process-FMEA and Product-FMEA are conducted seperately and are not intercorrelated by the method; FMEA is mainly focusing early Lifecycle phases
Product-Process-Resource Approach	quality measure aming for integration of product development data	-	-	-	-	-	X	X	-	-	o	PPR does not explicitely focus product quality; instead quality is assumed to be automatically assured by PPR application.
Quality Function Deployment	preventive quality measure for product development based on customer requirements	X	X	X	-	-	o	o	-	-	-	From the whole QFD toolset, often only House of Quality is use, limiting application to product planning phase (Analysis & Concept Design) onyl.
5S	systematic approach to create a tidy, clean and safe working environment	o	o	o	o	o	o	o	o	o	o	5S is not aiming to improve quality directly; instead quality is improved by reducing waste and non value adding activities
Balanced Score Card	tool to measure, document and control quality improvement activities	o	o	o	o	o	o	o	o	o	o	Balanced Score Card is no quality measure itslef, instead it helps to select and assess suitable quality measures
Design of Experiments	methodology to develop and improve products or processes based on experimental designs	-	X	-	-	X	-	X	-	-	X	DoE is mainly used to evaluate design alternatives or for product and process optimization; process and product domain are not integrated bur analyzed and optimized separately
Poka-Yoke	systematic approach to prevent errors or instantly recongnizing them to prevent further defects	-	-	-	X	o	-	-	-	X	o	Poka-Yoke can be applied within both doamins separately; It provides mainly input to prevent failures in the installation /production of plants and products but may also prevent in-use errors
Statistical Process Control	methodology to identify natural and artificial process variations and to ensure process compliance	-	-	-	X	X	-	-	-	X	X	SPC is used on real processes in order to reduce variance and to ensure coformance of process outcomes with predefined characterstics; quality improvement is out of focus for SPC
SWOT-Analysis	method for systematic match, conversion or avoidance of strengths, weaknesses, opportunities and threats	X	o	-	-	-	X	o	-	-	-	SWOT-Analysis is used within strategic planning and might be used for evaluating development alternatives in accordance to company targets

Key: "X" - approache/measure is directly managing/improving product quality within this phase
"o" - approach/measure is supporting management/improvment of product quality within this phase
"-" - approach/measure is not managing/improving product quality within this phase

Table 5-1: Comparison of quality management and assurance approaches

6 Concept to Describe Product Quality Dependencies – The MPFQ-Model

The dependencies of product quality to product design and plant engineering are very broad, as can be seen by the numerous differing dependency models shown in chapter 4. Besides direct influences of the product design, there are also dependencies between product quality and the plant engineering process. In [FLW11] a method has been described showing how these dependencies might be analyzed. By doing so, it is important to note that there are no direct influences of the plant engineering process on the product quality. Instead, the plant engineering process is defining the production system, which is creating product properties during production. These product properties again, define the final product quality. These dependencies are shown in Figure 6-1.

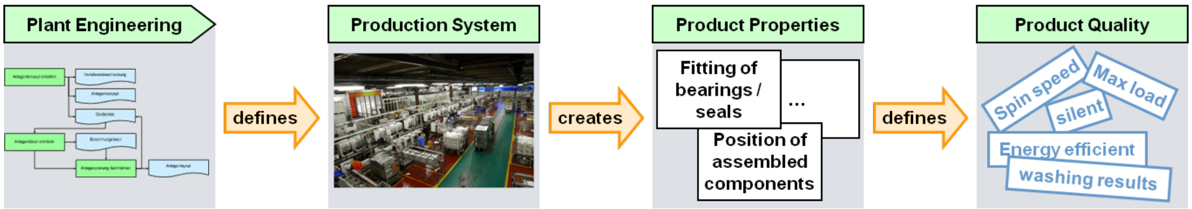

Figure 6-1: Dependencies between product quality and plant engineering process based on [FLW11]

In extension to [FLW11] the following chapter presents the concept of the MPFQ model which will be used as a new approach to systematically identify, analyze and use determinative influences on product quality. MPFQ is an acronym for the four elements product materials (M), production processes (P), product function (F) and product quality features (Q). These elements and their dependencies are collected within the MPFQ-model and are depicted in detail below.

To do so, this chapter is divided into six sub-chapters. The first sub-chapter will describe the essentiality of product for the product quality as this is the point in a product lifecycle, where virtual planned product quality is brought into reality. The second sub-chapter subsequently describes the four elements of the MPFQ-model, followed up by chapter 6.3, describing the overall MPFQ-model. After the model, its elements and dependencies are described, different representation types of the MPFQ-model will be shown. The last two sub-chapters will depict a lifecycle of the MPFQ-model and a modeling example.

6.1 Essentiality of Production for Product Quality

The discrete production of goods induces a close interaction of two, typically separated, lifecycles. The Product Lifecycle has been vastly investigated during the last decades (see chapter 2). It is closely related to Product Lifecycle Management Systems (PLM). Saaksvuori and Immonen [SaI08] describe the five phases of the Product Lifecycle in an Order-Delivery Process:

- sales
- procurement
- manufacturing (meaning manufacturing and assembling of products)
- delivery
- service/maintenance

Looking into other phase-models for Product Lifecycle Management, there are also phases like Portfolio Planning, Engineering and Recycling to be found [PLM08], [KaR11] depending on the granularity level of the phase description. Within this thesis, the definition based on these five phases should be used, as they are the common elements among most of the phase descriptions.

Besides this Order-Delivery Process in the Product Lifecycle, there is also a Plant Lifecycle. This plant lifecycle can be divided into the following phases (see chapter 2.3):

- analysis phase
- concept & basic design
- detailed design
- installation & commissioning
- use and optimization

When combining the Product and Plant Lifecycles, the crucial role of production regarding the product quality becomes evident. During product design, the product, its materials and functions are detailed. This information is then used in plant engineering to design a new production line containing one or several production processes. Finally, this line is set into operational mode. Thus, during production, procured materials are used to produce products like washing machines which are then sold on the market. The sale of products is crucial for the OEM as it is the main source of gaining money. All previous actions must be paid off by selling a specific amount of products. Hendricks and Singhal [HeS97], [HeS06] have shown the direct influence of quality on profit, growth and efficiency performance based on a study of 600 quality-award winning companies.

In Figure 6-2, this essentiality of production for the emerging product quality is shown. During the product design the goal for the final product quality is set by defining product materials build into and product functions realized by the product. Based on this information, the production processes of the production line are designed during plant engineering. The quality of these processes defines how well the requirements derived from product design can be fulfilled. In a last step the materials needed to produce the product are procured. Again the quality of these procured materials is crucial for fulfilling the required product quality defined in product design. All of these influences come together at the production of the product. Here, the final product quality is created based on designed product functions, production processes and procured product materials. Especially the quality of materials and processes is directly influencing the amount of scrap produced during the production and thus, for the amount of money spent without return on invest.

Finally, the product is being sold on the market. Here the product quality perceived by the end-user is inextricably connected to the business success of the OEM [HeS97], [HeS06].

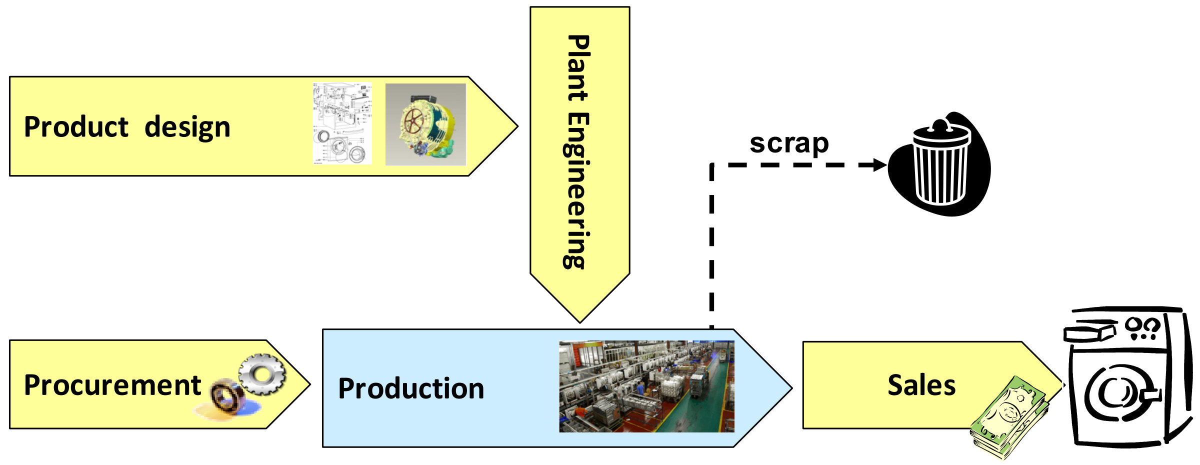

Figure 6-2: Production as central point for emerging product quality

Additional discussions of the influence of plant engineering and production on product quality were carried out in [IBH03] and [EIM09].

The following sub-sections define the terms product materials, production processes, product functions and product quality features and how these four elements might be integrated in order to describe product quality dependencies.

6.2 Elements of the MPFQ-model

The following sub-chapters describe the four elements of the MPFQ-model, namely the product materials (M), the production processes (P), the product functions (F) and the product quality features (Q).

6.2.1 Product Materials

In literature the term materials is related to substances from which things can be made. Gopalakrishnan [Gop02] divides materials into:

- raw materials like metal ores, woods, etc;
- semi-finished products like steel coils, sheets, pipes etc.;
- consumables and operating supplies like grease, oil, fuel, etc. and

- product components like motors, pumps, cables, etc.

As the share of software in products is rising [AbS07], the definition of product materials should be widened within this paper. Therefore, the four categories of Gopalakrishnan [Gop02] are collected under the term of physical materials. They can be defined as real, countable and touchable things that are used directly or indirectly within the production process of a product.

In addition to physical materials, there are also virtual materials and in-use materials. In this case, software is a typical virtual material. The software itself is not touchable but always connected to a physical device it is executed on (e.g. PLC, on-board controllers, FPGAs). This bisection of product materials into physical and virtual materials or in other words: hardware and software is widely used and can be found also in different standard documents [DIN EN ISO 9000], [DIN EN 50128].

As a third type of materials, in-use materials shall be defined now. To capture all influences on the product quality it is necessary to describe all materials that are needed within the use phase of a product. Taking the example of a washing machine, the product is built up from physical materials (metal sheets, plastic parts, bearings, screws, motor, …) and virtual materials (control-software running on the on-board controller). But within the use of the machine, additional in-use materials are also needed. The washing machine needs water, energy and soap to clean clothes. Without them, the product would not work, nevertheless these materials are not sold together with the washing machine. Instead part of the perceived quality is also to reduce the amount of in-use materials needed for the functionality of the product (e.g. energy class) [DTL06].

In addition to its type, each product material can also be described by its technical characteristics and measured data (including measures of physical, chemical, logical and other characteristics). The technical characteristics are unique for every product material and may include geometric tolerances, electrical specifications, pneumatical/hydraulical specifications, behavioral descriptions, etc. The technical characteristics of product materials can be defined following the mechatronical characteristics as described within [Kie07], [LHF10], [Mer12]. The measured data of the product material is a subset of its technical characteristics. The measured data is defined within the plant engineering process by specifying technical characteristics that are actually measured within the production. In some cases there might be technical characteristics which are not measureable due to technical or economical constraints.

Hence, product materials are defined as follows:

*The term **product materials** summarizes all physical and virtual materials (Hardware/Software) used within the production of the product and all materials needed for the usage of the product (in-use materials). Each product material can be defined by its type, technical characteristics and measured data.*

The describing elements of product materials are shown in Figure 6-3.

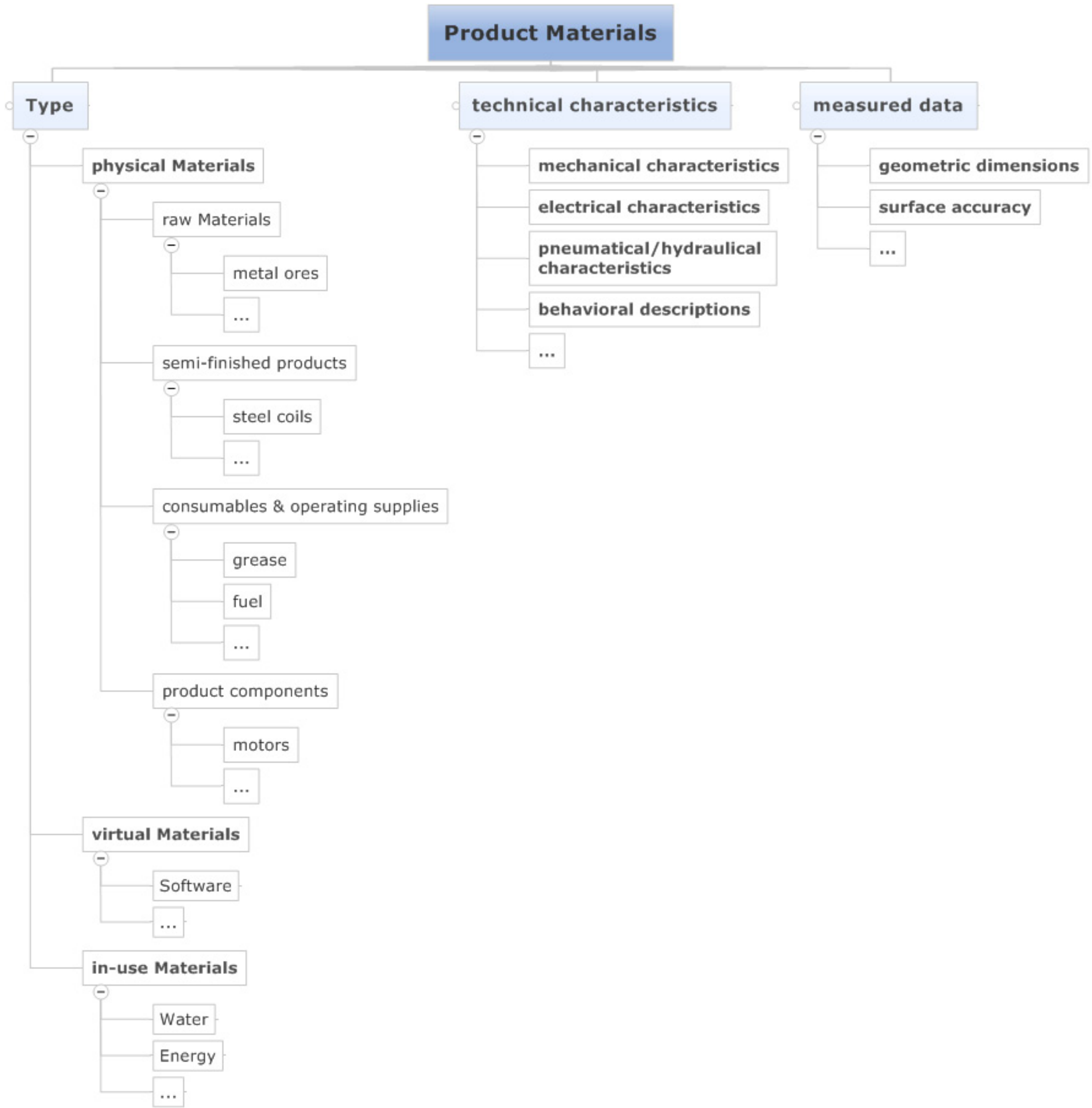

Figure 6-3: Classification of product materials

6.2.2 Production Processes

Manufacturing processes are creating products which are characterized by their product materials (see chapter 0) using machine, tools and human labor [DGF11], [FJT13]. According to [DIN 8580] these manufacturing processes can be distinguished into:

- primary forming
- transforming
- separating

- joining
- coating
- altering material properties

All these processes may be executed in a manual or automated way. As discussed in [Tay89] and [IBH03], automated processes will, in most cases, lead to higher product quality as they provide reliable, repeatable results. Hence, there will be a separation of these processes executed in automated manner and manual processes.

Beside these value-adding processes, there are also transportation and quality control processes which are not directly adding any value to the product. Nevertheless, they are crucial, as products and product materials need to be transported along the line and quality requirements have to be assured. In the end, guaranteeing specific minimal quality for all products is vital for every OEM as quality perceived by the customer can be directly related to business success [HeS06]. In this way, quality control stations are not improving quality itself, but help assuring it and thus business success.

In correspondence to product materials, production processes are also further detailed by their technical characteristics and measured data. Each production process is characterized by process parameters like limitations for forces, torques, rotations, etc. In parallel, there is an internal process sequence, which is describing the behavior of the production process. Process sequences are step-by-step descriptions of actions which need to be executed in serial and/or parallel. The same way around each single production process is contributing to the overall production. This contribution is described in the global process sequence. The global process sequence is describing which actions the individual production process is able to perform. This way it is possible to create hierarchies of production processes and to encapsulate them. This follows the idea of functional decomposition of production lines as shown in [Kie07], [LHF10] and [FWL11].

As production processes are using inputs, machines, tools and human labor to create some outputs, these inputs and outputs are also characteristically for each production process and thus are part of the technical characteristics [DIN 8580].

The measured data of production processes is again a subset of its technical characteristics. The measured data is defined within the plant engineering process by specifying which technical characteristics are actually measured within the production (e.g. insertion force, insertion depth, etc.).

*The term **production process** refers to all manual and automatic manufacturing, quality control and logistic processes used to create an output based on specific inputs. Each production process can be described by its type, technical characteristics and measured data.*

The describing elements of production processes are shown in Figure 6-4.

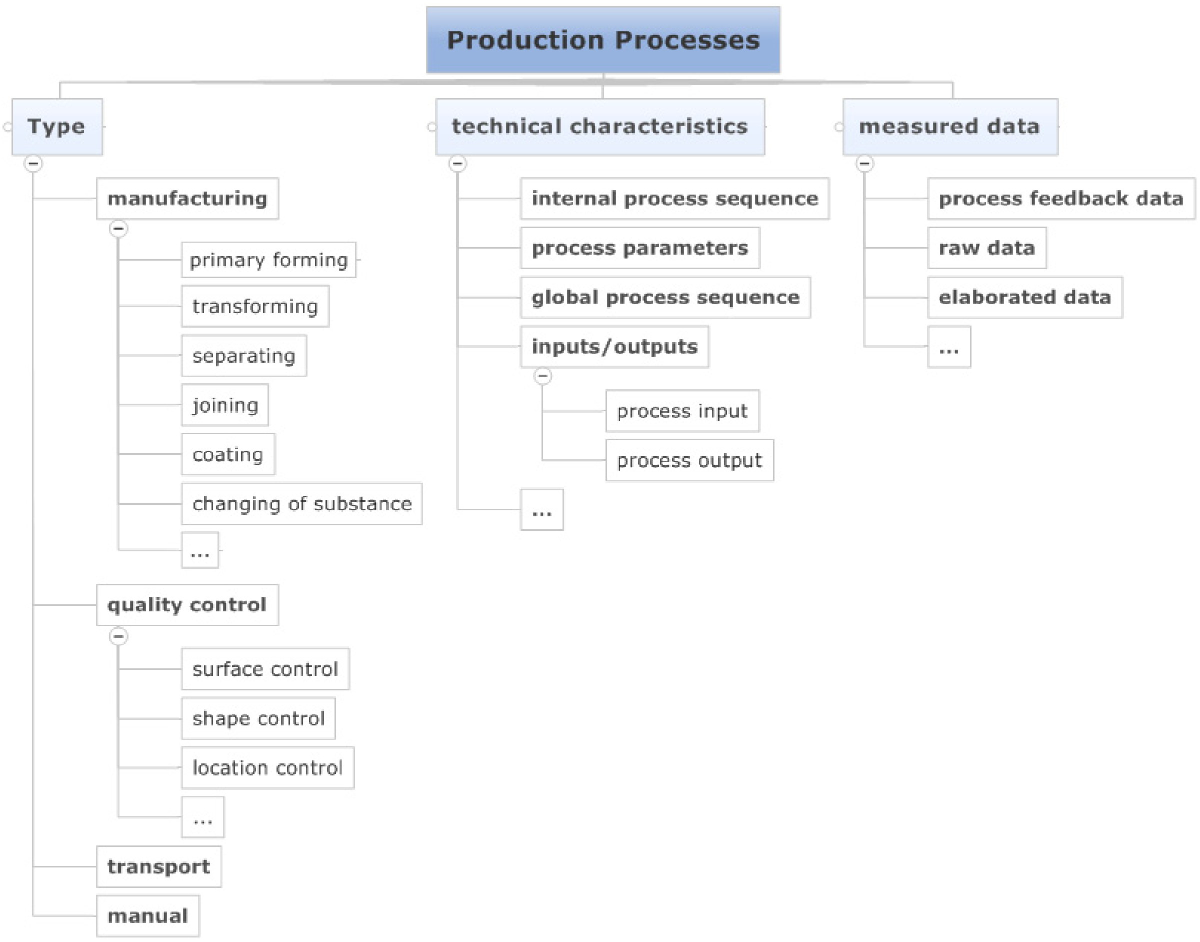

Figure 6-4: Classification of production processes

6.2.3 Product Functions

The function of an object is the abstract and solution neutral verbalization of its purpose or task [DGF11]. Following [DIN EN 1325-1], each function can be classified as either main function or minor function. Main functions represent the purpose of a system or object (e.g. move from point A to point B), whereas minor functions describe tasks needed for the execution of the main function (e.g. calibration runs for position sensors). Within literature, the idea of functional hierarchies is very common and can be seen for example in [VDI 2220], [LHF10] and [Lin09]. Thus functions are dividable into sub-functions or can be composed to realize other functions on a higher level.

In addition, there are also functions within a system which are not really intended. These unintentional functions are sometimes the reason for typical design trade-offs (e.g. high performance of a car vs. fuel consumption).

Taking these facts into consideration, there shall be four types of product functions defined within this paper:

- main functions
- minor functions
- basic functions
- unintentional functions

The first two functions are defined following [DIN EN 1325-1] and are composed functions which can be reasonably decomposed into other functions. The basic functions cannot reasonably be divided any further. Unintentional functions are not contributing to the purpose of the system, in fact they most likely negatively influence some product characteristics.

Each product function can be further described by its technical characteristics and measured data. There are performance indicators which can be defined to elaborate the degree to which a function is fulfilling its purpose. This purpose is described in the behavioral description of the function. Based on some measured raw data, the individual performance of a function can be elaborated.

*The term **product function** refers to the purpose of the product or specific parts of it. This includes intentional and unintentional purposes with different degree of impact. Each product function can be described by its type, technical characteristics and measured data.*

The describing elements of product functions are shown in Figure 6-5.

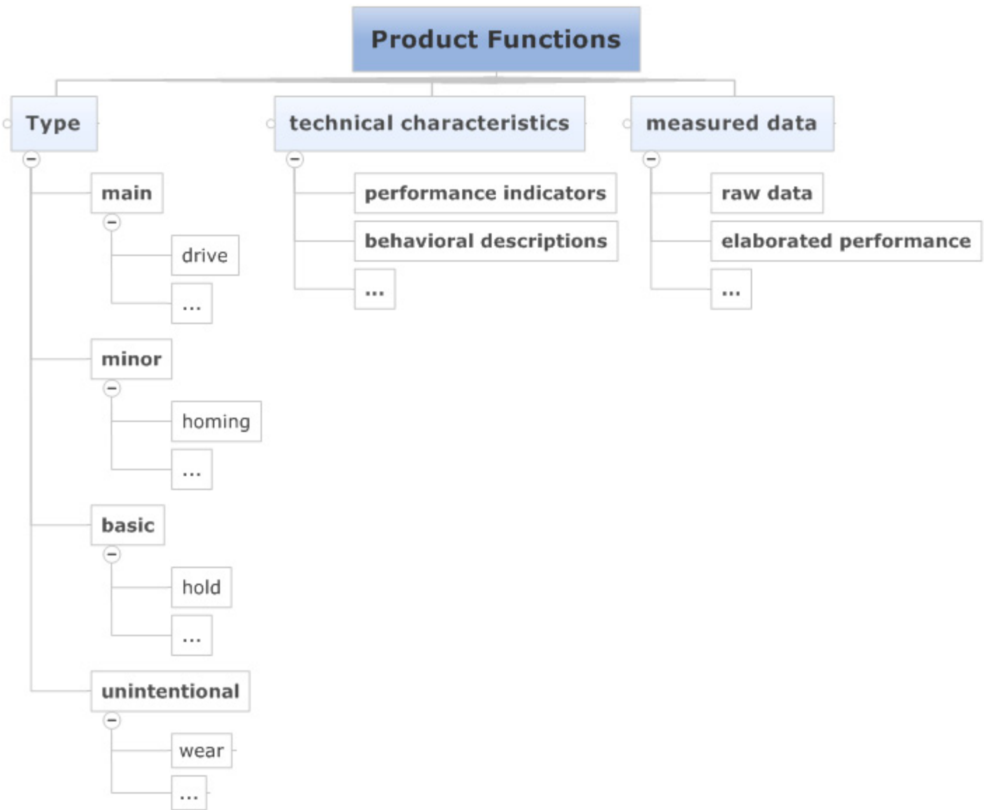

Figure 6-5: Classification of product functions

6.2.4 Product Quality Features

The different perspectives on product quality have been extensively described in chapter 3. Hence, here, there is only a short description of the elements used to characterize product quality features.

In accordance with the product materials, production processes and product functions, each product quality feature has a type. Here, the types of [Gar87] should be used:

- performance
- features
- conformance
- reliability
- durability
- serviceability
- aesthetics
- perceived quality

In addition to its type, each product quality feature can be defined by its technical characteristics and measured data. The technical characteristics present the required characteristics which should be fulfilled by product materials, production processes and product functions. The measured data in turn will be a subset of these characteristics, representing the actual data about the characteristics. Finally, a quality number is elaborated describing the quality level of the individual product quality feature with respect to the required characteristics and the fulfillment of these.

*The term **product quality features** refers to a specific aspect of the product quality. Each product quality feature can be described by its type, technical characteristics and measured data.*

The describing elements of product functions are shown in Figure 6-6.

Figure 6-6: Classification of product quality features

6.3 Description of MPFQ-model

In the late 1970s, Suh has presented the idea of Axiomatic Design for the first time [Suh90]. Within the Axiomatic Design he presented four different domains: Customer Domain, Functional Domain, Physical Domain and Process Domain. These domains are not independent among each other, instead they are executed following a product lifecycle like depicted in [Sal08]. In a first step, customer needs (CN) are identified and used within the product definition to derive functional requirements (FR). These requirements serve as basis for the product design where design parameters (DP) for the product are determined. In a last step these design parameters are used as an input for the process design step to derive the production process and the process variables (PV). This process is shown in Figure 6-7.

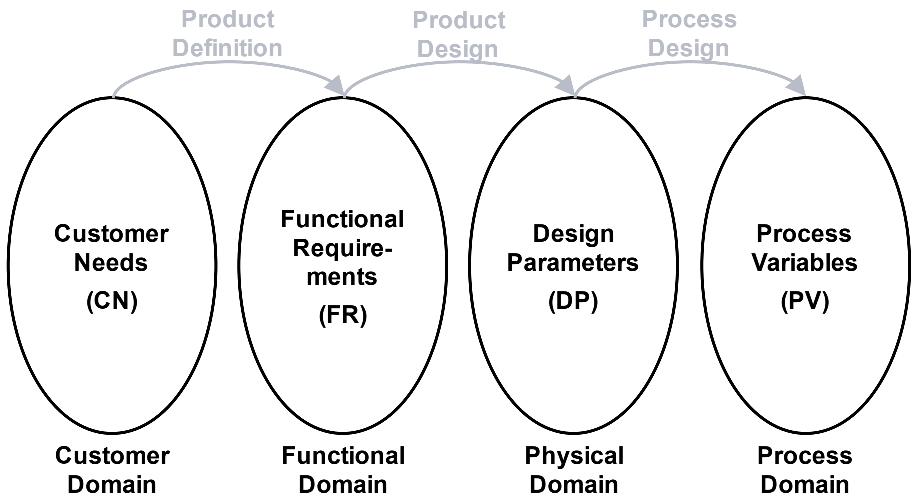

Figure 6-7: Axiomatic Design [Suh90]

Since the late 1970s, Axiomatic Design has been extended and improved multiple times according to specific focus topics of the respective research. Sohlenius [Soh00] extended Axiomatic Design in terms of productivity and quality and, therefore, split the process shown within Figure 6-7 into two sub-processes, one for the product development and another for the production system engineering. In 2005, Gumus [Gum05] added a Test Domain to the Axiomatic Design in order to create a product lifecycle model able to capture knowledge generated within the product development.

Looking into the four elements above, it becomes evident that they might be mapped to the four classical domains of the Axiomatic design. The product materials correspond to the physical domain, production processes to the process domain, product functions to the functional domain and product quality features to the customer domain.

Nevertheless, the proposed elements also include additional information. While customer needs are described by the required technical characteristics of the product quality features, there is also additional information like the actual quality of the real product being produced on the manufacturing system and the type of the individual quality feature. This characterization by types and additional data measurement information is also different for the production processes, product materials and product functions. Thus, the presented approach in this thesis goes beyond Axiomatic Design in that it presents additional correlations on a more detailed level and integrates them into the MPFQ-model described below.

Based on the required quality features of a product, the product design defines the product. Within product design, product materials and product functions generated by these product materials are defined. Product materials generate product functions by acting upon another product material. These functions are created and measured within production processes by measuring, assembling, forming, transforming or changing product materials. Thus, product materials are processed by production processes in order to create product functions, creating/transforming them into new product materials. Hence, there is a strong forward dependency of product materials being processed by production processes to create a product function. But by creating this product function a closed interrelation loop is created as one product material is generating the product function by acting upon another product material. This shows that not only these three elements are closely correlated, but in fact this also leads to a strong interrelation of product design and plant engineering as product materials and functions are defined within product design but are used, processed and created within production processes defined in plant engineering. Chapter 6.6 gives a real example for further clarification.

Following [DIN EN ISO 9000], product quality can be seen as conformance of inherent product features to customer requirements. Applying this fact to the MPFQ-model means that product quality features are obviously influenced primarily by product functions and product materials as they inherit the product features. This conformance can be checked by elaborating e.g. the product function performance indicators and technical characteristics of the product materials and comparing them to the required characteristics given in the product quality features.

Taking a special look into the product materials, it can be seen that the inherent product features are defined by the physical and virtual product materials. But besides these both there are also in-use materials. Obviously, these cannot be directly influenced within production, nevertheless they are of high interest. Building cars, washing machines, etc., one major selling point is the amount of in-use materials (e.g. fuel, water, energy) consumed by these products. Thus, by modeling these dependencies as well, the influencing factors on in-use material consumption can be identified.

In the first place production, processes are only indirectly influencing the product quality features by creating product materials and functions. Especially in the last years, green products have become more and more important and so does the conformance to requirements involved [DTL06], [HoC06]. Thus, process characteristics like energy consumptions are more and more getting influence on product quality. In turn this means that generally each product material, production process and product function might have an influence on the product quality features. As stated above, the quality features are at the same time building the basis for product design and plant engineering with their required characteristics. Hence, a correlation of all elements is given here also. Compared to the tight correlation of product materials, production processes and product functions among each other, the correlations to the product quality features are much looser. This can also be explained by looking into the nature of these correlations. Due to the inherent physical interrelations, the forward dependencies from product materials to production processes to product functions to product quality features and also the loop back from product functions to product materials are very tight. Opposed to this, the feedback loop from product quality features to product materials, production processes and product functions is not as tight, as there is no direct physical interrelation. Instead, this interrelation is of logical nature. The required characteristics described within product quality features are used as a basis for the engineering process. Then, the product design and plant engineering are executed and only after the production of real products there is a conformance check of the required features with the product features produced. The whole MPFQ-model and its correlations are given in Figure 6-8.

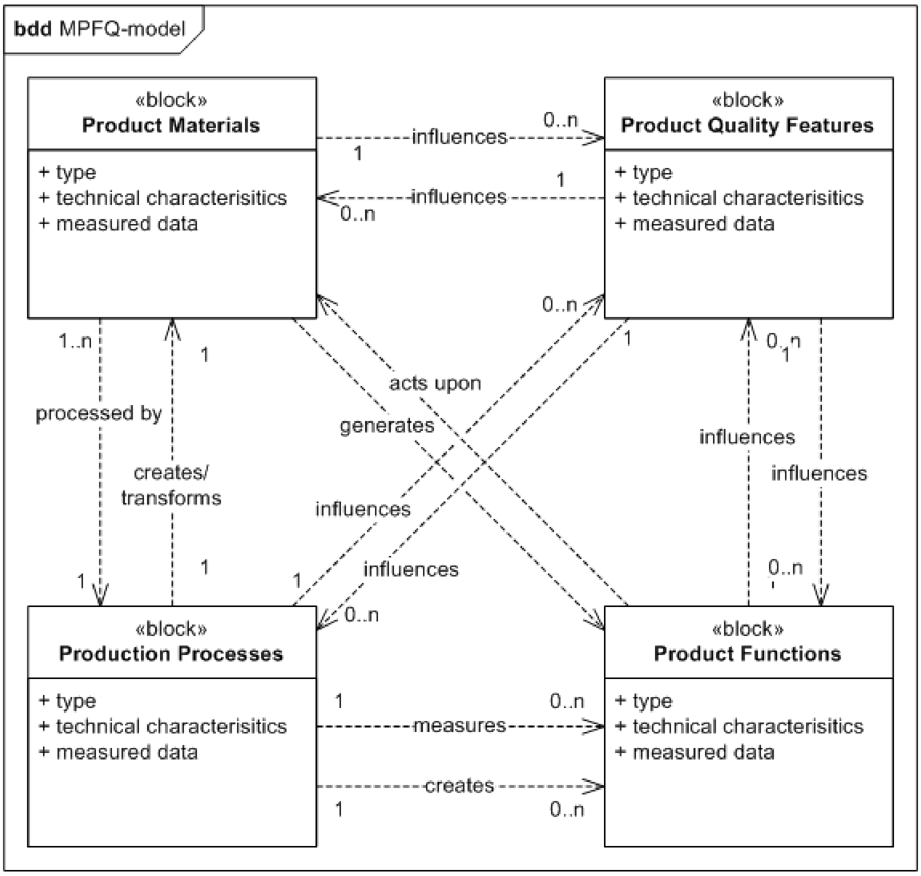

Figure 6-8: MPFQ-model

6.4 Representations Types of the MPFQ-Model

After describing the MPFQ-model within the previous chapter, the representation types for modeling shall be introduced. There are generally two different representations: the graphical representation and the matrix representation.

The graphical representation is primary used for visualization and analysis executed by humans. It depicts the dependencies between the four elements as arrows between boxes. Blue boxes show the product materials, orange boxes show the production processes, yellow boxes designate product functions and green hexagons show product quality features. The arrows indicate which product materials are used within a product process, which production process creates which product function, which product materials acts upon another product materials through a product function and which product materials, production processes and product function are influencing which product quality feature.

In addition to the pure graphical representation, all boxes and arrows might be enriched by meta-data. Every box or hexagon of a product material, production process, product function and product quality feature might be enriched by information regarding its type, technical characteristics and measured data. The detailed information are depicted in chapter 6.2. Analogous, each arrow pointing to a product quality features (black arrows in Figure 6-9) might be enriched by a weight, corresponding to the strength of its influence on the product quality feature.

These graphical representations might be drawn in suitable tools like Microsoft PowerPoint ®, Microsoft Visio®, IBM Rational Modeler® or similar tools. Figure 6-9 depicts the graphical representation of the MPFQ-model. Modeling excerpts and the overall MPFQ-model are shown in Figure 6-13 and Figure 8-5.

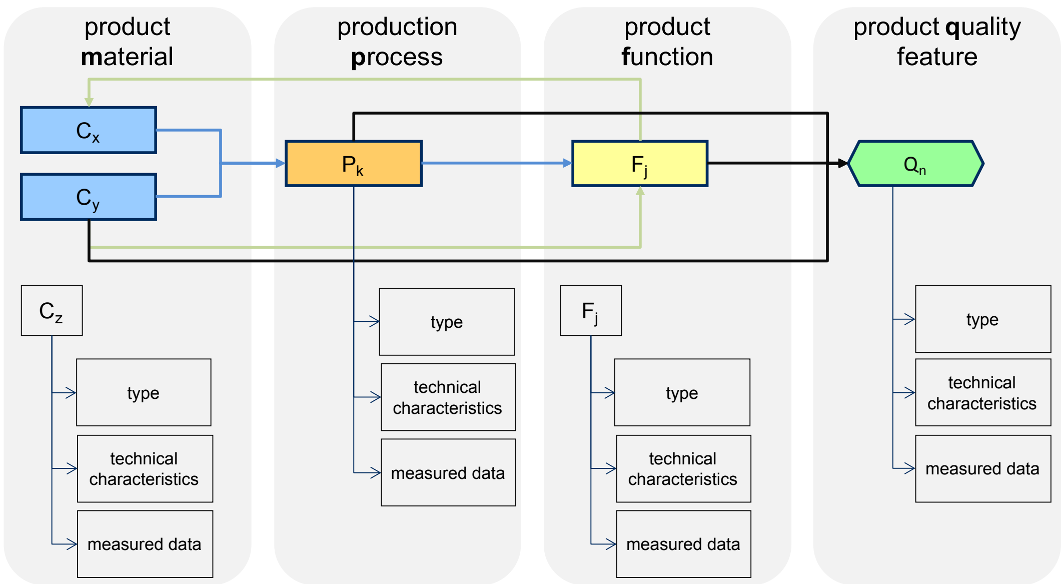

Figure 6-9: Graphical representation of MPFQ-model

In addition to the graphical representation, there is the matrix representation of the MPFQ-model. This representation type is mainly used for automatic evaluation and computation of the MPFQ-model as it is easier interpreted by a computer or PLC.

The matrix representation consists of three sets of rows. First the product materials are clustered and each material is represented by one row. Then the production processes and product features are clustered and stored in a similar manner. The first column of the matrix contains the name and ID of the item (product material, production process or product function). The last column cluster represents all product quality features. Hence, every product material, production process and product function (depicted in the rows) can be correlated to each product quality feature (in the last columns) and the strength of the influence of the item on the product quality feature can be represented by numerical values. These numerical values correspond to the meta-data on the arrows pointing on product quality features in the graphical representation.

In order to depict also the dependencies among product materials, production processes and product functions, there are three addition columns between the item name/ID and the product quality feature cluster. These columns represent the product material 1, product material 2 and the production process. They are only filled for the product function row cluster. This way it is possible to describe which product function is created by which product material (product material 1) by acting upon another material (product material 2) and in which production process this function is created.

This matrix representation is shown in Figure 6-9 (only clusters with an "X" have to be filled with correlation values). Real examples are shown in Table 8-1 and in [GRA13].

	item name/ID	product material 1	product material 2	production process	product quality features 1..n
product materials	X				X
production processes	X				X
product functions	X	X	X	X	X

Figure 6-10: Matrix representation of MPFQ-model

The graphical representation and the matrix representation can be lossless transformed into each other. In order to automate this transformation Microsoft Visio® and Microsoft Excel®

were chosen for modeling complex models within this thesis, and the transformation was automated by VisualBasic scripts.

After the representation of the MPFQ-model has been shown, the next chapter will describe a lifecycle of the MPFQ-model for gathering the correlations within the MPFQ-model.

6.5 Lifecycle of the MPFQ-Model

Gathering the complex correlations of the MPFQ-model can be quite comprehensive. Thus, a lifecycle for the MPFQ-model is needed to show how such a model can be created.

The lifecycle should take into consideration the properties of the model and also its peculiarities. To use the MPFQ-model, it is not necessary to model every detail of the product and production system. Instead, focusing on different aspects might be useful to get faster results and also to keep track of the dependencies (e.g. focusing on leakage of a washing machine, as this feature is reported to be a common problem as per service and maintenance technicians). If there is no suitable solution found based on the current model or if further aspects need to be regarded, the model can be updated to increase the solution base. Hence, the MPFQ-model is not static but rather vivid and variable and evolves over time as additional aspects may be considered. The proposed lifecycle for the MPFQ-model is depicted in Figure 6-11.

The initial phase of the MPFQ-model is a setup of a new model (1). In case a model is already existing for this product (e.g. there was already a model created for this product or a MPFQ-model of a similar product can be reused), this phase means an update of the original model. The initial MPFQ-model can be created using expert workshops and will be the most complex and time consuming activity within the lifecycle [FJT13]. Within these expert workshops, crucial quality dependencies are identified by analyzing congeneric products and production processes. As explained before, the MPFQ-model is not static and should be constantly updatable. Hence, there is no need to identify all existing dependencies from the beginning. Instead, it might be helpful to start with existing information like bill of materials, required product functions and already known production processes showing a high degree of automation. These items can be completed by a list of the most important product quality features. During the workshop, experts from product design and plant engineering examine the primary quality influences. One typical tool to be used especially within product design is the House of Quality [Ham11] (see also chapter 4.2.4), which will help deriving the influences of product functions and materials on the final product quality features. Based on these initial dependencies the production processes creating the product functions and the product materials used within these processes can be further investigated.

Following this approach, the initial setup of the MPFQ-model is closely correlated to the development of product functions (2) and process models (3). Thus, activities (1) to (3) will be carried out mostly in parallel to the initial setup of the MPFQ-model. In case there is already an existing MPFQ-model, this model needs to be updated and the first step will be significantly shorter. Usually, an existing model is updated to include further product quality features or to model further dependencies of already included product quality features to product functions, production processes and product materials.

In case of an MPFQ-model update, the activities (1) to (3) will be done on a less integrated manner. The product function model (2) will be updated, describing the new and changed product functions to be realized within the product. Thus, also inferences about the product materials realizing these product functions can be drawn. An example for the functional model of the washing machine is depicted in [GRA13]. For this activity, inputs from suitable FMEAs [DIN EN 60812] might also be used.

After updating the product function model and the corresponding Bill of Materials (BoM), the process model can be updated (3). As a starting point for this activity, every new and/or changed product function has to be analyzed regarding its creating processes and materials. Afterwards, it should be assured that there is no adaptation needed for processes creating product functions which have not changed. This might be especially needed if the MPFQ-model is updated due to unreliable results. This analysis step might be supported by the results of PPR-models [CYM07].

Independent from the fact if the initial MPFQ-model was setup or an existing model was changed, after the update of the process models, the MPF-part of the MPFQ model can be updated (4). Within this step, all information resulting from prior activities is integrated. As there are closed feedback loop dependencies between product materials, production processes and product functions (see 6.3), this needs to be done to ensure a consistent data base for further work. After the partial update of the MPFQ-model, it needs to be decided which product quality features should be especially focused on within the next modeling steps. This focus might be aligned to new or changed customer requirements, market and competitor analysis, production analysis, feedback from service department and other inputs. This quality focusing is used to update the MPFQ-model with new and/or changed product quality features (5). For every product quality feature it is checked by which product materials and functions and production processes it is influenced. Also new or changed product materials, production processes and product functions are analyzed with respect to their influence on new or changed product quality features.

After this full update of the MPFQ-model, it can be used to control the production of products or as tool for quality oriented optimization of the product and plant engineering processes. In order to have the MPFQ-model control the production, it needs to be implemented at Manufacturing Execution System (MES) level. Details about the MPFQ-model controlling production lines can be found in chapter 8 and [GRA13]. Subsequently, data can be collected (6) from the production. Based on the MPFQ-model it can be reasoned which measures can be taken within production. The production can be gathered from every product material, production process and product function and is stored within the production database for production monitoring and further elaboration.

In order to determine the quality of a specific product under production, the gathered data has to be elaborated (7). In order to do this, manufacturing process models are needed, describing how to elaborate the quality of product materials, production processes and product functions based on specific measured data. Exemplary models for screwing and bearing insertion processes can be found in [GRA12a]. Together with the MPFQ-model (5) and the gathered data (6), these models are used to elaborate quality-values for product materials, production processes and product functions (8). These values might then be used to determine the theoretical quality of a product or to improve it by providing feedback for production control (see chapter 8).

The final step within the Lifecycle of the MPFQ-model is to execute the quality interaction process (9). This step takes into account, that each model considers only specific characteristics of a system which are relevant for a specific context [Epp08]. To get an accurate model the real product quality produced on the production line needs to be compared with the quality predicted by the MPFQ-model. Based on this comparison, indications can be found which characteristics of the product and production system are well described and which need to be analyzed more deeply in order to close the gap between MPFQ-model and reality. These indications are the input for the next iteration of the MPFQ-model lifecycle.

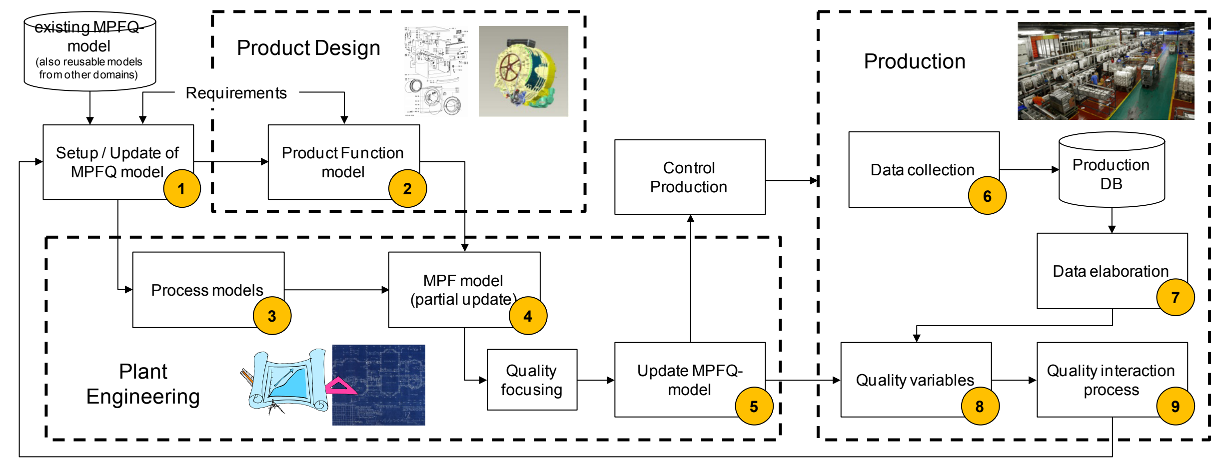

Figure 6-11: Lifecycle of MPFQ-model

6.6 MPFQ-Model – Example

In order to bring the abstract description of the MPFQ-model to a practical level, this section gives a short example.

Front-loading washers consist of a tub which holds the water and a drum which holds the clothes. For optimal washing, the drum has to be rotated within the tub. Therefore, a shaft is firmly connected to the drum and pivoted into bearings. In order to stop water from leaking outside the machine at this bearing, a seal is used. The seal is made from rubbery material and pressed into the tub. The inner circle of the seal is then pressing on the shaft to seal the water inside the tub. This construction is schematically shown in Figure 6-12.

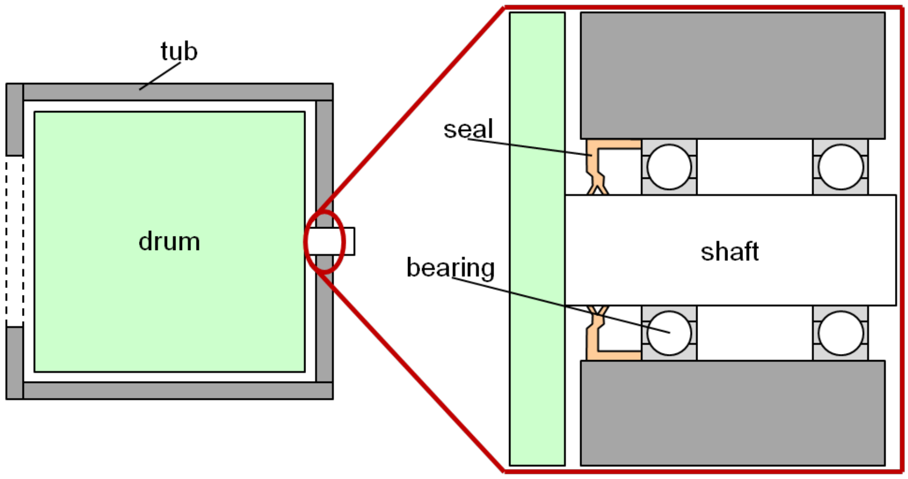

Figure 6-12: Schematic of the bearing sealing

For the example depicted here, only the interaction between shaft and seal is modeled. Both product materials are assembled in the "drum insertion" production process, which is itself influencing the green footprint product quality feature as it consumes energy for production. During this process two functions are created. The first one is that the shaft is pushing the seal, as the diameter of the shaft is a little bit bigger than the inner diameter of the seal. Due to this push-function the water is sealed inside the washing machine. Thus, the product function is directly influencing the product quality feature of "no leakage". Besides the push-function, also the product function "wearing" is created. This is an unintended function in the location where the seal wears the shaft, thus damaging it over time and reducing the durability of the washing machine. Additionally this wearing is a transformation of kinetic energy into thermal energy. Hence, the wearing function is also (negatively) influencing the green footprint and energy consumption of the product. Nevertheless, this product function is not avoidable, as otherwise no sealing would be achieved. This part of the MPFQ-model depicts very clearly that these product functions have to be designed very precisely in order to achieve the best solution for the tradeoff between durability, green footprint and leakage quality features.

The resulting MPFQ-model excerpt is depicted in Figure 6-13. For the detailed MPFQ-model, describing a whole washing unit and a washing unit production line, see [GRA13]

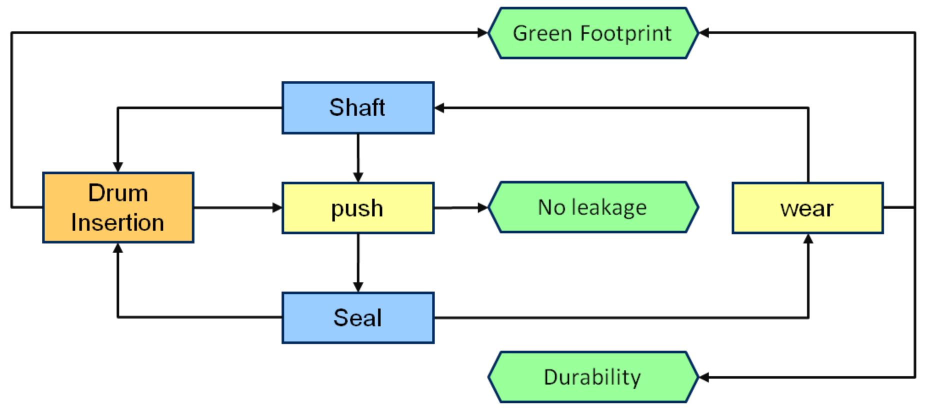

Figure 6-13: MPFQ-model example (excerpt)

The matrix representation of this MPFQ-model excerpt is shown in Table 8-1.

7 MPFQ as Analysis Instrument

The deployment of MPFQ-model can be separated into two areas. First, the purposeful planning and re-planning of new and changed production lines (see this chapter); second, the utilization of MPFQ-model within production control (see chapter 8). This chapter deals with the first area. It explains how MPFQ-models can be used to improve engineering process quality and how product quality problems may be analyzed to derive adequate measures.

7.1 Integrative Aspect of MPFQ

The MPFQ-model can be embedded into the product and plant lifecycle as shown in section 6.5. Thus, creating a MPFQ-model is not a parallel process within the engineering of product and production systems, but strongly connected to them. In fact, there are synergies automatically constituted by these interrelations. Within the product design, requirements to the product under development are defined. They serve as a main basis for the following engineering activities. Thus, their importance cannot be under-estimated. Based on these product requirements, a product structure (BoM) and product functions are defined. These are the starting point for the subsequent plant engineering process. Within a first analysis phase, among others, the input from the product design is taken in order to derive requirements to the production system. Again, these requirements are highly important as they serve as a basis for following engineering activities like the definition of plant hierarchies and production processes.

At this point, the MPF-part of the MPFQ-model can be created or in case that a MPFQ-model already exists for the product or a similar product, can be updated. Just by the process of consciously correlating product materials, production processes and product functions, the engineers get a deeper insight into dependencies among these elements resulting in a better integration of product design and production system engineering. Referring to Figure 6-11, this is achieved within step (4) and thus, early in the product lifecycle. Hence, issues can be identified very early before the product design or even productions system engineering is finished leading to significantly lower non-conformance costs [VDI 2235], [SMM04], [Per92].

7.2 Predictive Measures of MPFQ

But the use of the MPFQ-model is not restricted to this integration aspect. Within the product design and production system engineering there are also specific product quality features to be focused on. The way how these product quality features are identified is quite different.

Some focus features might be derived from product quality problems of previous product generations in order to avoid them in the actual product generation. Others might be aligned with the strategic vision and mission of the company, e.g. being not only **a** manufacturer of energy efficient products, but instead being **the** manufacturer of energy efficient products. Independently from the reason, there are product quality features to focus on. As shown in step (5) of Figure 6-11, these product quality features are used to amend the MPFQ-model. By bringing product quality features and their dependencies to product materials, production processes and product functions to mind this early in the engineering process, a purposeful analysis of product quality itself becomes possible by just amending the MPFQ-model.

Thus, the MPFQ-model is able to improve product quality by just forcing engineers to model and thus, think about dependencies between product materials, production processes, product functions and product quality features. Beside these intrinsic benefits, there are also direct measures to be taken based on the updated MPFQ-model. By using the modeled dependencies and focusing on specific product quality problems, an in-depth analysis can be conducted. Using moderated expert workshops, it is possible to analyze known quality dependencies, identify unknown and thus improve the MPFQ-model. In a second step, starting from the product quality features to be analyzed, it can be traced which technical characteristics of the product materials, production processes and product functions will have an influence. Thus, product design requirements and plant engineering requirements might be added, extended or sharpened. Figure 7-1 shows an excerpt of this process.

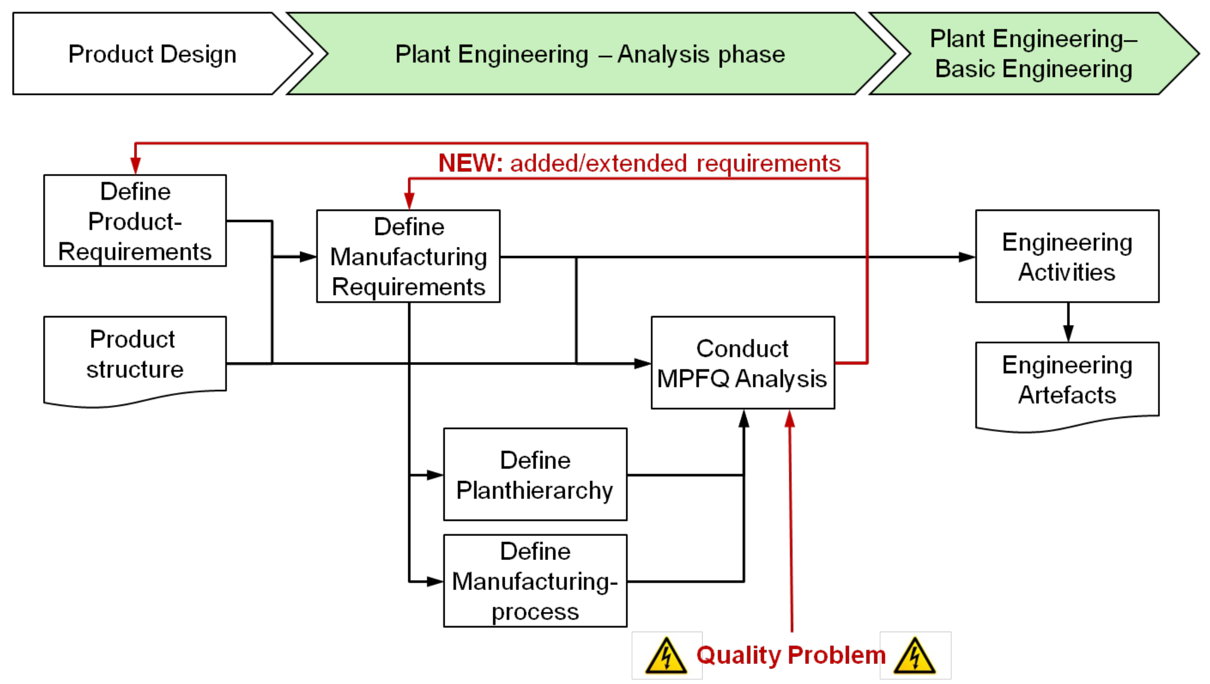

Figure 7-1: Supporting requirements definition by MPFQ-model

An expert workshop conducted based on the MPFQ-model and focusing the leakage of a washing machine as product quality feature, reduced suitable insertion technologies for a seal insertion from three to one technology. Both insertion technologies discarded could be proven to provide a worse and more uncertain product quality. These facts were derived from the narrow dependencies between product materials, production processes, product functions and the product quality feature of “leakage”. Detailed results can be seen in [GRA12a].

Due to this proceeding, it is possible to provide a more solid and complete requirement-basis for all following engineering activities. Thus, a significant increase of final product quality can be expected [Poh07], [DIN EN ISO 9000]. Following this, the MPFQ-model and related analysis are able to provide crucial input for both, product design and plant engineering processes.

Another input to be taken from already existing MPFQ-models is the Bill of Materials and Bill of Operations (BoO). They can be derived from the product materials and product functions included in the model. Thus, they might be used as a starting point for future product generation designs. Compared to BoM and BoO actually used, they already provide the dependencies between product materials and product functions. Additionally, the previous MPFQ-model already shows which function was created by which production processes and how these functions interact with specific product quality features. Hence, already proven solutions are documented and need not be reinvented or they might be proven to be sub-optimal and thus be discarded for future use. In any case the use of old MPFQ-models and the knowledge documented within holds a big opportunity for product design and plant engineering to reduce risks, increase engineering efficiency and quality of results.

The reuse of already existing MPFQ-models is not restricted to products of the same type. As MPFQ-models may be created for parts of technical systems only, it is also possible to reuse only some parts from other product types. Thus, it is possible to combine a new MPFQ-model for dish-washers from other parts of cooking, refrigeration or washing machine models. E.g., the sealing of the dishwasher door might be functionally reused from a washing machine door. Hence, additional input to product design and plant engineering is available, although the actual product type under development has never been model by MPFQ. This reuse of information shows also, that the MPFQ-modeling yields high potentials in knowledge representation and conversation.

Another aspect of the MPFQ-model analysis is connected to the plant engineering in particular. During plant engineering, a plant layout is defined [MuH79]. Part of this layout is the position of quality control stations within the production line. To define them, it is crucial to know which characteristics have to be measured and where this can be done. Utilizing the knowledge of the MPFQ-model, it is possible to support this analysis. Based on the product quality features, it can be identified which product materials, production processes and product functions have a crucial influence. These main influences on product quality features should be measured in order to control final product quality. At this point, the influences can be divided into two parts: first, product influences and second, production influences. The production influences can typically be measured by using production process feedback data like forces or torques applied during the production step. Thus, production processes might be measured directly during their execution. In order to be able to do that, appropriate equipment is needed. Hence, knowing which processes and especially process parameters are having a crucial influence on product quality features supports the plant engineers by defining the right equipment for each station. E.g., if a screwing process is crucial, a screw driver with an exact feedback about the applied torque and screwing angle should be used. Some other screwing stations might not have the same impact. Therefore, simpler and also cheaper, but yet sufficient screw drivers might be chosen there.

In the case of product influences there are product materials and product functions to be measured. How this can be done is depending on the individual material or function. The hold function of the bearing inserted to the rear tub can be easily measured in direct correlation to the insertion force applied during the insertion process, as the restore force needed to extract the bearing from the rear tub in the first approximation equals the insertion force applied. For the seal insertion, the reality is different. The primary function here is to seal the water inside the washing machine. This sealing cannot be directly derived from the insertion process feedback. Instead, features like these are measured using special quality control stations.

The identification of crucial product quality influences might be improved by applying cybernetics thinking. Using passive summations like in [Ves03] could help elaborating product materials, production processes and product functions which are very respondent to changes of system parameters and, therefore, suitable to identify product quality features.

Within Figure 7-2, the analysis of the leakage at the rear tub is shown as an example. On the left side, the product characteristics defining part of this sealing are shown. They are always measured based on process feedback. Here, the problem occurs that these process feedbacks are not suitable to precisely deduce the resulting product quality. Hence, a quality control station should be used to improve quality control within production.

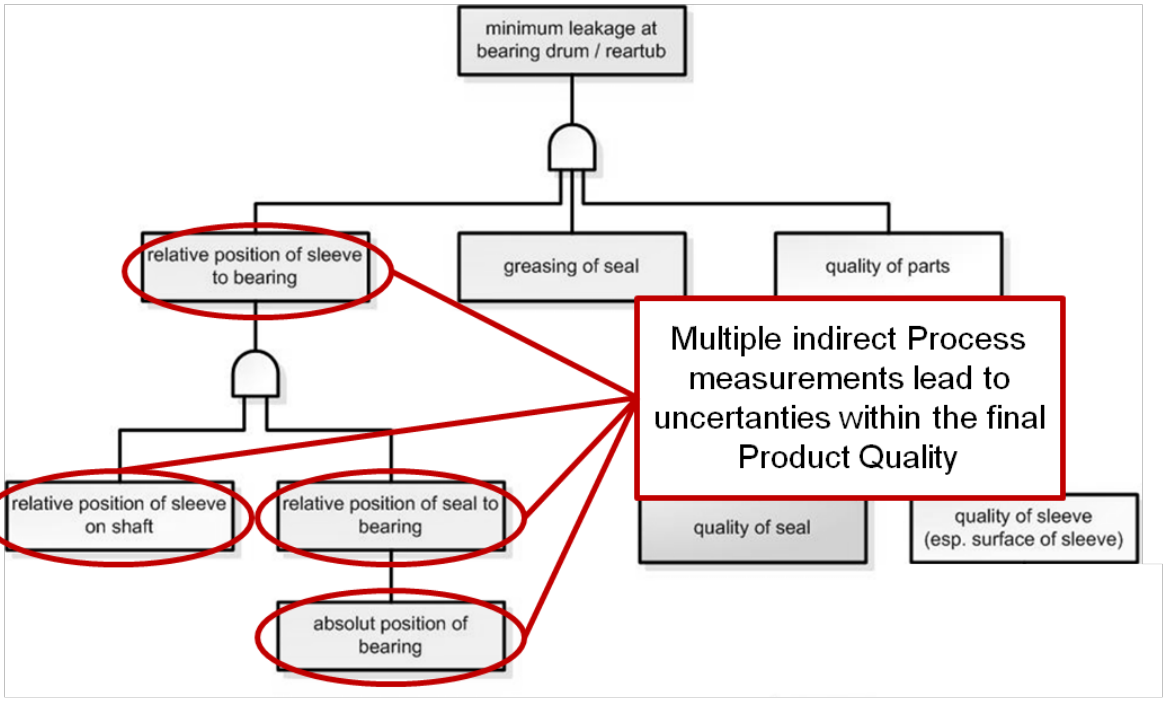

Figure 7-2: Identification of quality uncertainties applying MPFQ

7.3 Corrective Measures of MPFQ

In a similar way to the predictive measures, it is also possible to use the MPFQ model as a corrective instrument. Taking the example of quality control stations, it is possible to identify which quality control stations are actually needed. In some cases, there are quality control stations planned, giving none or only few additional information for quality control as this information might also be derived from feedback data of prior production processes. Hence, it is possible to use the MPFQ-model to analyze which quality control stations are needed to ensure the right product quality and where they are best positioned in order to ensure product quality. Further application examples can be found in [GRA12a], [FLW11], [GRA13].

Another typical corrective measure using the MPFQ-model is given if quality problems arise during production. These problems might manifest themselves through high amounts of scraps produced, high failure rates in reliability and durability tests or also through feedback of service personal. In any case, the target of each OEM would be to solve these quality issues. As the problem is known it can be added to the MPFQ-model and dependencies to the rest of the modeled product materials, production processes and product functions can be analyzed. If the quality problem is already modeled as a product quality feature, its dependencies should be reviewed.

Based on the updated MPFQ-model, an analysis can be conducted identifying possible root causes. The MPFQ-model provides some support here, as all known dependencies are already modeled. If the root cause is reasoned by some unknown dependencies, traditional quality measurement tools (see chapter 4) should be used additionally in order to identify them. After the identification of possible causes they can be clustered into product related causes and plant related causes. Product related problems are mainly caused by product materials and product functions due to design failures or low quality inbound materials. Plant related problems are caused by production processes. This might mean inadequately designed production processes or issues arising during the execution of production processes.

In order to solve the quality problem with a minimum amount of resources spent, e.g. time, money, labor, the MPFQ-model can be used to identify a maximum of potential solutions. Product related quality problems caused by failures in the product design are hardly solved without redesigning the product itself. Nevertheless , MPFQ can point out other solutions which may not solve the problem but lower the consequences to a level where good product quality may still be produced. This proceeding is shown in Figure 7-3.

In this case, the application of cybernetic thinking will be also helpful, as active summations [Ves03] will show which product materials, production processes and product functions can be changed in order to achieve high impact on the product quality features. In the special case of already running production lines, another effect has to be regarded. Here, some elements may not be changed as they lead to very high costs, e.g. changing the product itself means to re-design the product, thus leading to a need of re-engineering the production line and production processes. Instead, an optimization has to be done between elements yielding the highest impact on product quality features and the subsequent costs of changing these elements.

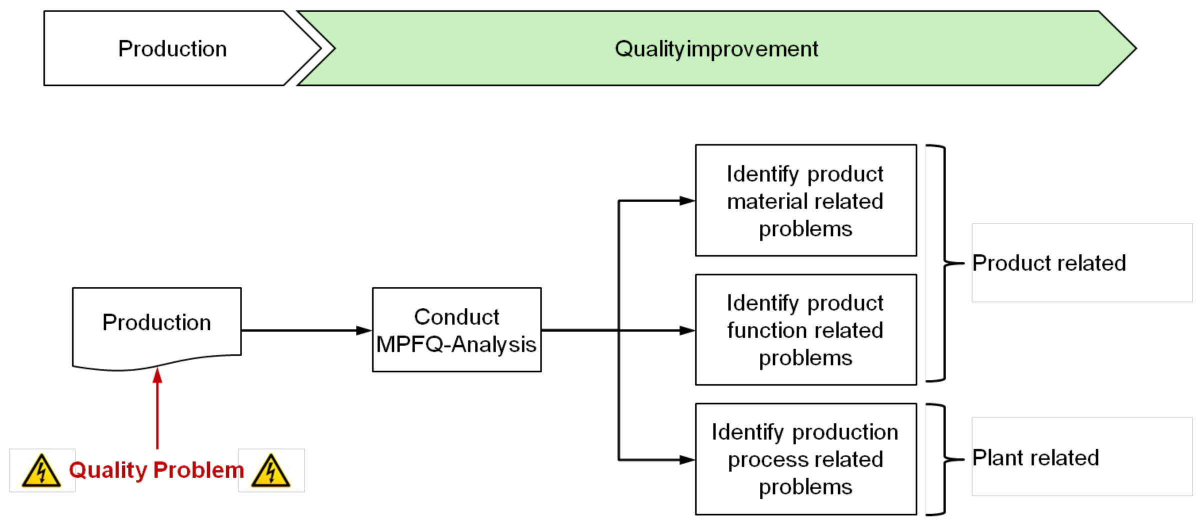

Figure 7-3: Quality failure identification using MPFQ

Such analysis was conducted for the sealing of the rear tub and drum shaft. The quality problem observed may be a leakage at the seal although production processes have been executed within predefined limits. A first solution to the problem can be to replace the supplier of the seals, thus trying to increase the bought in material quality. This approach might show some improvements but still problems with the leakage quality remain. Thus, the production process may be analyzed in order to elaborate if the limits set for the process are inadequate or the process itself is causing problems. Within [GRA12a] a detailed description of technological solutions is shown for this problem. Finally, MPFQ can be utilized to analyze suitable solution alternatives as well.

8 MPFQ in Production Control

In section 6.5 it was discussed that the MPFQ-model can be utilized in order to support production control. This chapter gives an insight how this support may be realized as well as giving an prototypical implementation. Finally, results achieved within the prototypical implementation will be described.

8.1 Applying MPFQ to Production Control Systems

The first step in order to improve quality is to make quality measurable. This also follows the statement of Harrington: "*Measurement is the first step that leads to control and eventually to improvement. If you can't measure something, you can't understand it. If you can't understand it, you can't control it. If you can't control it, you can't improve it."* (H. James Harrington following [The13]).

To apply quality control to production systems using the MPFQ-model, the first step is to measure production data. This includes the measurement of product materials, production processes and product functions. This raw data is stored within a production database. To achieve traceability, each set of raw data is stored together with the unique identifier (e.g. serial number) of the product. After the pure data acquisition and storage, this data can be elaborated. Based on the technical, physical and logical coherences, quality numbers for product materials, production processes and production function can be generated. For the bearing insertion process, the main raw data to be elaborated are the insertion force and insertion depth. Based on the resulting force-depth-diagram, the quality of the insertion process can be determined. A detailed description of production process quality elaboration is given in [SIN12]. In analogy to the production processes, product materials and product functions may also be elaborated. This process is shown in Figure 8-1. The elaboration of data ends in a quality number for a specific product material, production process or product function. These quality numbers, describing the quality level of the specific item can be again stored within the production database.

For production, it can be assumed that the quality level of product materials, production processes and product functions are normally distributed, whereas the peak of the Gaussian bell curve will be identical with the optimal quality. The resulting quality number gives the position on the normal-distribution curve. By aggregating multiple quality numbers, resulting from different product materials, several production processes of a product and multiple product function created within these processes, the current, respectively final product quality of a product can be elaborated. To do so, a correlation of product materials, production processes and product functions to product quality features is needed. This correlation table is nothing more than the matrix representation of the MPFQ-model. Instead of the graphical representation as shown in Figure 6-13 it is also possible to represent the

MPFQ-model as a matrix (further on called also MPFQ correlation table). Here, the direct influences of all product materials, production processes and product functions on specific product quality features are given. These representations can be also weighted e.g. Null, Low, Medium or High dependency. An example for this matrix representation is given in section 8.2.

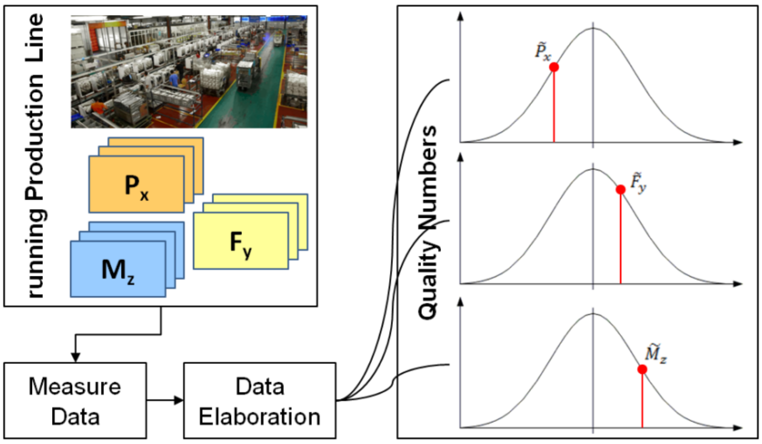

Figure 8-1: MPFQ-model - data acquisition and elaboration

This correlation table can subsequently be used to identify the impact of each quality number on the overall quality of a product quality features, respectively the overall product quality. Hence, using product specific quality numbers and MPFQ correlation table, quality of a specific product can be determined and stored into the production database.

Besides this quality elaboration, it is also possible to analyze production trends. These analysis can be conducted based on raw data, quality numbers or product quality tables. If a trend in one of these data tables shows up, it can be recognized by specific algorithms. In [GRA12a] detailed information on the implementation of these trend analysis algorithms is given. Finally, these trend analysis may provide feedback for the production e.g. of tools to be exchanged as they are attrited. The process of quality evaluation and trend analysis is shown in Figure 8-2.

In addition to these evaluating steps, it is also possible to directly influence product quality during production. As the current product quality for a product under production can be calculated at nearly any time in production, this information may be used to improve/adapt future production processes.

As explained before, data can be measured during production and stored within the database. Subsequently, these data are elaborated to calculate quality numbers for each product material, production process and product function. By correlating these data with the MPFQ correlation table, the current product quality can be evaluated. This means that after a specific amount of time needed for data elaboration, the product quality of a product still under production can be evaluated. This way it is possible to identify to which degree the quality is already defined and to which degree there are still influences provided by future product materials assembled, production processes executed and product functions created. Hence, additional possibilities for production efficiency and product quality optimization are enabled.

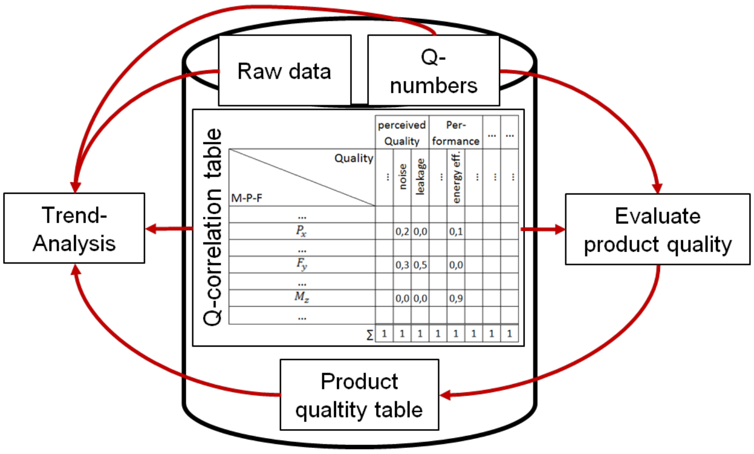

Figure 8-2: MPFQ- product quality evaluation and trend analysis

The MPFQ correlation table can show to which degree the product quality is already defined as all influences are given there and the already assembled product materials, executed production processes and realized product function are known. If the actual product quality is not sufficient, it will thus be possible to evaluate if there are enough influence possibilities left to enhance this quality. This can be easily shown with a simple example. Assuming that the product quality feature of "noise" was evaluated to a actual degree of 60%, while 90% of the overall influences from product materials, production processes and product functions are already built in/executed/realized. This leads to the fact that only a 10% influence is left on this product quality feature. Hence, producing 100% quality in these remaining product materials, production processes or product functions would increase the product quality to a maximum of 64% (90% * 60% + 10% * 100%). Assuming that typical product quality numbers have a threshold of 85% or more this would mean that no action can be taken to increase the product quality to a suitable amount. Hence, the product should already be scrapped or handed over to the repair department. This way it is possible to identify product quality independently from specific quality control stations, leading to an earlier identification of products to be scrapped or repaired and thus to an increase of production efficiency.

Another possibility is the product specific customization of production process parameters. By evaluating the product quality of product under production, it becomes possible to identify the current trend of the product specific quality. Hence, instead of using standard parameters for the following production processes, it will be possible to elaborate the process parameters which are optimal for this specific product. Imagine a situation where product quality was evaluated and found to be drifted to the right side of the optimum on the Gaussian-bell curve. Applying standard parameters to the following production processes would lead to the fact that the quality may increase, but it would always stay at the right side of the Gaussian-bell curve. Instead of using the standard parameters, some product specific production process parameters can be used leading to the fact that the quality is willingly pushed more to the left side of the Gaussian-bell curve, resulting in a better overall quality which is ideally exactly the peak of the curve.

This way of influencing production parameters is shown in Figure 8-3.

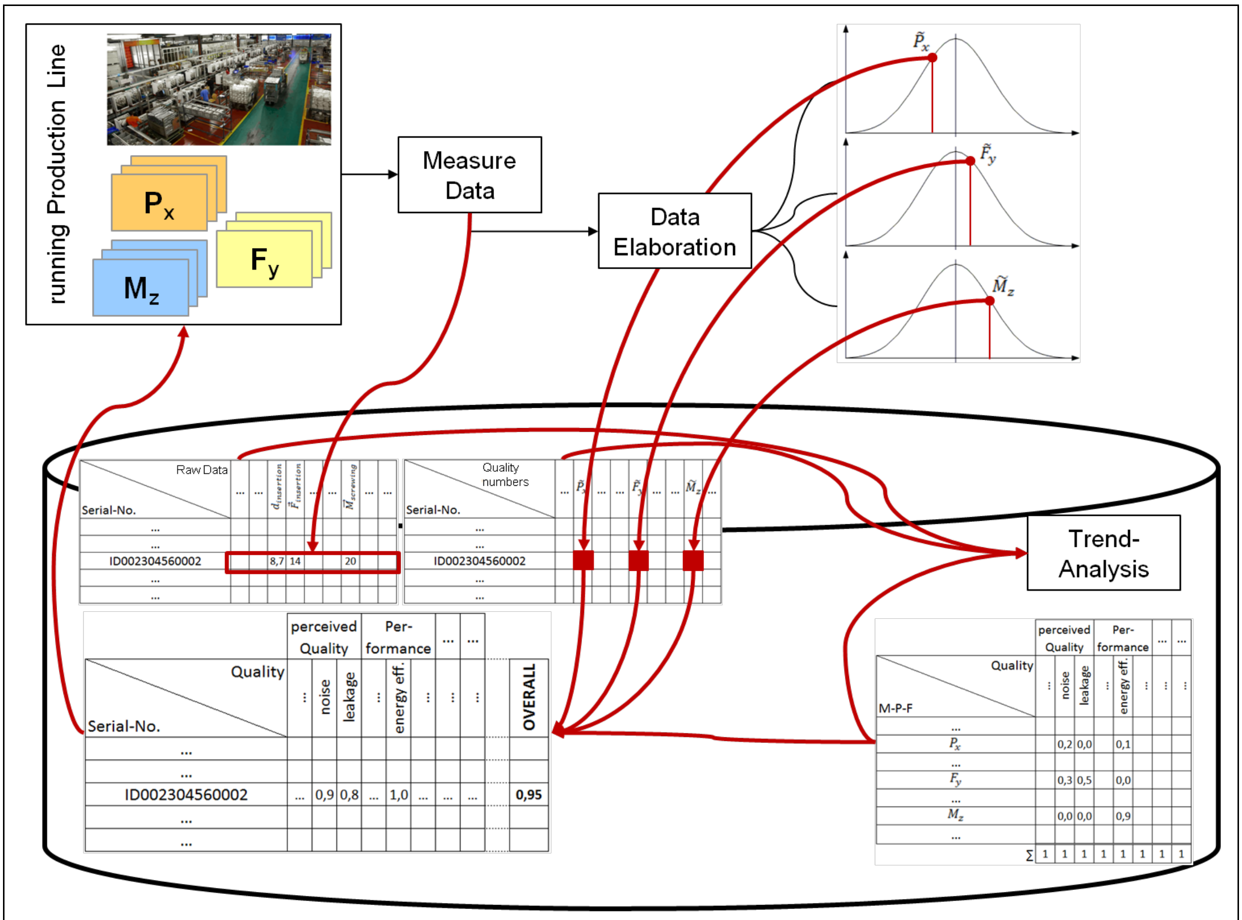

Figure 8-3: MPFQ in production control

8.2 Prototypical Implementation of MPFQ in a Washing Machine Production Line

The previous section has shown the general improvements and optimizations to be reached by utilizing the MPFQ-model. With the European research project "inteGration of pRocess and quAlity Control using multi-agEnt technologies (GRACE)" [GRA11b] a prototypical implementation of the MPFQ-model was carried out using a washing machine production line. This chapter will give a brief overview of this implementation.

As the title of the GRACE project already suggests, the implementation was done using multi-agent technologies. For an introduction to Multi-Agent Systems and to the GRACE multi-agent architecture see [JeW00], [Woo09], [BCB01], [GiB04], [LüF12], [Par98] and

[SHY06]. Special information on GRACE MAS can be found in [LeR11a], [LeR11b], [Ins10], [Ins11] and [Ins12]. Nevertheless, MPFQ-model was not implemented as an agent-specific tool, thus implementation based on other control system architectures is also possible.

The washing machine production line and the washing machine models produced on that line consist of more than 100 product materials, over 70 production stations and over 400 product functions. Within the implementation, 8 product quality features have been analyzed, namely:

- Noise of the washing machine during the washing cycle
- Energy efficiency, including power and water consumption
- Component conformity, meaning the conformance of product materials to predefined requirements
- Assembly conformity, meaning the conformance of product materials and product functions to predefined requirements after their assembling/creation within production processes
- Leakage of the washing machine during the washing cycle (amount of water leaked out of the machine)
- Washing performance, including the cleansing and drying of clothes
- Safety during the washing cycle, meaning the risk of the user to suffer any harm or damage emanating from the washing machine
- Green footprint of the product focusing on a resource-conserving production and use of the product

As the mere amount of elements to be regarded in the MPFQ-model would be very confusing, the prototypical implementation focused on one part of the washing machine production, which is the washing unit production line. This line was chosen as it yields the highest degree of process automation within the washing machine production and the washing unit itself represents the core technological system of a washing machine. In [GRA13] the 56 product materials, 42 production processes and 146 product functions model along the washing unit production line are shown in detail.

The implementation architecture of the MPFQ-model is combining the already existing MES architecture of the washing unit production line with the GRACE multi-agent architecture. To this purpose, different types of agents have been defined. The machine agents (MA) are controlling the production stations of the production line. The concept within GRACE was to not replace the production control, instead the agents should provide intelligence, flexibility, self-optimization, self-adaptation and self-learning, while the low level control is still processed by the PLCs. Thus, the machine agent is connected to the production stations and interacting via process parameters etc. In the same way, the quality control agents (QCA) are interacting with the quality control stations. Besides there are also other hardware near agents like transport agents and operator agents which should be not especially focused as they are of minor interest for the MPFQ-model implementation.

For each product to be produced, a product agent (PA) is instantiated from the product type agent (PTA). The product agents are controlling production of the specific product as well as collecting data about the production process. Besides these agent types, there are also independent meta-agents (IMA) responsible for global system view and techniques like global adaptation and trend analysis.

Data and information is handled in two different ways:

1. All agents store data within an own local database and send information request to other agents if information are required;
2. Data which is gathered by production resources not controlled by any agent are stored within a production database. This database can be queried by all agents.

As the production database was already used prior to the project and inadvertent interaction, as well as performance interferences should be avoided, an additional MPFQ-database has been connected to the communication bus of the automation system. The implementation architecture of the prototype can be seen in Figure 8-4.

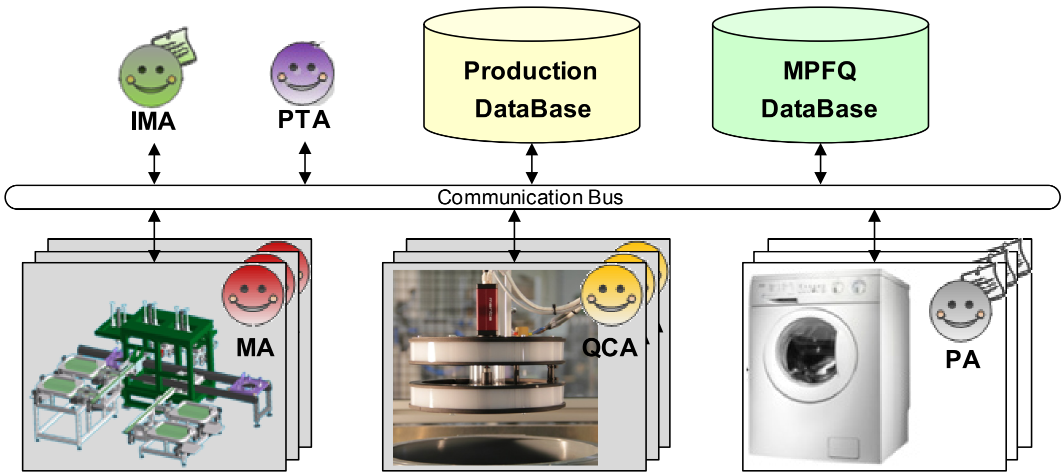

Figure 8-4: MPFQ Pilot Implementation Architecture

In order to implement the MPFQ-model, the correlation tables are needed. Table 8-1 shows the matrix representation of the MPFQ-model excerpt depicted in Figure 6-13. It is the result of a common workshop with different product designers and plant engineers. Within this workshop, every person rated the influence of a product material, production process or product function to the eight product quality features described above from "Null" (equals 0) to "High" (equals 3). After the first rating given by every engineer, the results have been summarized by calculating medium values and maximum deviations of the single ratings. In case major deviations were found, they have been discussed by all participants. Finally, the results have been consolidated to the matrix representation of the MPFQ-model (showing medium values).

							MPFQ Correlations							
Type	ID	Item	Material 1	Material 2	Process	Process ID	Q1 - Noise	Q2 - Energy Saving	Q3 - Component Conformity	Q4 - Assembly Conformity	Q5 - No Leakage	Q6 - Washing Performance	Q7 - Safety	Q8 - Green Footprint
Materials														
	5560	Shaft					1,00	0,00	3,00	3,00	0,00	2,00	0,00	0,00
	5090	Seal					0,00	1,00	3,00	0,00	3,00	0,00	0,00	0,00
Processes														
	6170	Drum insertion					2,00	0,33	0,00	3,00	1,50	0,50	0,00	1,00
Functions														
	7110	push	Shaft	Seal	Drum insertion	6170	1,33	0,33	0,00	3,00	3,00	0,00	0,00	0,00
	7180	wear	Seal	Shaft	Drum insertion	6170	1,00	0,67	1,00	3,00	3,00	0,00	0,00	0,50

Table 8-1: Matrix representation of the MPFQ-model excerpt

This matrix representation can be easily translated into a graphical representation. In Figure 8-5 the high level graphical representation of the MPFQ-model is shown. This representation is blurred for confidentiality reasons but can be read in [GRA13]. Green boxes in the middle represent the product quality features, yellow bubbles are for product functions, blue boxes for product materials and orange boxes for production processes.

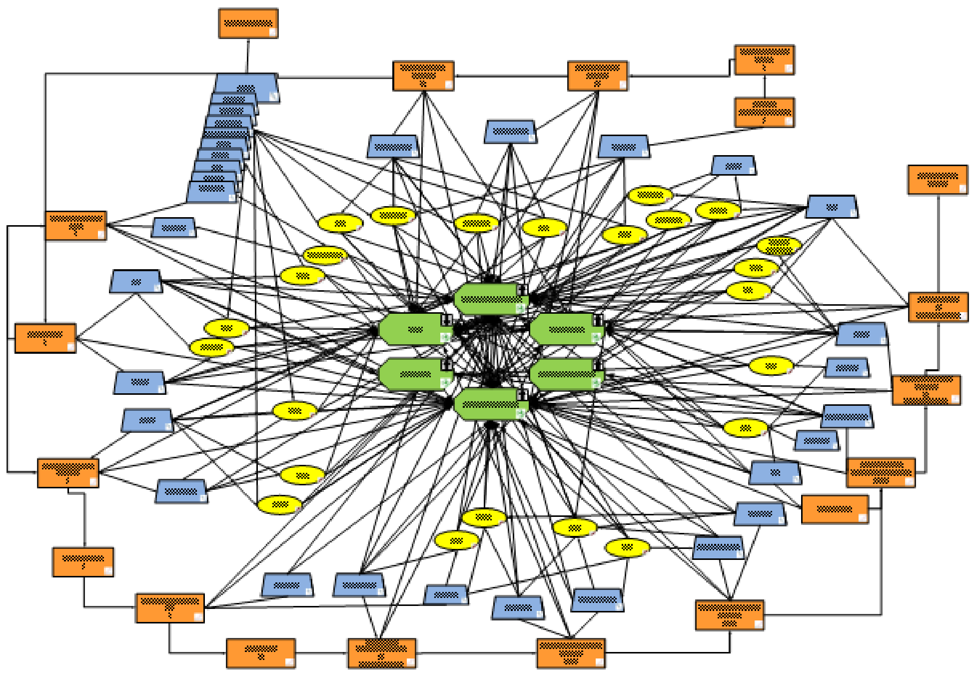

Figure 8-5: Graphical representation of MPFQ-model for the Washing Unit

Looking into the mere amount of data to be processed for calculation of product quality, performance problems are conceivable. When only considering the washing unit and its production line, approximately 300 product materials, production processes and product functions have to be correlated with the 8 product quality features. Hence, 2400 multiplications are needed in order to evaluate the final product quality of one product instance. This amount is simply impracticable when used in real-time production systems, as either the real-time constraints would be violated or very powerful (and thus expensive) control hardware is needed.

To avoid these problems another correlation was done, taking into consideration the quality that can be measured by specific production stations. The correlation itself is quite simple, as for every product material, production process and product function correlated within the MPFQ correlation, a analogous correlation is done to quality control stations, manufacturing stations with high quality feedback and other testing stations. Within the washing unit production line, 9 stations have been identified as main quality feedback stations. For these stations, a team of product designers and plant engineers rated which station may measure the quality of which product material, production process or product function. These simple binary ratings have been used to identify the rate to which a station may measure a specific element. An excerpt of this station correlation is given in Table 8-2. Here, it can be seen that the quality of the shaft is mainly measured within quality control stations three and six, while wearing function between seal and shaft could not be measured by any of these stations.

							Station Correlations								
Type	ID	Item	Material 1	Material 2	Process	Process ID	Manufacturing Station 4	Manufacturing Station 6	Quality Control Station 3	Functional Test Station	Manufacturing Station 34	Quality Control Station 6	Visual Control 1	Visual Control 2	Visual Control 3
Materials															
	5560	Shaft					0,00	0,00	**0,75**	0,00	**0,40**	**0,80**	0,00	0,00	0,00
	5090	Seal					0,00	0,00	0,00	**0,20**	0,00	**0,25**	0,00	0,00	0,00
Processes															
	6170	Drum insertion					0,00	0,00	**0,60**	0,00	**0,20**	0,00	0,00	0,00	0,00
Functions															
	7110	push	Shaft	Seal	Drum insertion	6170	0,00	0,00	0,00	0,00	0,00	**0,20**	0,00	0,00	0,00
	7180	wear	Seal	Shaft	Drum insertion	6170	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Table 8-2: Station Correlation of MPFQ-model excerpt

Combining the MPFQ correlation and the station correlation tables, a MPFQ quality-station correlation can be derived. This correlation gives the degree to which each of the selected production stations is able to measure the final product quality feature of a product. Hence, these correlations can be used to evaluate final product quality on a superior level. The resulting quality-station correlation table is shown in Table 8-3. The depicted values recite the real values in means of magnitude. Original values can be seen in [GRA13].

	Quality-Station Correlation							
	Q1 - Noise	Q2 - Energy Saving	Q3 - Component Conformity	Q4 - Assembly Conformity	Q5 - No Leakage	Q6 - Washing Performance	Q7 - Safety	Q8 - Green Footprint
Selected Stations								
Manufacturing Station 4	7%	6%	4%	3%	3%	3%	1%	5%
Manufacturing Station 6	2%	7%	4%	3%	2%	5%	3%	7%
Quality Control Station 3	5%	3%	6%	5%	7%	4%	5%	8%
Functional Test Station	18%	28%	20%	23%	24%	27%	22%	24%
Manufacturing Station 34	10%	5%	12%	10%	6%	6%	14%	12%
Quality Control Station 6	27%	16%	18%	18%	8%	14%	15%	16%
Visual Control 1	11%	15%	13%	14%	20%	17%	15%	8%
Visual Control 2	7%	3%	9%	10%	16%	10%	12%	4%
Visual Control 3	7%	12%	7%	7%	10%	9%	7%	6%
Sum(influence)	**94%**	**95%**	**93%**	**93%**	**96%**	**95%**	**94%**	**90%**
Influence Others	6%	5%	7%	7%	4%	5%	6%	10%

Table 8-3: MPFQ Quality-Station Correlation

Using the quality-station correlation, only quality numbers for the nine selected product stations have to be evaluated. These values are subsequently used in order to evaluate the final product quality. Hence, the number of multiplications needed for the final evaluation is reduced from approximately 2400 to 72, increasing practicability of the approach significantly. This way, the knowledge of the engineers is still explicitly contained in the MPFQ-model, but transformed for applicability reasons. Hence, some detailed dependencies are not explicitly used within production control. Nevertheless, if quality problems should arise, a deeper analysis based on the original MPFQ correlations and raw data measurements is still possible.

Subsuming all influencing stations, the nine selected stations yield an impact share of 94% while all other 33 stations only share an impact of 6%. This is depicted in Figure 8-6. This kind of evaluation also helps in the plant engineering phase. Conducting these types of analysis upfront would help to indentify which stations are crucial for product quality evaluation and therefore should explicitly be considered when it comes to equipment accuracy and cost tradeoffs. As can be seen in Figure 8-6, the functional test is able to identify a share 23% of the overall product quality. The same applies to the 31% total share of the three similar constructed visual control stations.

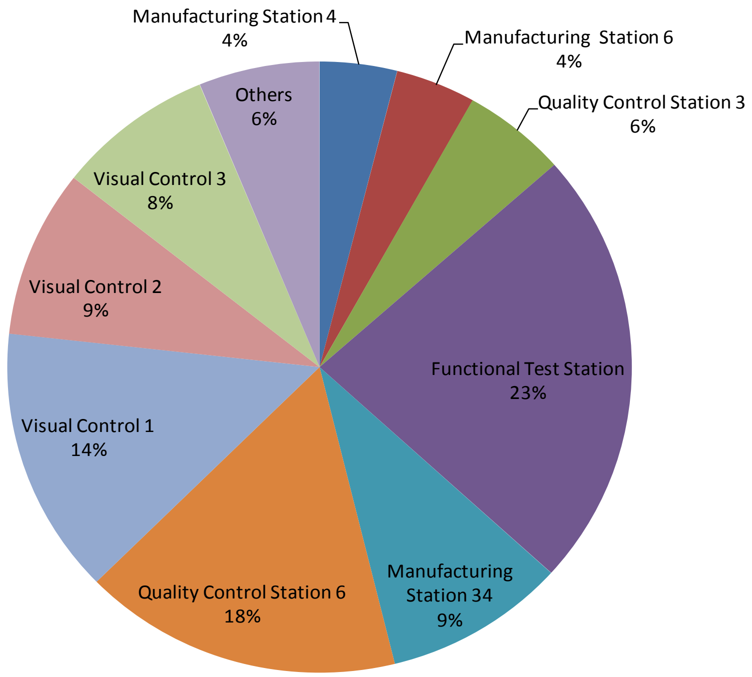

Figure 8-6: Overall Quality-Station correlation based on MPFQ analysis

After all correlation tables are created, they are stored into the MPFQ database. Based on the implementation architecture shown in Figure 8-4, the production line is now ready. As soon as a new production order arrives, the product type to be produced is chosen and the respective product type agent instantiates the amount of product agents required according to the production order. Subsequently, product agents are entering the production line and start with the production of washing units. After each production station, the raw data is stored to the production database by the resource agents controlling the station. Additionally, the raw data is send to the product agents, which are evaluating the quality numbers based on this information. These numbers are also stored to the production database. When arriving at a new production station, the product agent queries the MPFQ database in order to receive MPFQ correlation tables. Afterwards, it calculates the customized production parameters for the next production station and provides them as soon as it arrives. These new production parameters are used by the resource agents for the production process. After finishing the process, the raw data is again stored to production database and handed over to product agent for further evaluation. This process is shown in Figure 8-7.

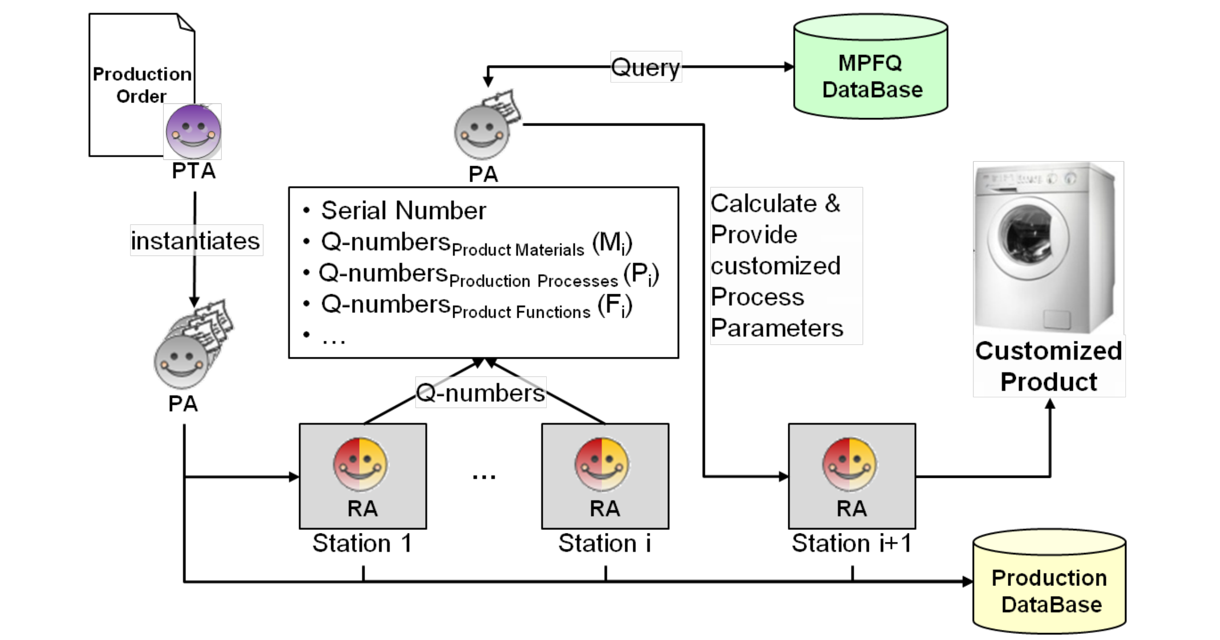

Figure 8-7: Washing Machine Production - MPFQ Pilot

An exemplary description of the product agent behavior as a Petri-Net is given in Figure 8-8 based on [Ins11]. For further information on the detailed implementation of GRACE agents see [Ins10], [Ins11] and [Ins12]. A detailed description of the adaptation of the functional test of washing machines is given in [RLF13].

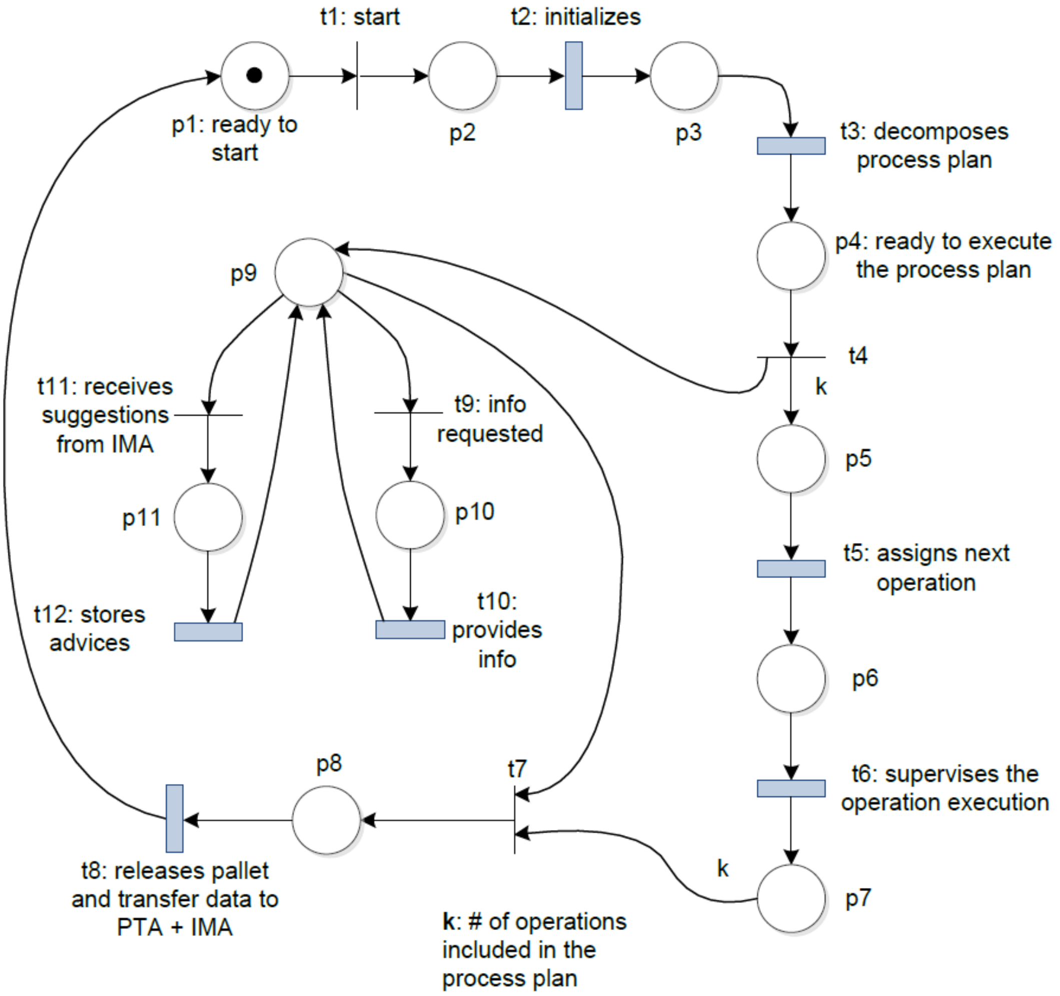

Figure 8-8: Petri-Net description of a Product Agent [Ins11]

8.3 Results of Prototypical Implementation of MPFQ

The implementation of the MPFQ-model was used to produce test charges in the real production line for washing machines at Whirlpool Europe s.r.l. premises. Based on the evaluation of results during production, but also of findings generated within the expert workshops in preparation of the pilot implementation, the MPFQ-model has been proven as very useful tool in order to increase product quality, production efficiency and production performance. It could be shown that the implementation of the MPFQ-model enables quality oriented monitoring of appliance (product) performance, production equipment and production processes.

The continuous feedback between production results, MPFQ-model and production processes, paired with the ability of production process paramterization, increases product quality significantly.

Generally, a quasi-real-time monitoring of product quality within the production line was enabled. Instead of calculating quality at any time in production, product quality has been calculated after crucial processes. Compared with the initial situation, the product quality can now be evaluated more precisely and with less gaps of uncertainty. While in the classic production line, quality was only evaluated at 6 points in production, now there are 12 stations after which product quality can be calculated. In priciple, it is even possible to calculate product quality right after each production process, which was discarded due to high performance requirements to the production system hardware.

Overall, the quality of washing machines produced on the production line increased due to the quality oriented customization of production process parameters. Additionally, a customization of product control parameters in the washing machine control board was enabled, resulting in customized products optimized based on the measurements during their production. This way a significant optimization of product efficiency was reached, resulting in approximately 12%-13% reduction of water consumption and 18%-22% reduction of energy consumption. The adaptation of function test plans yielded a reduction of cycle times up to 30% [Foe13].

Besides these effects, production cost could be descrease. This was reached by an early identification of defect products, resulting in less materials and thus less money assembled to products which are already scrap but, up to then, not identified as such.

Taking all these results into consideration the following statement on MPFQ was done by Whirlpool Europe s.r.l. after evaluating prototypical implementation: “MPFQ is a new and innovative approach which gives us the opportunity to consistently integrate product design and plant engineering with quality management and production control. We intend to use this approach within further internal projects to enhance quality of our products.” [Foe13]

9 Summary and Outlook

This thesis presented a new methodology for managing and improving product quality. The most important aspect was to design a model which is not only applicable in few phases of the product lifecycle, but can be actually used throughout all phases.

In the first analytical part, current processes, methodologies and tools for product design and production system engineering, as well as for product quality management and improvement have been shown. Within the analysis, focus was set on targeted measures to improve product quality as well as on consistent application of these measures throughout the product lifecycle. In the end of this analysis part, it was shown that multiple successful approaches exist, but that none of them was able to provide consistent knowledge and information transfer.

Based on these results, a model-based approach to indentify, analyze and capture key influence factors on product quality was presented. Here, the focus was set on technical characteristics of products and production processes. The presented MPFQ-model is able to capture four main elements: the product materials, production processes, product functions and product quality features. Thereby, it naturally integrates elements of both the domains of product design and plant engineering and therefore provides valuable support for domain integration.

The final part of this thesis was dedicated to the application, implementation and validation of the solution approach. Here, it was shown that the MPFQ-model provides consistent and useful knowledge and information transfer and that knowledge and information stored within the MPFQ-model is directly applicable to support production control and product customization.

Thus, the solution developed within this work contributes to the management and improvement of product quality.

9.1 Discussion of the Solution and Answering the Research Questions

Within the introduction to this thesis, three research questions have been asked in order to provide guidance for the development of a solution. In the following, these question should be answered and the solution should be discussed with respect to existing approaches.

Research question 1:

Which measures can be taken on the product and/or its production system in order to manage and/or improve predefined quality features?

The MPFQ-model shows the correlations between product materials, production processes, product functions and product quality features. If a quality problem occurs or a specific quality feature should be improved, it is possible to identify suitable influence factors based on the MPFQ-model.

This analysis is also possible with other approaches like FMEA and Six-Sigma. The advantage of MPFQ is that it may provide inputs for an appropriate starting point for these methods. MPFQ itself is not designed to develop a technical analysis like error probabilities as done within FMEA. Still, the correlation among product materials may provide valuable input to FMEAs in order to derive fault-trees more easily. Additionally it was shown in [FLW11] that combining the idea of MPFQ with a workflow analysis, multiple influences of engineering on product quality can be identified. Thus, it is not only possible to identify failures within the technical systems of product and product line, it is also possible to see whether faulty decisions have been taken within the engineering of these systems.

Research question 2:

Which is the (technical) influence of identified quality measures and where does it have additional effects on?

This question is again answered by the technical correlation within the MPFQ-model. If a quality measure is identified, it can be analyzed where there is a probability to influence it by following the correlations and technical characteristics of the element which shall be improved by the quality measure. Thus it can be analyzed if there are any further impacts on product quality. This process is similar to solutions provided by QFD, FMEA or PPR. All of them focus on quite different aspects of product quality and impact of quality measures becomes traceable. The advantage of the MPFQ-model is that it provides a more holistic view on the correlations of quality measures. A simple product FMEA could not provide influences which might be created through production processes.

Research question 3:

How can information about product quality be used in an integrated manner along all lifecycle stages in order to assure, manage and/or improve product quality?

This questions is answered by considering different application examples from chapters 7 and 8. It was shown that MPFQ is applicable as an instrument during product design and plant engineering by supporting decision processes and fault analysis. But additionally, the same knowledge can be used to control production processes by analyzing product quality during production and customizing product process parameters accordingly. The same way it is also possible to provide customized parameters for product on-board controllers, which would improve quality during the use phase of a product. Comparable approaches are not available so far. Approaches like TQM provide a similar idea of integrating everyone into a product quality framework, but they stay at a management level and thus are hard to be applied to technical characteristics.

9.2 Assessment of the Solution

In contrary to the quality measurements presented in chapter 4, the MPFQ-model provides a consistent quality assurance along the whole product and plant lifecycle. Starting with the quality requirements definition and enhancement based on MPFQ analysis, over product definition in terms of product materials and product functions, over support in plant engineering right up to enabling quality assurance in production, the MPFQ-model provides a crucial backbone in quality management. By enforcing the integration of product design, plant engineering and production, this model provides a systematic view on the core dependencies among these disciplines and thus overcomes typical boundaries and quality problems resulting from discipline specific approaches.

It can be seen that the MPFQ-model provides an approach which is situated between the quality management level and the technical process level with a propensity to technical processes. Thus, the model is able to combine advantages but also disadvantages of both worlds. The integration of technical characteristics, measurement results, etc., into the MPFQ-model enables the production control capabilities and the integrated consideration of elements from product design and plant engineering. Nevertheless, a model covering all these different domains and detail depths is likely to grow in complexity very fast which makes it confusing and not easy to handle. Here, technical approaches like Six-Sigma, FMEA, QFD, DoCoDe, etc provide much clearer and more manageable solutions for large systems. The only way to maintain clearness and manageability within MPFQ is applying different levels of abstractions which is currently a huge amount of work since tool support for MPFQ is missing.

Compared to the current situation in production control, MPFQ is able to provide real benefits in terms of product quality assessment. The storage of feedback data and quality control data is state of the art in many production lines these days. Currently, feedback data from processes is stored in a production database without further use within production. Only when quality problems are identified, this data is used to analyze sources for incompliance etc. The MPFQ-model enables a utilization of this information in order to derive additional quality assessments as it was done in chapter 8. This can be done without major changes on the production line, only by providing a PC with access to the production database.

The combination of product design and plant engineering also forces a stronger interaction of engineers from both sides in order to build up a MPFQ-model. This has shown to be very fruitful, as a forced interaction gives both sides the opportunity to see drawbacks and effects of their design decisions on engineering activities of other parties, but also to identify benefits and opportunities for synergies between both of them. But this forced interaction is also something that is an additional and time consuming activity. Taking into consideration that most engineering departments are designed as cost centers [GAV13], this interaction is hardly achievable without management commitment. Additionally it has shown up within the workshops aligned to this work that a lot sensitivity for the needs of product designers and plant engineers as well as translation between both “worlds” (e.g. use of the same terms in different meanings, etc.) is needed to successfully derive information required to be included in the MPFQ-model. Thus, it has to be said that the setup of this model is a lot more complicated than a FMEA analysis as integrating humans from different domains shows to be a non-negligible hurdle. Nevertheless, MPFQ would provide a common backbone for all different quality management techniques and quality measures, thus improving consistency among them.

As stated above, the MPFQ-model is likely to grow exponentially when applied to large scale systems. Nevertheless, it is possible to set up the model in a real flexible way. By focusing on small functional modules with few dependencies to other product materials, production processes and product functions and on only few quality features it is possible to create small size models yielding good results. This flexibility also allows to comply with external demands regarding cost and time as not the whole MPFQ model needs to be derived before yields are gained. Instead only little effort is spend in order to yield minor improvements in quality cost and time. This way of iterative setup of the MPFQ-model for one product type allows to keep efforts small and to improve the model over time by rising possible yields in parallel.

9.3 Outlook

The results obtained within this thesis as well as observations made along the way lead to different fields of action for future work.

One of the main weaknesses of MPFQ is the exponential growth in complexity for large scale systems. Yet, especially large scale systems would benefit from this kind of modeling approach as rising complexity leads to rising correlations among system elements and thus MPFQ might provide additional input for quality problems. One solution to this is the application of functional modeling approaches. Within the thesis references to this were made but it is questionable if current functional or mechatronical approaches fit the demands of MPFQ. It showed up during the modeling that functions may have to be considered in a different way. The leakage of a washing machine is depending on different sealings all over the product (e.g. sealing at the bearings, sealing at the door, sealing at the exhaust pipe, etc). In terms of MPFQ, each part may be regarded as a separate functional unit within nearly no correlations to the other ones. Just at the end, all of them are contributing to the leakage quality. This way of functional hierarchization is different from current approaches and could be analyzed in order to provide support in product and also production system decomposition/composition for MPFQ means.

Another way to support MPFQ in large scale systems is the improvement of tool support. Currently, standard software and macros are used to build up MPFQ-models and to convert them into different representations. This is still error prone and thus implies high efforts on manual checks. A suitable software tool support would improve cost and time performance of MPFQ modeling. Additionally, such a tool support might also come up with abilities like setting up of hierarchies. Currently hierarchies within MPFQ are manually modeled and conversion is done based on manual matching of models. A suitable tool support would enhance modeling by providing high-level correlation of MPFQ with the possibility to detail only specific building blocks, thus enhancing also clearness for further analysis.

The weighted influences of different product materials, production processes and product functions have been weighted within expert workshops. These influence estimations are no fixed values and need to be adapted and tuned especially in the first applications, as they might not fit to the real technical influence of the single elements. These tunings and adaptations might also be done in an automatic manner, using the numbers from the expert workshops as initial values. Thus, due to multiple automatic iterations the "real" influence estimation can be calculated. The according mechanisms for this tuning and adaptation of influence factors is also subject for further examinations.

Currently MPFQ focuses on technical perspectives on a product. Efficiency increase and cost reduction as reported within the prototypical implementation are still a kind of side effects which come naturally by improving the technical perspective. Nevertheless, it may be worth to add these dimensions into the model, maybe as further technical characteristics in order to enable MPFQ for target time and cost improvements while assuring a certain basic level of product quality. This is currently done manually.

Another perspective to be added might be the "human factor". Within this work and the prototypical implementation a production line with high degree of automation was focused. Applying MPFQ to a primary manual processes reduces the feedback from processes and thus lowers the ability to predict product quality. Still, the product quality produced within these processes is an important factor for business success of the considered company. Within the prototypical implementation manual processes have been measured by subsequent quality control stations. Nevertheless, there was no feedback given to manual processes. Examining this gap could bring further application domains to MPFQ.

The last field of activity which showed up during the work on this model is also dedicated to application domains of MPFQ. Currently, the model was developed for production of discrete goods. There have been some investigations if MPFQ is also applicable to process industry. Within these investigations the example of a power plant producing electrical energy was analyzed. First results have been very positive, so that it is assumed that an application of

MPFQ in process industry might be worthwhile. Still, further research is needed in order to verify these first investigations.

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