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On Manufacturing System Development in the Context of Concurrent Engineering

A Doctoral thesis
by
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How all things live and work, and ever blending,
Weave one vast whole from Being`s ample range!
How powers celestial, rising and descending,
Their golden buckets ceaseless interchange!
Their flight on rapture - breathing pinions winging,
From heaven to earth their genial influence bringing,
Through the wild sphere their chimes melodious ringing!

Tragedy of Faust by J.W. von Goethe

ABSTRACT

This thesis presents an extension of the contemporary engineering design theory towards a unified view on simultaneous development of products and manufacturing systems, i.e. concurrent engineering.

The traditional engineering design theory explains the realization of a product design as a development of product structure from four perspectives: technical process, function, technical solution, and physical embodiment. This thesis extends the engineering design theory with a set of definitions and universal statements. These definitions and universal statements describe manufacturing systems from same four perspectives. In that context they also describe the relationship between a product and its manufacturing system. The thesis contributes to the creation of a single theoretical system based on an integration of theories from two engineering design schools, the WDK and the Axiomatic Design. WDK-theories are in this new context utilized for qualitative synthesis of the developed artifacts, while the Axiomatic Design is utilized for structuring and analyzing the corresponding quantitative parameters.

The definitions and universal statements describe the development structures for products and manufacturing systems. This description is utilized for definition of a system for development of these structures, i.e. (i) a stage-gate-based manufacturing system development process, (ii) a development methodology toolbox, and (iii) an information management framework consisted of an information model harmonized with the systems engineering data management standard STEP AP 233.

The research has been carried out in a close collaboration with Swedish manufacturing industry. The utilized research methodology is the hypothetic-deductive method, with case study as an observation method.

Keywords: *Concurrent Engineering, Engineering Design, Development Methods and Tools, Manufacturing System, Information Management.*

ACKNOWLEDGMENTS

Four years ago, when I started my journey beyond the frontiers of the ”accepted knowledge”, I didn’t realize the magnitude of joy and frustration inherent in the research work. Now, when I look at this pile of paper that is my doctoral thesis, I can feel only the joy manifested not just in pride but also in gratefulness. I am proud because I believe that the work that I have conducted has carried the knowledge frontier one step further. I am also proud because I am the author of a thick book that carries the emblem of a distinguished academic institution. My gratefulness, on the other hand, is a prolongation of pride, because I would never been able to perform this work without strong support from my ground service. Now, what is such a ground service made up of?

First of all, my supervisor, Professor Bengt Lindberg, who have always encouraged me in developing new ideas, always believed in my ability to make feasible decisions and who has led me through the graduate school with a discreet but firm hand. Professor emeritus Gunnar Sohlenius, a man of great scientific intuition, has been a source of inspiration who always has had the ability to express himself in an interesting but slightly incomprehensive way, which in turn stimulated my curiosity and helped me to incrementally build up my understanding of the research area.

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PUBLICATIONS

The work presented in this thesis is based on the following previously published papers and reports:

1. Aganovic, D., Bjelkemyr, M., 2004, *A Model for Project-Based Education in Manufacturing System Design and its Application on Testing Research Results*, Proceedings of the 8th International Design Conference DESIGN 2004, Dubrovnik, Croatia.
2. Aganovic, D., Bjelkemyr, M., Lindberg, B., 2003, *Applicability of Engineering Design Theory on Manufacturing System Design in the Context of Concurrent Engineering*, in “Methods and Tools for Co-operative and Integrated Design” edited by S. Tichkiewitch and D. Brissaud, Kluwer Academic Publishers, Amsterdam.
3. Aganovic, D., Pandikow, A., 2002, *Towards Enabling an Innovation Process for Extended Manufacturing Enterprises*, Proceedings of the 1st International Conference on Digital Enterprise Technologies DET’02, Durham, UK.
4. Fagerström, J., Aganovic, D., Nielsen, J., Falkman, P., 2002, *Multi-viewpoint Modeling of the Innovation System - Using a Hermeneutic Method*, Proceedings of the 2nd International Conference on Axiomatic Design ICAD 2002, Cambridge, USA.
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6. Aganovic, D., Nielsen, J., Fagerström, J., Clausson, L., Falkman, P., 2002, *A Concurrent Engineering Information Model Based on the STEP Standard and the Theory of Domains*, Proceedings of the 7th International Design Conference DESIGN 2002, Dubrovnik, Croatia.
7. Aganovic, D., 2002, *The LUPUS-project: selection of a strategic information system vendor*, Executive Report, Ericsson AB, Stockholm.

8. Aganovic, D., Svensson, D., 2002, *Analysis of the New Product Introduction Process: a prerequisite for successful information system implementation*, Internal Material, Ericsson AB, Stockholm.
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CONTENTS

Part I:

Research Problem and Research Method

In this part, the research presented in this thesis is motivated and a set of research questions is stated. Furthermore, the research methodology employed during the course of research work is discussed. This part of the thesis also provides the reader with an explanation of the thesis' structure.

1 INTRODUCTION

1.1 Concurrent Engineering

Manufacturing companies develop their products by gathering product requirements from customers and, along with taking the company's strategies and external and internal constraints into account, synthesizing appropriate product functions. These product functions are embodied in a customized hardware, software and professional service offer from manufacturer to customer. A manufacturer needs to, besides direct functional requirements, gather also business requirements that mirror customer's quality and productivity demands on the product's manufacturing system. In order to be able to deliver the product according to the whole demand picture, the manufacturing company needs to coordinate The development of the product and its manufacturing system (Sahlin (1999)).

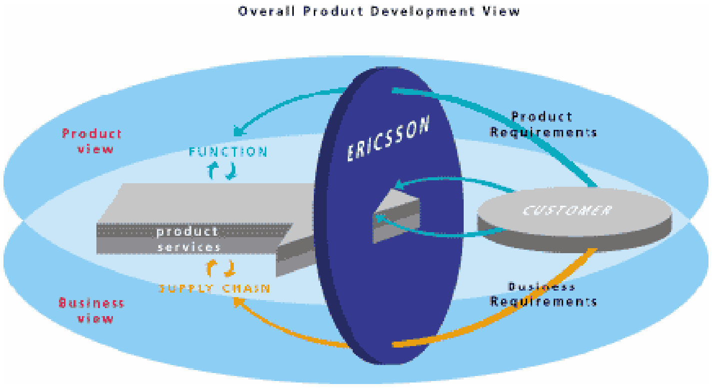

Figure 1: Overall product development view, Sahlin (1999)

A manufacturing system consists of manufacturing resources that execute a set of manufacturing processes in order to create a product, which is desired by a customer. It is recognized that the capabilities of a manufacturing system are highly dependant on, and strongly contribute to, the properties of the corresponding product.

Products and manufacturing systems are developed in an organization consisting of niche professionals that are responsible for executing a variety of the development tasks and are often distributed through the different organizational entities. In order to increase productivity and quality of the development process, a product and a corresponding manufacturing system should be developed by executing product-specific and manufacturing system-specific development tasks concurrently. Such work principle, called concurrent engineering, is characterized by an extremely intensive information exchange between the different tasks (Eppinger et al. (1994), Fagerström et al. (2002)).

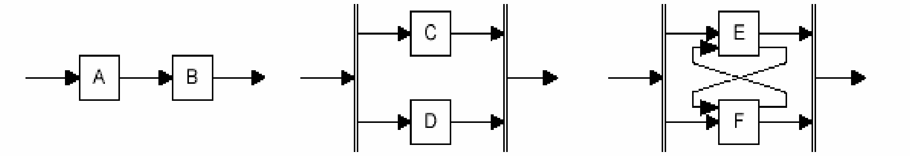

Figure 2: Three different dependency patterns in the development process: (i) B depends on the result from A, therefore serial process, (ii) C and D are independent, therefore parallel process, and (iii) E and F are interdependent, therefore concurrent process, adapted from Eppinger et al. (1994)

Figure 3 shows an activity model (NIST (1993)) for a development system, where products and their corresponding manufacturing systems are developed and implemented. The model[1] consists of five activities:

- Develop Product (A1): This activity includes all the tasks that are carried out during the development of a product model.
- Develop Manufacturing System (A2): This activity includes all the tasks that are carried out during the development of the corresponding manufacturing system model.

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[1] This activity model is based on a model developed in collaboration with Jonas Fagerström and Johan Nielsen at KTH Production Engineering. The model was originally published in proceedings of ICAD 2002 (Fagerström et al. (2002)). The changes in the original model are partly based on the comments from Anders Claesson at Saab Automobile AB.

- Implement Manufacturing System (A3): This activity includes all the tasks that are carried out during the installation of the manufacturing system. Here the virtual models are realized, i.e. a physical manufacturing system is installed and approved for operation.

- Configure Customer Specific Product and Manufacturing System (A4): This activity includes all the tasks that are carried out during the configuration of the product and the corresponding manufacturing system to meet a specific customer's needs during the pre-series production.

- Manufacture Product (A5): This activity includes all the tasks that are carried out during the pre-series production, i.e. manufacturing of product to the selected customers in order to physically verify and tune product and manufacturing system design.

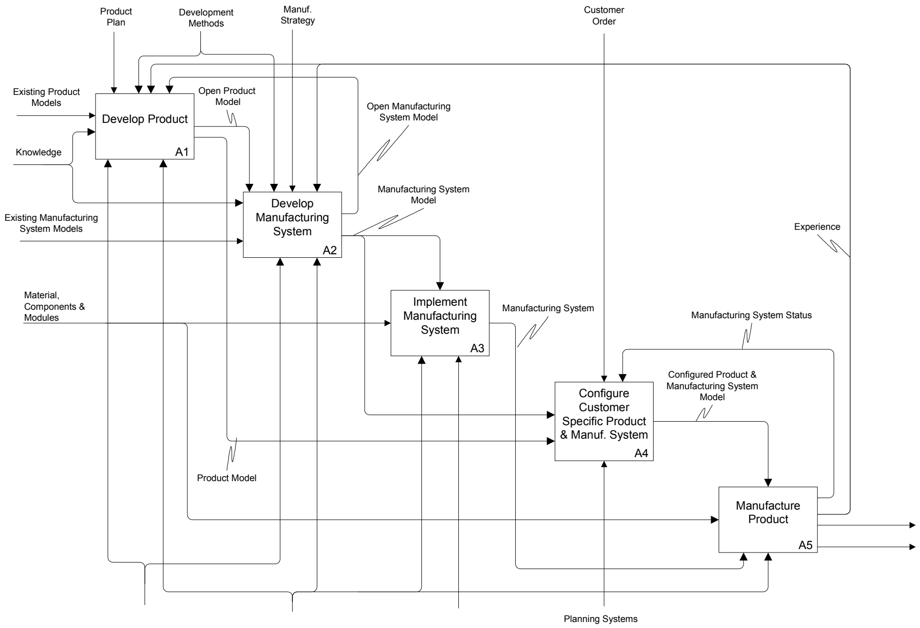


Figure 3: An activity model for a development system, adapted from Fagerström et al. (2002)

In the activity model depicted in Figure 3 it is possible to infer that activities, which represent product development (A1) and manufacturing system development (A2) are interdependent. Open product models are during early phases of product development released to control the manufacturing system development activity. In same manner, open manufacturing system models are released to control the product development activity. This control relationship is maintained during the all stages of product and manufacturing system development and it consist a very soul of concurrent engineering.

According to Nielsen (2003), concurrent engineering is the simultaneous consideration of more than one aspect of a system during its design phase. This idea is illustrated in Figure 4, i.e. Toyota Motor Company's view on concurrency.

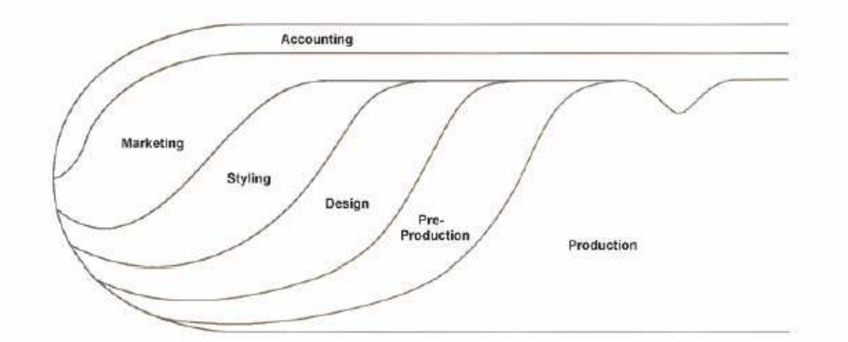


Figure 4: Concurrent Engineering at Toyota Motor Company, Liker et al. (1995)

In this thesis, the meaning of concurrent engineering is the simultaneous development of a product and its manufacturing system where special attention is directed towards product-related factors that impact manufacturing system design and manufacturing system-related factors that impact product design.

1.2 A Process View on Development Activities

The development activity is executed in several stages of a development process. In these stages, i.e. sub-processes, various development methods and tools are used in order to carry out the various development tasks. Development processes are often formalized as so called stage-gate models (cf. Figure 5).

Figure 5: A development process model, Stage-Gate (2004)

However, the development processes are usually product development oriented and are focusing on conceptually explaining how various product development tasks and corresponding methods are related. Although they are sometimes treating the manufacturing aspects, e.g. Andreasen and Hein (1987) and Ulrich and Eppinger (2000), their elucidation of manufacturing system development tasks and corresponding methods is, at best, very modest.

Furthermore, a somewhat managerial orientation of the development process models may be the reason behind the fact that the existing models mainly focus on explaining some general development tasks and corresponding methods and are not concerned with extensively explaining how the various structures of a design object are gradually decomposed. This hinders engineers in general and manufacturing system designers in particular, from gaining a deep insight in various system development issues as well as in concurrent engineering problems.

Therefore, there is a need for a development process model that shows how various engineering methods and tools are utilized in creation of product and, *especially*, manufacturing system structures.

1.3 Design Objects

The relationship between a product and a manufacturing system is addressed in the engineering design theory. The engineering design theory describes how product models should be structured, e.g. Andreasen (1980), Hubka and Eder (1988), Suh (1990).

A product model structure is a product design decomposition representing the intent with the design as well as the design history. By making controlled and well-documented product design decomposition it is possible to track the design decisions made by the developers. The different approaches in the engineering design field are focused on product design. A manufacturing system can be regarded as a product of it own and thus covered by the theories.

However, a generic description of the structural coupling between two design objects, a product and a manufacturing system, has not been in focus of the engineering design research community. There are, off-course, few researchers, e.g. Andreasen (1992), Olesen (1992), Vallhagen (1996), and Sohlenius (2000), who have discussed the dependency between products and manufacturing systems on a conceptual level (cf. Figure 6), but it is not possible to claim that the engineering design theory is clearly explaining *manufacturing system development* in the context of concurrent engineering and development methods and -processes.

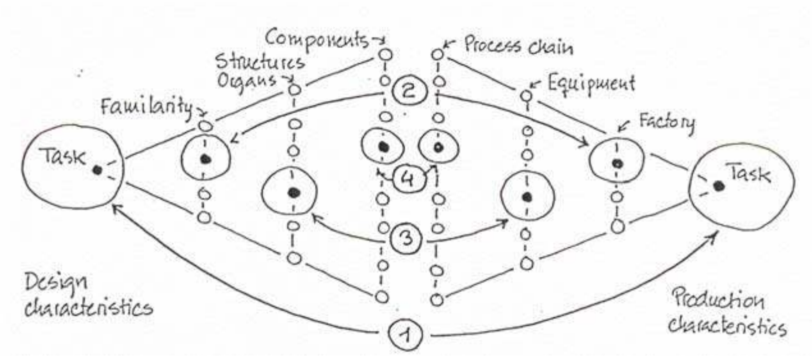


Figure 6: A conceptual relationship between product design characteristics and production characteristics, Andreasen (1992)

An elucidation of the inherent characteristics of various structural views on the developed products and corresponding manufacturing systems as well as elucidation of their mutual dependency pattern are important prerequisites for gaining the understanding for the relationship between the design objects, engineering methods and tools, and the development process. When this understanding is gained it will be possible to provide a comprehensive methodology platform for manufacturing system development.

It will also be easier to extract the formal information requirements for the manufacturing system development process, which in its turn, will facilitate implementation of effective and efficient development information management systems.

1.4 Development Information Management

As already stated in Section 1.1, the manufacturing system development in the context of concurrent engineering is conducted through numerous tasks where several engineers use various development methods and -tools to shift the focus between different views on the design objects and between different development problems that can occur. This system development philosophy is characterized by an extensive information exchange between different methods/tools as well as between engineers.

Furthermore, the manufacturing companies of today are geographically, organizationally, and culturally diversified, as so-called *extended enterprises*. Opportunistic alliances among multiple organizational entities, each contributing niche core components, are becoming the new business model replacing the more static version of vertically integrated companies and their traditional "buyer/seller" relationships. These alliances can be temporary and project-specific yielding more complexity, and thus more costs in the collaboration domain of concurrent engineering.

Executions of development processes can be improved using information systems, for example engineering tools that belong to CAD (Computer Aided Design), CAE (Computer Aided Engineering), or CAPE (Computer Aided Production Engineering) area as well as data management systems that implement PDM (Product Data Management). If such information systems are used in an extended enterprise the issue of uniform representation of information should be addressed by using common, application domain specific, information models. Since extended enterprises are built on multiple and often opportunistic relationships, such information models should be widely accepted international standards, for example described within ISO 10303-STEP standardization framework (STEP (1993)).

Another issue with the execution of development processes in dynamic extended enterprises is the utilization of the Internet as an infrastructure for providing services for the actors in the process. A modeling framework for creation of models for integrated and uniform access to information sources and services, suited for "intelligent" information processing applications, is needed in order to efficiently manage the potential of the Internet in an innovation environment. This model framework must provide standard mechanisms for data interchanges, preserving the semantics of the exchanged data. The Resource Description Framework (RDF) is such a model framework, which is regarded as a foundation for the next generation of the Internet, the *Semantic Web* (Lassila and Swick (1999). While discussions about the future industrial use of web-services are intensifying the issue of common information models comes in focus. Information models that are already developed and can be used in a RDF-implementation are application protocols of the STEP-standard. First step towards this is already taken by the EPISTLE-community (Leal (2001)), which is concerned with development of STEP for use within process industry. IT/IS-development community that is covering electromechanical industries is currently not involved in any similar activity.

Furthermore, there has not been any attempt to, based on the engineering design theory and corresponding development methods, -tools-, and -processes, create an information model for manufacturing system development in the context of concurrent engineering.

The research community has already created a firm base for creation of such a model by conducting the research in the areas of: development of information models based on engineering design theory and focused on product development (e.g. Malmqvist and Schachinger (1997)), Harmonization of information models based on engineering design theory (product-focused approach) with STEP (e.g. Sivard (2001)), development of STEP-information models for concurrent development of products and manufacturing systems (Johansson (2001)), and development of general information models within the field of manufacturing engineering (e.g Gabbar et al. 2003))

An information model for manufacturing system development could be harmonized with a standardized information model, e.g. STEP. This harmonized information model could be implemented as a RDF-schema, which, in its turn, can be used as a foundation for creation of web-services that may be seen as a basis for operation of dynamic extended enterprises.

1.5 Research Questions

The research work presented in this thesis has been conducted in order to answer following research questions:

1. Which are the main characteristics of the relationship between a product and its manufacturing system in the context of manufacturing system development based on concurrent engineering philosophy?
2. How can the development tasks, where various methods and tools are utilized for gradual creation of detailed manufacturing system structure models, be coordinated during the manufacturing system development process?
3. How can the methodological framework for manufacturing system development be utilized in creation of systems for development information management in extended enterprises?

1.6 Delimitations

The research results presented in this thesis have been generated under following delimitating conditions:

- Only development of the manufacturing systems for electromechanical products is within the research scope. Electromechanical products are those that are normally manufactured in non-fixed-position workshop layouts, e.g. mobile phones, refrigerators, cars. This implies that large electromechanical products like submarines and aircrafts are not within the research scope.
- The research focus should lie primarily on manufacturing system development activities and their mutual relationships. Product development activities that are not directly related to the technical manufacturing issues are not considered. Relationship with product development is therefore managed from the manufacturability point of view, i.e. the main focus is on the relationship between physical properties of the product and the manufacturing system structure.

1.7 Disposition

This thesis has the following disposition (cf. Figure 12 on page 30):

- Chapter 1 introduces the research problem and states the research questions and delimitations.
- Chapter 2 explains the researcher's perspective on the scientific work and presents a research methodology.
- Chapter 3 gives an overview of the frame of reference within the manufacturing systems development area.
- Chapter 4 gives an overview of the frame of reference within the area of product (and manufacturing system) development processes.
- Chapter 5 gives an overview of the frame of reference within the engineering design theory.
- Chapter 6 gives an overview of the frame of reference within the development information management area.
- Chapter 7 presents a set of five industrial case studies that provides a basis for formulation of a set of hypotheses and creation of development process and information models.
- Chapter 8 presents a set of hypotheses that together with the existing knowledge base form a manufacturing system development theory. This theory is also validated in a "semi-fictive" industrial case. Also a manufacturing system development process with a corresponding toolbox is presented.
- Chapter 9 presents an information model for manufacturing system development based on the theory developed in Chapter 8. This information model is then harmonized with the STEP-standard and implemented as a RDF-schema.
- Chapter 10 briefly discusses some aspects of the presented research results and the applied research method. Here, directions for further research are indicated and the thesis is concluded.

2 SCIENTIFIC APPROACH

2.1 Introduction

In this chapter, methodology employed during the course of research presented in this thesis is discussed. A researcher's task is to do research and a basic professional skill that a researcher must be able to demonstrate its understanding of science and properties of scientific theories as well as mastering the application of research methodology. Furthermore, in order to be able to make reflections about validity and implications of a research result, a reader of a scientific report must understand writer's attitude towards scientific work as well as his/hers methodological framework.

2.2 Engineering Science and its Methodological Implications

The world around us consists of various creations of nature that, in similarity to ourselves, obey the natural laws. Within the boundaries of possibility set by these laws, humans are allowed to create artifacts, which are made to fill some purpose as specified by their creator. Such artifacts are often referred to as products and their creators are often referred to as engineers. When creating products engineers apply various technologies. These technologies, which provide effects needed in order to employ functions of the created product, are applications of natural phenomena.

Now, products are embodiments of functions and these functions are desired by an intended user of the product. In order to be able to create a product an engineer must understand requirements, which are indirectly or directly set by all the stakeholders of the product, e.g. users, shareholders, authorities.

Shareholders are interested in profit maximization as an effect of selling the product. Authorities are interested in increased welfare through, e.g. higher economic growth as a result of producing and using the product or creation and maintenance of a sustainable living environment. Users are interested in satisfaction of a certain functional need. Such functional needs might be of an emotional nature as well. Mårdsjö and Carlshamre (2000) state that a product's user interface can be divided into three categories:

- Functionalistic Perspective, which focuses on the technology and admits the usage.
- Usage Perspective, which focuses on the assignment and helps the user to perform something within certain boundaries.
- Societal Perspective, which focuses on the social context that stimulates the intended users to desire, use and understand the product in a greater whole.

Furthermore, besides awareness and understanding of stakeholder requirements an engineer must have knowledge of how the various requirements are transferred into products.

According to Simon (1996), natural science is concerned with the generation of knowledge about natural objects and phenomena. The engineered objects, as described above, differ from the natural objects by being the results of human intentions and needs. Engineering science, is thus studying the principles of creation and application of technology, which results in various products. A possible implication of such a view on engineering science is the conclusion that engineering science exists in the borderland between the natural science and human as well as social science. Another example of such a "borderland-science" is medical science, which also bridges natural and human sciences.

Figure 7 shows engineering science as a "borderland-science" that consists of study of technology creation and study of technology application. The boundary between the two perspectives on the engineering science is not drawn with a solid line since these two perspectives are not always easy to distinguish from each other, e.g. the technology creation sometimes results in a new product. A conclusion that can be drawn from Figure 7 and Chapter 1 is that this thesis will focus on engineering science as study of technology application (product development and realization).

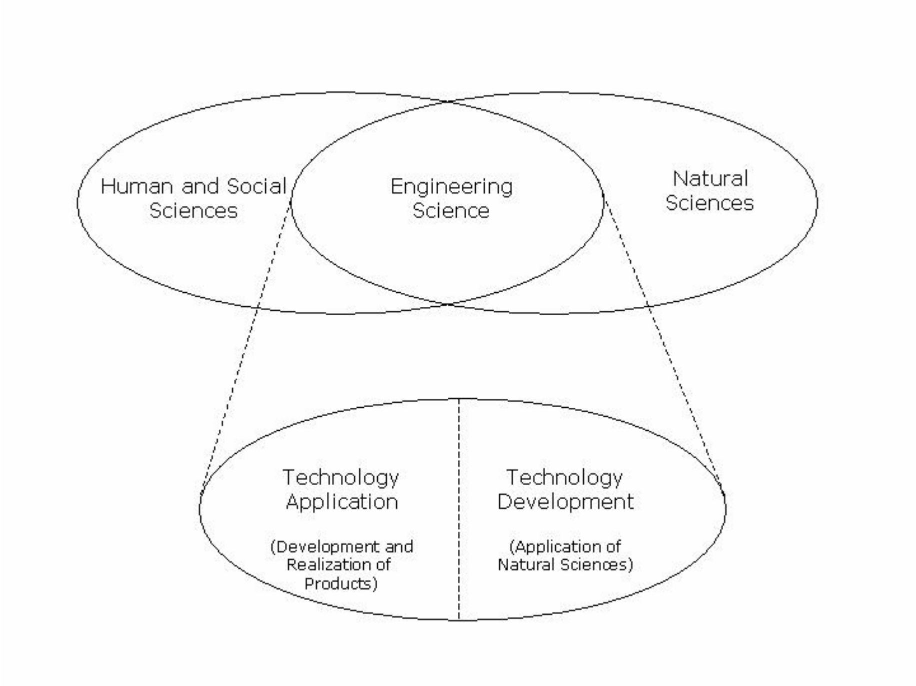


Figure 7: Engineering science as a "borderland-science"

From the discussion above it can be concluded that the context in which products are created and used is a complex socio-technical environment. This implies that creation of research results within the engineering science area should be carried out through utilization of a unified research methodology consisting elements from research methodologies applied in both natural and human/social sciences.

But, do these different scientific disciplines have similar views on science? Although they share many opinions about the nature of science and use similar methodological frameworks, two scientists from different fields do not always regard each other as dignified practicians of the art of science. Physicist Richard P. Feynman has said:

Because of the success of science, there is, I think, a kind of pseudoscience. Social science is an example of a science which is not a science; they don't do [things] scientifically, they follow the forms – or you gather data, you do so-and-so and so forth but they don't get any laws, *they haven't found out anything.* Feynman (2001)

However, even if this kind of emotion-loaded utterance is very common among the members of scientific communities, a premise taken in this thesis is that, regardless of what the object of a research study is, there is a methodological framework that can help the researcher to structure the study and to present the results to the public. The "enlightened" public will in its turn make the conclusion whether the presented results are acceptable or not. A unified methodology, which has been used throughout the research presented in this thesis, will be presented in sections 2.3 and 2.4.

2.3 A Scientific Theory and Research Methodology Framework for Engineering Science

Fagerström and Moestam Ahlström (2001) illustrate a comprehensive map of the relationship between elements of a scientific theory-building process in a general model of scientific research presented in Figure 8.

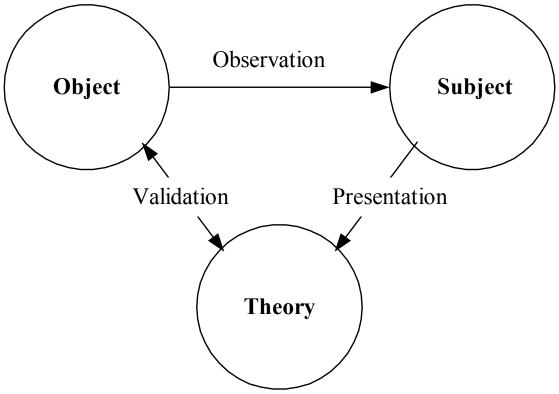


Figure 8: The model of scientific research, Fagerström and Moestam Ahlström (2001)

In this model Fagerström and Moestam Ahlström present a set of nouns and verbs that represent the elements of a research process:

- Nouns:
    - Object – physical things, processes and behaviors observed in the real world.

    - Subject – the researcher who performs the observation, analyzes the data and presents the theory.
    - Theory – the result of the research activity that answers the research questions.
- Verbs:
    - Observation – the collection of data about the object, a scientific tool.
    - Presentation – the result of data analysis performed by the subject and description of used research method.
    - Validation – the securing of consistency between the presented theory and relevant objects.

In sections 2.3.1-2.3.5, fundamental issues of scientific research, as applied during the course of research presented in this thesis, are going to be discussed. Section 2.3.1 will deal with discussing the concept of scientific theories, while section 2.3.2 will focus on the relationship between objects and subjects in the context of observations. Section 2.3.3 will treat the issue of theory building, presentation, and -validation through definitions and –tests of hypotheses. Section 2.3.4 will modulate the issue of theory building, presentation, and -validation by placing it in the context of complex theoretical systems. Section 2.3.5 will discuss the presented concepts from an interdisciplinary perspective, i.e. human/social sciences and natural sciences. An activity model for scientific research in the field of engineering science will thereafter be presented in section 2.3.6.

2.3.1 Theories

2.3.1.1 Universal Statements

According to Popper (1959), scientific theories are systems of universal statements about the world around us. These universal statements are laws, which are always regarded to be valid within the scope of the theory that they are a part of. Theories can be used to explain the world as well as to explain and predict events and consequences of events, which occur in the world.

Chalmers (1995) presents an example of a universal statement:

When a ray of light beams from a medium into another one, it shifts its direction so that sine of angle of incidence divided by sine of angle of refraction is a constant property for both media.

2.3.1.2 Truthfulness of Scientific Theories

Theories are reflections of our belief in a relationship between certain properties of the world. When we believe something, we assume that something is true. Hartman (1999) presents three views on what the truthfulness of a universal statement should be determined by:

- Its correspondence with events that occur in the world.
- Its coherence with other universal statements in the theory.
- Its usefulness in solving the "real-world" problems.

Theories are thus creations that help us to understand certain aspects of the world and to control the certain events in the world to result in wanted consequences. They are not to be regarded as being universal and objective truths. This point is also illustrated by dramatist Michael Frayn, who in his play "Copenhagen" made an attempt to reproduce a discussion between two giants of physics Niels Bohr and Werner Heisenberg. Bohr reflects over the theories' connection to reality:

It starts with Einstein. He shows that measurement – measurement, on which the whole possibility of science depends – measurement is not an impersonal event that occurs with impartial universality. It's a human act, carried out from a specific point of view in time and space, from the one particular viewpoint of a possible observer. Then, here in Copenhagen in those three years in the mid-twenties we discover that there is no precisely determinable objective universe. That the universe exists only as a series of approximations. Only within the limits determined by our relationship with it. Only through the understanding lodged inside the human head. Frayn (1998)

This issue of observations' theory-dependence and inconstancy of the scientific truth will be further discussed in sections 2.3.2-2.3.4.

2.3.1.3 Models

As tools that help us to understand certain aspects of the world, theories are often regarded as models. Hartman (1999) defines a model as a simplified representation of a domain that aims to express a domain's content and relationships between elements of the content. Føllesdal et al (1993) add that the representation contains only properties that are important for the purpose that the model is going to be used for, while all other properties are excluded. Føllesdal et al (1993) also claim that all theories are models while all models are not to be regarded as theories; only models that are expressed in natural language or by mathematical symbols may be regarded as theories. Mechanical or electrical models can be used to simulate a reality from a certain perspective and thus can be used to explain implications of a theory or to create an artificial world where experiments can be performed while the theory that lies behind is consisted of universal statements expressed in natural language or mathematical formulas.

2.3.2 Observations

2.3.2.1 Singular Statements

Besides universal statements (cf. Section 2.3.1.1), Popper (1959) discusses singular statements. A singular statement states the fact that a certain phenomenon has occurred in a certain space-time region. Singular statements can be explained by universal statements.

Chalmers (1995) presents an example of a singular statement that can be explained by the universal statement on light refraction, which was presented in the previous section:

When that stick is partially sunken in the water, it appears to be bended.

Popper (1959) claims that occurred events, which are referred to by singular statements must be inter-subjectively observable. In other words, a singular statement may be regarded as an observation statement. This observation must be possible to be re-performed by a different subject. A subject is also referred to as a researcher, a person who performs the observation. Here, it is important to be aware of the fact that an observation, as a perceptual experience is not to be regarded as objective – standing free from all pre-assumptions. Observations are set-up, carried out, and interpreted in the light of a background theory; all the observations are theory dependent. Chalmers (1995) argues that all singular statements (observations) are presented in a language that is tied to a certain theory and that a well-defined theory is prerequisite for precise singular statements. Chalmers also points out the risk that unreliable theories can lead to omission of important observation data. The only way to compensate for this risk is to be aware of it.

It is possible to conclude that observations, presented as singular statements, are often carried out in order to test universal statements (theories). This relationship will be discussed in more detail in section 2.3.3.

2.3.2.2 Hermeneutics

So far, the relationship between observations and statements about observational findings has been discussed. An interesting question is that about the relationship between the object of observation and the subject that is observing it. In engineering science, researchers deal with elements of socio-technical environments, which are objects and context of observation. When observing complex objects as persons, their actions, and products of their actions, subjects get into a process of continuous interpretation and gradually increased understanding of observed facts.

According to Andersen (1994), this observational attitude that aims towards understanding of human sphere of existence through interpretation is a part of a scientific research strategy, which is called hermeneutics. An inherent characteristic of hermeneutic research is continuously improved understanding of observed objects through gradual adjustment of subject's pre-assumptions as a result of previous observations and interpretations. Andersen calls this way of conducting research through incrementally refined understanding of observed object for "the hermeneutic circle" (cf. Figure 9).

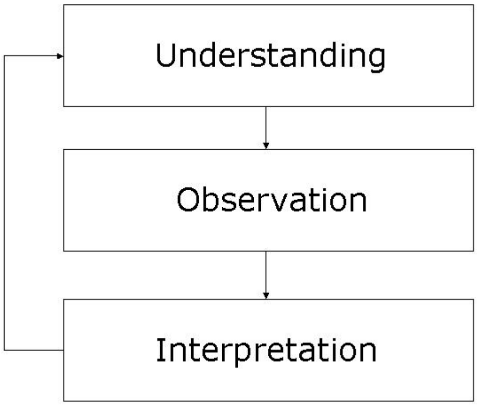


Figure 9: The Hermeneutic Circle

2.3.2.3 Case Studies

When conducting observations the subject needs to develop and apply a suitable investigation strategy. Yin (1994) presents the concept of case studies. Case studies are especially suitable for studying complex phenomena, often social ones, where research objectives are expressed as "how" and "why" questions about research objects. Case studies can be designed as single case studies or multiple case studies (several objects subjected to similar study).

The following procedure, based on the concept of case studies as presented by Yin (1994), may be a suitable approach for conducting observation of socio-technical research objects:

1. Identify the problem within the existing body of theory.
2. State the case study questions.
3. Select an engineering assignment together with the partner company, i.e. the research object container.
4. Propose answers to the case study questions or state formal hypotheses (cf. Section 2.3.3) that can be tested within the study.
5. Perform the observation, i.e. collect the evidence by interviews, documentation study, study of archival records, study of physical artefacts, direct observation, and/or participant-observation.

6. Map the evidence to the propositions (cf. step 4) and interpret the findings.
7. Present the conclusions.

2.3.3 Hypotheses

2.3.3.1 Induction and Deduction

According to Popper (1959), a singular statement can be explained by a universal statement, but universal statement can never be induced from a singular statement and claimed to be true. No matter how many observations of a phenomenon that researchers can perform, it is not possible to be completely certain that the phenomenon will occur in the next observation. Therefore, a universal statement can be put up on the basis of observations or theoretical predictions, but it can never be verified. It can be falsified or corroborated but never verified.

Consequently, universal statements are assumptions that are always subjected to rigorous tests, which aim to either falsify the statement or corroborate it. According to Hartman (1999) a universal statement that is an assumption subjected to a test is called a hypothesis. Hypotheses are tested through deduction, i.e. from a hypothesis (universal statement) and initial conditions (singular statements) consequences (singular statements) are derived.

2.3.3.2 Testing of Hypotheses: Falsification

Hypotheses must be formulated so that they can be falsified. While a hypothesis sustains all the falsification-attempts it is regarded as the best description of the world for the time being. When a hypothesis is falsified, it must be replaced with a better one, which in its turn gets subjected to rigorous tests. According to this view, the only way for science to advance is through actively searching for contradictions between events in the world and our apprehensions of it, and thereafter resolving them while creating a new conflict that is to be found, and so on.

Consequently, Popper (1959) gives two methodological rules for scientific research:

1. *The game of science is, in principle, without end. He who decides one day that scientific statements do not call for any further test, and that they can be regarded as finally verified, retires from the*

game.

2. *Once a hypothesis has been proposed and tested and has proved its mettle it may not be allowed to drop out without "good reason". A "good reason" may be, for instance: replacement of the hypothesis by another which is better testable; or the falsification of one of the consequences of the hypothesis.*

According to Chalmers (1995) a hypothesis is falsifiable if there exists a logical possible observation expressed in a corresponding singular statement, or set of singular statements, which is incompatible with the hypothesis.

Føllesdal et al. (1993) present a common procedure for testing hypotheses by first stating a hypothesis (H), then making a prediction on hypothesis' empirical consequence (E), thereafter performing the observation, and finally comparing the result of the observation with predicted empirical consequences. If the observation corresponds with the empirical consequence, then the tested hypothesis is regarded as corroborated, if there is no correspondence, the hypothesis is falsified. This can be also written as:

If H, then E

not E (observation)

---

not H

2.3.3.3 Definition of Hypotheses

Now, how should a hypothesis be formulated in order to be falsifiable/testable? It is important to remember that a hypothesis is a universal statement and not a singular statement. Singular statements are sometimes called existential statements, which are also referred to as "there-is" statements. In other words, a singular statement may claim that a certain phenomenon exists in the world. Here, a singular statement may refer to an observation. According to Popper (1959), when a universal statement is formulated as a "there is" statement and it is supported by an observation it is impossible to falsify it and the science cannot continue its development from that point. Such a statement is not a hypothesis, but an observable fact, a singular statement. If a universal statement is formulated as a “there is” statement and it is not supported by an observation it is impossible to search the entire universe in order to establish that something does not exist, has never existed, and will never exist. Therefore, universal statements formulated as “there is” statements cannot be falsified and thus are not to be regarded as testable. Generally, it is better to formulate universal statements, which claim that something does not exist, that something is prohibited. Natural laws, for example, are formulated as rules that restrict possible courses of events in the world. When formulated in that way a hypothesis can always be tested and falsified (or corroborated) by an observation.

Furthermore, if a certain hypothesis claims something about a wider section of the world it is more falsifiable than a hypothesis, which claims something about a narrower section of the world. Chalmers (1995) exemplifies this with two hypotheses among which the second one is more falsifiable and thus has a higher scientific status:

1. *Mars moves around the sun in an elliptic trajectory.*
2. *All planets move around their sun in an elliptic trajectory.*

It is sufficient to find a single planet that does not shows similar behavior to falsify the second hypothesis. In fact, falsification of first hypothesis in the example above, falsifies also the second one. Popper (1959) claims that falsifiability of a hypothesis is determined by the amount of its potential falsifiers. Knudsen (1994) illustrates this idea in Figure 10. According to Knudsen, the larger potential falsification area of a hypothesis is, the higher information content it has and the higher is its scientific significance.

In other words, an objective when defining a hypothesis is to try to gain as exact information about the world as possible, to test the limits, and to drive the science towards higher precision. One way to achieve such an objective is through creating hypotheses that do not lose their scientific significance and do not compromise with our thirst for knowledge, by desperately constructed robustness through ambiguous definitions. Chalmers (1995) points out that considerable scientific progress is achieved when a bold hypothesis is corroborated or a cautiously formulated hypothesis is falsified.

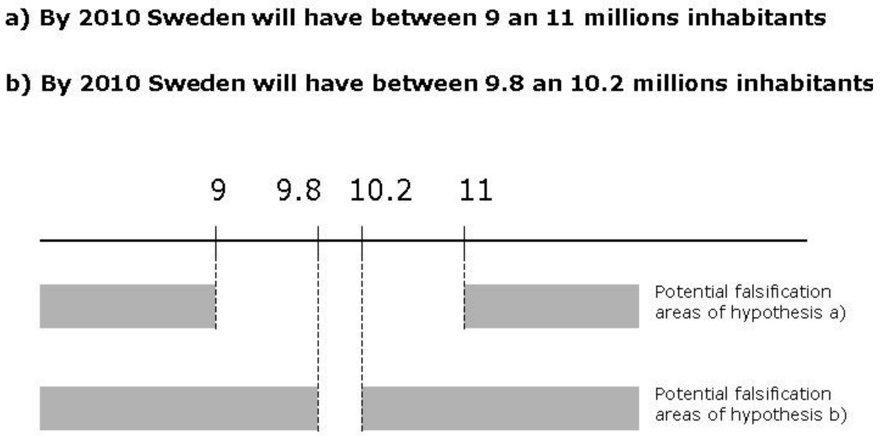


Figure 10: Comparison of potential falsification areas for two hypotheses a) and b) (adapted from Knudsen (1994))

2.3.3.4 Auxiliary Hypotheses

However, it is still possible to evade falsification of a hypothesis by supporting it with one or several auxiliary hypotheses. Auxiliary hypotheses are sometimes called "ad-hoc" hypotheses if their only purpose is to defend a hypothesis while not having any testable consequences of their own. According to Popper (1959) an auxiliary hypothesis is not "ad hoc", and is thus valid, only if it is independently testable. A valid auxiliary hypothesis must increase the degree of falsifiability/testability of the theory system in question instead of diminishing it. Johansson (2000) claims that an auxiliary hypothesis helps in deriving the observation consequences of the main hypothesis that is going to be tested. Auxiliary hypotheses are assumed to be true when a test of main hypothesis is being conducted.

According to Føllesdal et al. (1993), if an observation do not corroborate a hypothesis, it is not always true that the tested hypothesis is false. Falsity can be attributed to one or several auxiliary hypotheses (AH). In other words:

If H, AH_1, AH_2, …, and AH_n, then E

not E (observation)

---

not H, AH_1, AH_2, …, and/or AH_n

2.3.4 Theory Building: Theoretical Systems

Principles of hypothesis tests, presented in the section 2.3.3, are somewhat simplified. When a researcher deals with hypothesis definition and testing he/she usually navigate in a complex theoretical system. This theoretical system is built up of a number of universal statements, which are used as prerequisites for that certain researcher's scientific work. This working method is illustrated in a quotation by Sir Isaac Newton:

If I have seen further, it is by standing on the shoulders of giants.

When Albert Einstein two centuries later presented his theory of relativity, which falsified some of universal statements set by Newton he had to struggle against both Newton and the giants on whose shoulders Newton was standing as well as the giants that were standing on Newton's shoulders. In other words, even with convincing evidence, it is hard for a single scientist to confute established theories.

2.3.4.1 Paradigms in Science

A single scientist, who succeeds in falsifying a universal statement or a set of universal statements on which a great amount of contemporary research rests, contradicts, what Kuhn (1992) calls, a paradigm. Such a paradigm may be comprised of e.g. values and attitudes, terminology, universal statements, research methods and deduction methods. Usually, it is needed more than a single falsification of a universal statement/hypothesis to introduce a new paradigm. Such transfer, according to Kuhn (1992), starts with a crisis, i.e. a number of falsifications of significant universal statements, and ends with a scientific revolution and introduction of a new paradigm. Kuhn states that the development of every scientific discipline begins with a pre-scientific period, continues with a normal scientific period (i.e. a paradigm), crisis and revolution, new normal scientific period (i.e. a new paradigm), new crisis and revolution, and so on.

2.3.4.2 Research Programs

The concept of complex theoretical systems is also discussed by Lakatos (1974). According to Chalmers (1995), Lakatos generally regards theories as structural wholes, in which universal statements are partially meaningful in relationship to each other and not only in relationship to the “reality” (cf. section 2.3.1.2). These structural wholes expose their empty spots and give clues on what research efforts should be directed. Lakatos denominates these structural wholes as research programs. Research programs have similar content as Kuhn’s paradigms, e.g. terminology, universal statements, and observation methods (e.g. experiments, case studies, hermeneutic circle)

According to Lakatos (1974), a theory is consisted of a hard core of universal statements, which is not allowed to be questioned or rejected. The core is embedded in a system of “non ‘ad-hoc’” auxiliary hypotheses, which protects the core from falsification. This uncritical feature is termed a research program’s negative heuristics. If a researcher modifies the hard core and persist in committing to the modification, he/she is not longer a part of the research society that works on that program. He/she has therewith declared a new research program.

A research program’s positive heuristics consists of coarse guidelines on how a theory should develop, i.e. how the hard core should be supplemented towards better practical application or a higher level of completeness.

A consequence of applying research program approach as described above, is that a carefully constructed complex theoretical system cannot be falsified by a single observation. Singular statements can, off course, falsify a universal statement, but it is important to make sure that the singular statement of interest does not represent an invalid observation or invalid interpretation of observation. When a concept of research programs is adapted, it is possible to commit to and develop a useful complex theoretical system, which rests on well-defined core of universal statements, where every falsification is extremely carefully examined before acceptance. Moreover, a falsification here must result in a very concrete improvement; is not accepted until an alternative, better hypothesis is corroborated and the science has therewith taken a significant step forward.

2.3.5 An Interdisciplinary Approach to Scientific Research

Research methodology, which research work presented in this thesis is based on is by a great extent based on theories by philosophers Karl Popper, Thomas Kuhn, and Imre Lakatos. These three philosophers are regarded to belong to a school in philosophy of science, called falsificationalism. Falsificationalism is mainly based on studies of physics and is therefore often regarded as the scientific basis of natural sciences.

However, the idea of progress through interaction between contradictions, the very soul of falsificionalism, was widely spread among scientists in various branches during the course of history. This ideological feature is significant for scientific contributions by e.g. ancient Greek philosopher Herakleitos, German philosophers and social scientists Friedrich Hegel and Karl Marx as well as engineering scientist and the creator of the well-known artifact concept generation method TIPS (Theory of Inventive Problem Solving), Genrich Altschuller. Moreover, application of falsificationism in advancement of the field of economics is discussed by Knudsen (1994).

Observations play a central role in natural sciences and the falsificaionalsm. Observations through case studies (Yin (1994)) are mostly performed in social sciences while the inherent hermeneutic mechanism of observation (Andersen (1994)) originates from human sciences and is also frequently applied in social sciences. Approach to observation through case studies and hermeneutics as well as theory building, hypotheses definitions and -tests based on falsificionalism are most important characteristic of the research work in the field of engineering science as presented in this thesis

2.3.6 Activities During the Course of a Scientific Research Study

Now, having the issues discussed in previous sections in mind, how should a research study be performed? In Figure 11, an activity model for scientific research in the field of engineering science is presented.

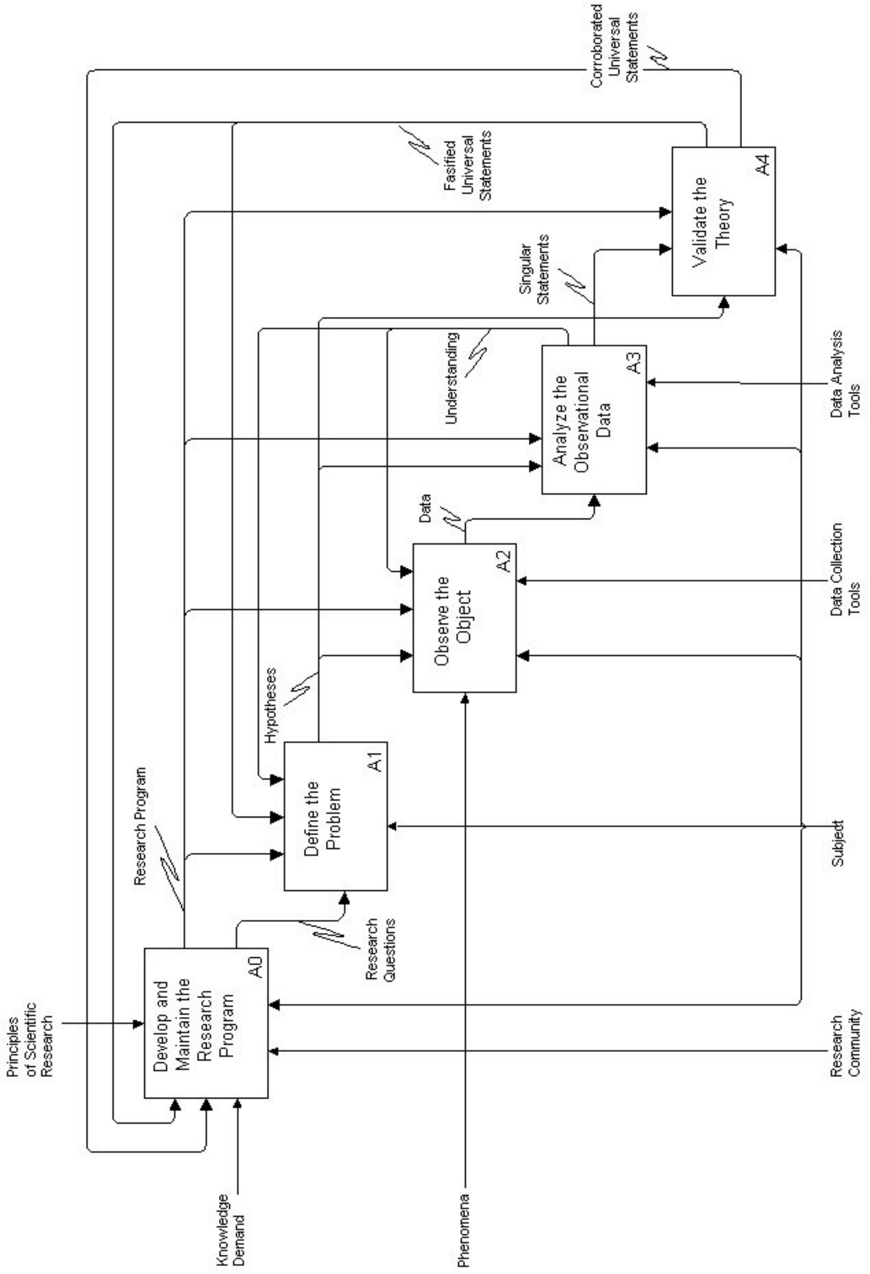


Figure 11: Scientific Research Activity Model

Activities A1-A4 are to be regarded as some of the ingredients of the activity A0. Two main flows of data are found:

- *Knowledge Demand – Research Questions – Hypotheses – Corroborated/Falsified Universal Statements*
- *Phenomena – Data – Singular Statements*

Furthermore, two other important data types are depicted in the model, namely *Research Program* and *Understanding*. *Research program* controls the research activities through accepted terminology and universal statements as well as guidelines regarding the case study methodology and hermeneutic method. *Understanding* is a product of observation and interpretation of data according to the hermeneutic method. *Understanding* is used to aid the continued observation as well as hypotheses (re)definition.

2.4 Emergence of This Thesis

Setting out from the scientific theory and research methodology presented in Section 2.3, how can emergence and presentation of this thesis be explained?

This research project has started by defining the research questions based on the knowledge demand from project's sponsors and on the review of research results in the area of industrial development (development processes, concurrent engineering), engineering design theory and development information management. This is briefly presented, among with the research questions, in Chapter 1.

Research questions have resulted in a deeper investigation within several frames of reference (FoRs, cf. Figure 12), i.e. manufacturing systems development, development processes, engineering design theories, and development information management. This, in order to refine the definition of the research problem and formulate hypotheses.

2.4.1 Manufacturing System Development Theory

Two research programs in the area of engineering design (FoR 3 in Figure 12), WDK (Theory of Technical Systems and Theory of Domains) and Axiomatic Design, have been investigated from the perspective of manufacturing system development. This investigation, which led to a system of hypotheses, has been carried out through literature studies and two case studies. The first case study (Case Study 2 in Figure 12) started with study questions and propositions (informal hypotheses) generated as a result from literature study. It then has provided the understanding, which was essential for formulating new study questions and propositions for the second case study (Case Study 3 in Figure 12). Finally, the findings from the case studies resulted in three formal hypotheses. Case study 2 has been concerned with the development of a telecommunication product, Bias-T, and its assembly system. Case study 3 has been concerned with the development of a biotech product, Attana 100, and its manufacturing system.

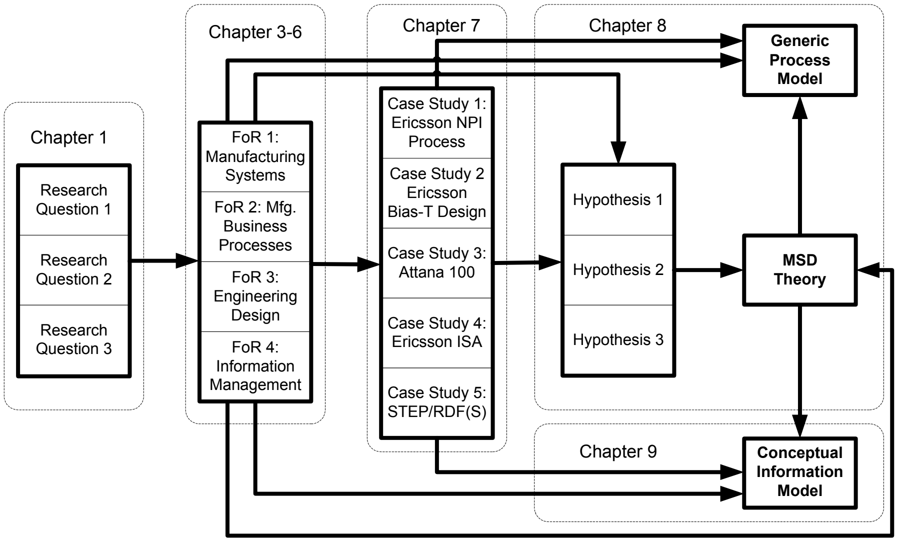


Figure 12: The research procedure

The system of generated hypotheses was then tested in a validation case study and a manufacturing system design theory (MSD Theory in Figure 12) was released. The object of this validation case study was development of a miniature piezoceramic actuator and its manufacturing system. These results are presented in Chapter 8.

2.4.2 Generic Process Model

The investigation, case studies and hypotheses definition in the area of engineering design has also been supported by the literature study in several research programs within the area of manufacturing system development (FoR 1 in Figure 12), e.g. design for manufacturing, operations management, manufacturing process planning. Also a literature study (FoR 2 in Figure 12) and a case study (Case Study 1 in Figure 12) within the research program on development processes has been conducted. The object of this case study was New Product Introduction (NPI) process employed by a telecommunications manufacturer.

Besides supporting the generation and validation of the above mentioned hypotheses the literature studies (FoR 1 and FoR 2) and the case study (Case Study 1) led to the specification of a development toolbox and the creation of a generic development process model (Generic Process Model in Figure 12). The specification of a development toolbox and the creation of a generic development process model were also supported by the findings that resulted in the presented MSD Theory.

2.4.3 Conceptual Information Model

In the area of information management, two research programs have been investigated, standardized representation and exchange of engineering data according to STEP-standard as well as information management by utilization of Semantic Web technology.

This investigation has been carried out through literature studies (FoR 4 in Figure 12) and three case studies (Case Study 2, Case Study 4, and Case Study 5 in Figure 12). Case Study 2 was concerned with studying the harmonization of a generic development information model (based on engineering design theory) with STEP AP214. Case Study 4 was concerned with studying development information system architecture employed by a telecommunications manufacturer. Case Study 5 continued the work started in Case Study 2 and attempted to study harmonization of a generic development information model with STEP AP233. It also studied the implementation of the harmonized information model as a RDF-schema.

The literature study and the case studies helped in representing the information requirements set by the novel MSD Theory in a generic information model for manufacturing system development, its harmonization with STEP AP233, and its implementation as a RDF-schema.

Part II:
Frame of Reference

In this part, the frame of reference for the research presented in this thesis is further elaborated. The relevant literature, related to the different aspects on the research problem, as identified in the introduction chapter in Part I, is presented and a basis for the research results presented in Part III is thereby established.

3 MANUFACTURING SYSTEMS

3.1 Manufacturing Systems Categorization

A manufacturing system consists of manufacturing resources that execute a set of manufacturing processes in order to create a product, which is desired by a customer.

Manufacturing systems can be categorized in various ways. Wild (1995) categorize manufacturing systems by their operating structures into four categories:

a) All products are stocked and the customer is served from a stock of finished goods.

b) No material stocks are held but all products are still manufactured to stock.

c) Material is stocked but products are made only against customer order.

d) There are no stocks in the system and all products are made against customer order.

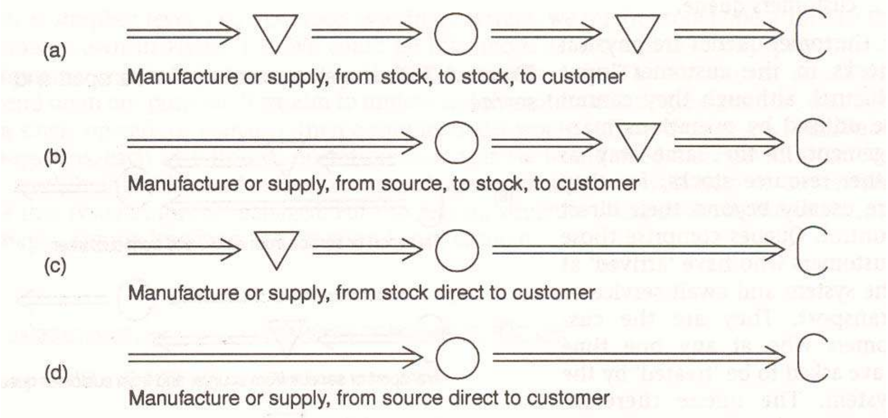


Figure 13: Manufacturing systems categories (for the legend cf. Figure 16), Wild (1995)

Another common way of categorization is by process types based on volume-variety relationship. Slack et al (1998) discuss five categories of manufacturing processes, namely project, jobbing, batch, mass and continuous processes (cf. Figure 14).

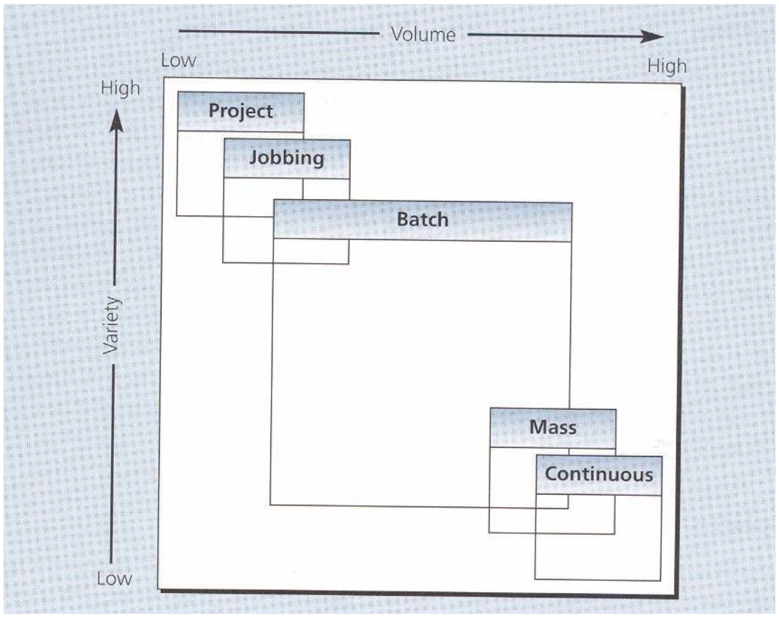


Figure 14: Categorization of process types based on volume-variety relationship, Slack et al (1998)

Project processes are most often concerned with manufacturing large, one-of-a-kind, fixed position products, e.g. bridges or manufacturing plants.

Jobbing processes are similar to project processes, but the manufactured items are usually smaller and are usually produced once, often in a larger quantity than one, e.g. special tools or tickets for the local social event.

Batch processes usually produce a set of similar or identical products, i.e. manufacturing sub-processes and their sequence are repeating themselves during processing of a batch. Typical batch products are machine tools or automotive parts.

Mass processes usually produce large quantities of identical or similar products, e.g. television-sets or frozen food. Sometimes, mass processes can offer a great variety of products while maintaining large total volumes. This type of manufacturing is sometimes termed "mass-customization". Womack et al (1989) show an example of successful "mass-customization" by presenting automobile manufacturing where a customer can choose a custom configuration within a predetermined selection space. These customized automobiles are assembled against the customer order and rapidly delivered to the customer. The manufacturing system here operates without finished goods stock and with negligible material and intermittent stocks (type d structure in Wild (1995)). According to Womack and his colleagues, even the suppliers of parts to this automobile manufacturer operate the "type d" manufacturing system. The manufacturing in this system of manufacturing systems is trigged by customer orders and reliable forecasts. This type of manufacturing is sometimes termed "Just-In-Time" (JIT) and is controlled by the so-called "kanban"-principle. According to Shingo (1984) a JIT-manufacturing system is characterized by the fact that every manufacturing sub-process is provided by right input material, in right quantity at the right time. Kanban is here a mean for achieving JIT-manufacturing.

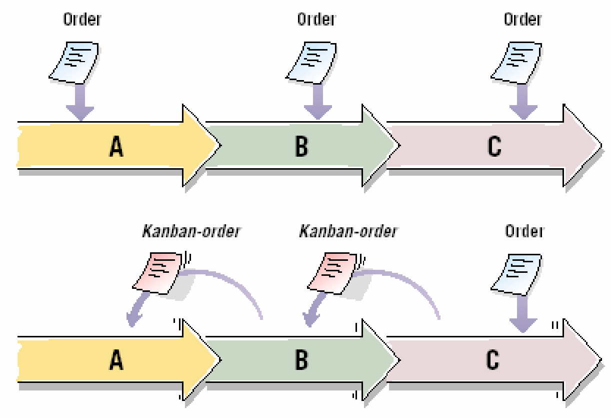


Figure 15: The Kanban-koncept, Aganovic and Jonsson (2001)

Finally, continuous processes operate for long periods of time manufacturing inseparable products in a continuous flow, e.g. electricity or chemicals.

As stated in the introduction section, this thesis is concerned with the methodology for development of smaller assembled electromechanical products, which means that only batching and mass processes are within the scope of this thesis. Therefore, all further discussion will be concentrated on that type of manufacturing systems.

3.2 Manufacturing Resources and -Processes

Manufacturing resources use energy to transform material into desired condition by changing its physical or chemical properties. This can be done by either creating discrete parts (e.g. machining, casting, stamping) or merging discrete parts into a more or less complex assembly (e.g. surface mount assembly, joining).

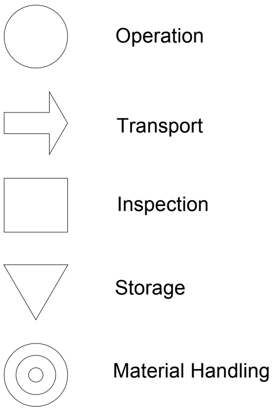


Figure 16: Process flow chart symbols, adapted from Olhager (2000)

Discrete part manufacturing and assembly are regarded as value-adding processes. But, not all of a manufacturing system’s processes are value adding. According to Olhager (2000), it is evident that besides value adding resources, which change material’s physical or chemical properties, a manufacturing system consists of transportation resources, storing resources, material-handling resources (e.g. loading/unloading a machine), and inspection resources. In process flow charts, the operations performed by these resources are represented by a set of symbols, cf. Figure 16. In Anglo-American literature, the symbol for material handling is not used. Instead the symbol for delay (D) is utilized for representing a queue of objects (input material) waiting for a processing resource to become available. In Olhager (2000), delay is represented by the storage symbol.

When discussing the above mentioned resources one usually thinks about technical artifacts such as NC-machines and industrial robots. However, even human resources are part of a manufacturing system. Human resources can either directly be involved in the execution of a manufacturing process (e.g. manual assembly, manual material handling, visual quality control) or participate by operating and maintaining machines that execute the manufacturing process. Continuous improvements of manufacturing processes as well as order planning activities are often carried out by human resources, Sohlenius (2001).

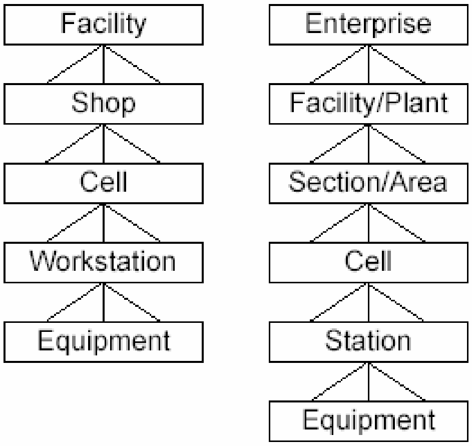


Figure 17: NIST-model (left) and ISO-model (right) for manufacturing systems hierarchy, adapted from Bauer et al. (1991)

Execution of order planning activities is usually supported by an information system that implements the function of Enterprise Resource Planning (ERP). Control of manufacturing lines and machines is in most cases executed by using information systems called Manufacturing Execution Systems (MES) and various controllers such as Programmable Logical Controllers (PLC), robot controllers, and Computerized Numerical Controllers (CNC), Aganovic and Jonsson (2001).

Machines, humans and information systems are types of resources that manufacturing systems are constituted of. These resources are often parts in a complex system. In order to be able to better understand and thus have possibility to easier develop, control, and maintain such a complex system, manufacturing systems can be organized in formal hierarchies. Bauer et al. (1991) presents two standardized hierarchies, NIST- and ISO-model (cf. Figure 17).

3.3 Relationship Between a Product and its Manufacturing System

It has already been stated in the Section 3.1 that the primary aim of a manufacturing system is to execute manufacturing processes, which transform material into products that are desired by manufacturing systems' customers. In Chapter 4, some product design approaches and their applicability on manufacturing systems design will be discussed. In order to support that future discussion and in order to be able to understand manufacturing systems design in the context of concurrent engineering some general issues concerning the relationship between products and manufacturing systems must be highlighted. In this section, this coupling will be discussed from the perspectives of four related knowledge areas.

But first, is there any fundamental difference between a product and a manufacturing system? A manufacturing system is a technical artifact with an intended function, a product of its own, and from a general point of view there is no fundamental difference between a product and a manufacturing system. Some people would object to this statement by claiming that manufacturing systems do comprise human beings while products do not. Nevertheless, human beings are, like all other resources in a manufacturing system, function carriers. When a human being is directly involved in transforming material into products (processing, transport, inspection, material handling) he/she is, like a machine, carrying fundamental functions of a manufacturing system. In cases where humans are not directly involved in transforming material into products they either operate machines and information systems or they make management decisions, i.e. they operate human resources in a manufacturing system. In other words, in same manner as they operate products (e.g. making a call with a mobile phone), humans can operate resources in a manufacturing system.

Manufacturing systems design is, however, a very complex activity. When developing a product a designer is concerned with creating a technical artifact that is going to be able to transform an operand, e.g. a pocket calculator transfers signals that represent the definition of a mathematical function and its inputs into signals that represent that function's outputs and presents them on a display. Accordingly, a manufacturing system designer is creating a (socio-) technical artifact that is going to be able to transform input material into products, e.g. an assembly system transfers components into pocket calculators. An important issue to consider is that a manufacturing system designer must carry out development of a technical artifact concurrently with the development of the operands, which are going to be transformed by the artifact.

3.3.1 Process Planning and Manufacturing Capabilities

The relationship between a product and its manufacturing system is determined in a process plan. According to Chang and Wysk (1985) a process plan usually contains the information about manufacturing process sequence for a product, processes, process parameters, and machine and tool selection. A process plan provides all necessary instructions for manufacturing of a product. These instructions dictate the cost, quailty, and rate of production. Accordingly, Chang and Wysk define process planning as a function that establishes which machining processes and parameters (as well as machines capable of performing those processes) should be used to convert a piece part from an initial form into a final form predetermined in the product drawing.

Chang and Wysk (1985) assume that a detailed product design specification exists prior to beginning of the process planning activity. Same assumption is made by Kayacan and Celik (2003) in their work on process planning system for prismatic parts. According to Feng and Song (2000), this assumption is very common in the process planning research community. Feng and Song (2000) claim that the focus of the process planning research community is primarily on machining feature recognition, fixturing and setup parts, and detailed NC tool-path generation, while research on conceptual process planning is still in an infancy stage.

However, the detailed nature of process plans may help in better understanding the relationship between products and manufacturing systems. Chang and Wysk (1985) mentioned the selection of machines capable of performing certain manufacturing processes. The capabilities of a manufacturing resource are determined by products it is dedicated to make. Analogously, properties of a product are determined by the capability of its manufacturing system.

Magrab (1997) categorizes product-properties, which are closely related to the manufacturing system capabilities as: surface condition, dimensional accuracy, complexity (shape, form), production rate, cost, and size.

According to Chang and Wysk (1985) manufacturing system capabilities can be expressed in terms of:

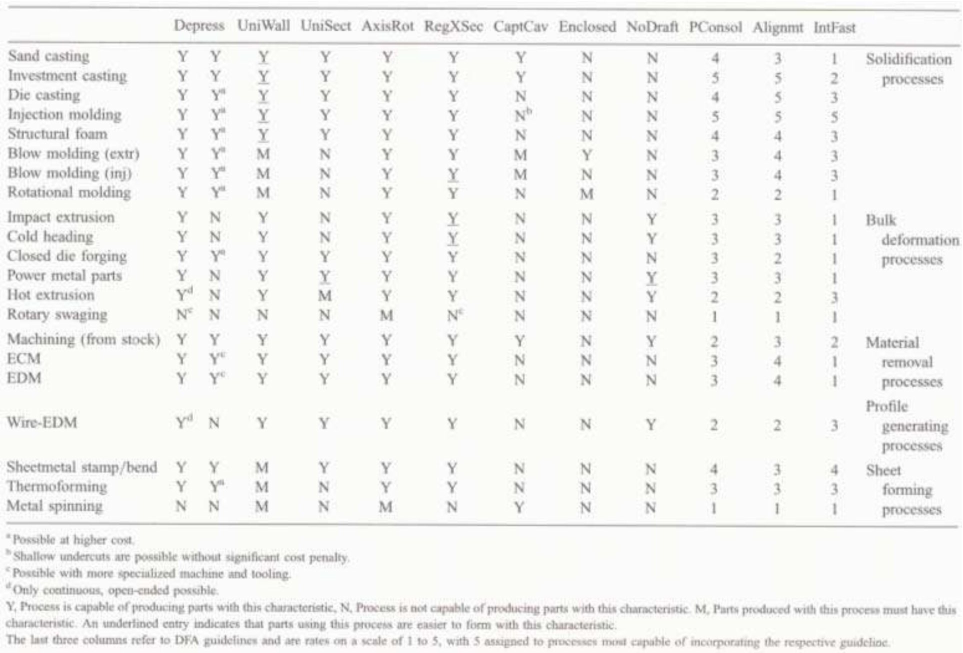
- The shapes and size a manufacturing process can produce
- The dimensions and geometric tolerances that can be obtained
- The surface finish attainable
- The material removal rate
- The relative cost
- Other cutting characteristics/constraints

Information about manufacturing capabilities is available in a wide range of handbooks. For example, Boothroyd et al (2002) discuss and categorize shape-generating manufacturing process capabilities:

- Depressions, i.e. the ability to form recesses or grooves in the surfaces of the part.
- Uniform Wall, i.e. ability to create walls of uniform thickness.
- Uniform Cross Section, i.e. ability to create parts where any cross section normal to a part axis is identical (excluding draft).
- Axis of Rotation, i.e. ability to create shapes by rotation about a single axis.

- Regular Cross Section, i.e. ability to create cross sections of a regular pattern (e.g. hexagonal shaft).
- Captured Cavities, i.e. ability to form cavities with re-entrant surfaces.
- Enclosed, i.e. ability to form hollow and completely enclosed parts.
- Draft-free Surfaces, i.e. ability to form constant cross sections in the direction of tooling motion.

Boothroyd et al (2002) use these capability categories to evaluate a range of commonly used manufacturing processes (cf. Figure 18).



	Depress		UniWall	UniSect	AxisRot	RegXSec	CaptCav	Enclosed	NoDraft	PConsol	Alignmt	IntFast	
Sand casting	Y	Y	Y	Y	Y	Y	Y	N	N	4	3	1	Solidification processes
Investment casting	Y	Y	Y	Y	Y	Y	Y	N	N	5	5	2	
Die casting	Y	Y^a	Y	Y	Y	Y	N	N	N	4	5	3	
Injection molding	Y	Y^a	Y	Y	Y	Y	N^b	N	N	5	5	5	
Structural foam	Y	Y^a	Y	Y	Y	Y	N	N	N	4	4	3	
Blow molding (extr)	Y	Y^a	M	N	Y	Y	M	Y	N	3	4	3	
Blow molding (inj)	Y	Y^a	M	N	Y	Y	M	N	N	3	4	3	
Rotational molding	Y	Y^a	M	N	Y	Y	N	M	N	2	2	1	
Impact extrusion	Y	N	Y	N	Y	Y	N	N	Y	3	3	1	Bulk deformation processes
Cold heading	Y	N	Y	N	Y	Y	N	N	Y	3	3	1	
Closed die forging	Y	Y^a	Y	Y	Y	Y	N	N	N	3	2	1	
Power metal parts	Y	N	Y	Y	Y	Y	N	N	Y	3	3	1	
Hot extrusion	Y^d	N	Y	M	Y	Y	N	N	Y	2	2	3	
Rotary swaging	N^c	N	N	N	M	N^c	N	N	N	1	1	1	
Machining (from stock)	Y	Y	Y	Y	Y	Y	Y	N	Y	2	3	2	Material removal processes
ECM	Y	Y^c	Y	Y	Y	Y	N	N	N	3	4	1	
EDM	Y	Y^c	Y	Y	Y	Y	N	N	N	3	4	1	
Wire-EDM	Y^d	N	Y	Y	Y	Y	N	N	Y	2	2	3	Profile generating processes
Sheetmetal stamp/bend	Y	Y	M	Y	Y	Y	N	N	N	4	3	4	Sheet forming processes
Thermoforming	Y	Y^a	M	N	Y	Y	N	N	N	3	3	3	
Metal spinning	N	N	M	N	M	N	Y	N	N	1	1	1	

[a] Possible at higher cost.

[b] Shallow undercuts are possible without significant cost penalty.

[c] Possible with more specialized machine and tooling.

[d] Only continuous, open-ended possible.

Y, Process is capable of producing parts with this characteristic, N, Process is not capable of producing parts with this characteristic. M, Parts produced with this process must have this characteristic. An underlined entry indicates that parts using this process are easier to form with this characteristic.

The last three columns refer to DFA guidelines and are rates on a scale of 1 to 5, with 5 assigned to processes most capable of incorporating the respective guideline.

Figure 18: Shape generation capabilities of manufacturing processes, adapted from Boothroyd et al (2002)

3.3.1.1 Group Technology

Knowledge about process capabilities can be utilized to describe a set of generic physical features that a manufacturing process is able to generate. This idea is utilized in Group Technology (GT) concept. According to Askin and Standridge (1993) GT can be viewed as an attempt to standardize products and process plans. GT helps product and manufacturing system designers to reuse existing product and process designs by mapping product's geometric features to a set of generic features and manufacturing processes that are able to generate these features. Product designer is then able to start out from a set of generic features that an e.g. existing manufacturing system can produce, when he/she is developing a product. Items with similar geometric features should be manufactured with similar manufacturing processes. Krajewski and Ritzman (2002) state that when GT concept is in use it is possible to group items that have similar geometric features and manufacture them in the same manufacturing process executed by a set of same or similar manufacturing resources. GT is here regarded to be an important enabler for agile cellular manufacturing systems.

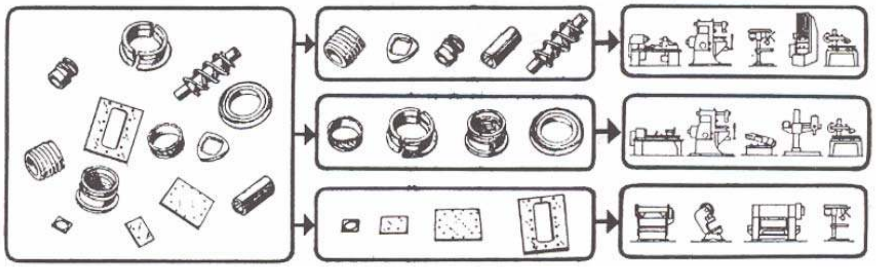


Figure 19: Group technology concept, Andersson et al. (1992)

3.3.1.2 Requirement-Capability Assignment During Operation

The focus on process capability of manufacturing resources have also led to the idea that the coupling between a product's process requirements (e.g. geometrical features) and a manufacturing resource's process capability can be established and utilized during manufacturing system operation, Nielsen (2003). In other words, when a customer places an order, an available manufacturing resource is assigned to producing an individual part if its process capability fits part's process requirements. Since this concept does not rely on manufacturing resources dedicated to creating certain parts, every instance of a part might take a slightly different route through the manufacturing system. Lee and Saitou (2002) use detailed descriptions of product part geometries and utilize geometrical features to create a constraint network of a product, which in turn is used as a blueprint for generation of a process (requirements) plan, allocation of capable resources, and generation of a firing sequence for a set of customer orders.

3.3.2 Capability Variability and Robust Design

Process capability of manufacturing resources maps to process requirements set by the products. If a manufacturing resource has the capability to alter a product feature, i.e. if it satisfies process requirements, it is regarded as suitable and is thus selected as a part of the manufacturing system.

According to Juran (1988), all manufacturing processes exhibit variability. When quantifying manufacturing process capability, the variability of that process must be regarded. Juran (1988), Bergman and Klefsjö (1991), and Magnusson et al (2000) are some of the sources who claim that in manufacturing, capability of a process is related to its standard deviation and to the allowed values of the targeted product feature. Process capability index can therefore be expressed as a quote between a product's tolerance and six standard deviations for the process. Juran states that a widely preferred minimum for the process capability index is 1.33, which means that process capability interval should be no greater than 0.75 of tolerance width for the targeted product feature. Process selection through mapping between product features and process capabilities could then be performed during the manufacturing system design phase by e.g. qualitatively utilizing historic capability data for existing processes, simulating existing processes based on historic capability data or simulating a non-existing process based on process theories expressed in mathematical models.

3.3.2.1 Key Characteristics

Thornton et al (2000) claim that the manufacturing industry is in great need for methods and tools for product and process variation risk management. According to Thornton and her colleagues, the industry needs especially methods that allow systematic brake down of quantitative product characteristics, which are at all hierarchical levels related to manufacturing process capability. This relationship allows for the capability index prediction on all levels of detail in product and manufacturing system design. Lee and Thornton (1996) present a method that focuses on management of the parameters that characterize a product and its manufacturing system. These parameters are called Key Characteristics (KC). The method is a compilation of best practices from the American manufacturing industry, which has resulted in a framework that consists of the KC-definitions as well as the procedures for KC-identification and KC-prioritization. Lee and Thornton (1996) present three categories of KCs:

- Product Key Characteristics (PKC)
- Manufacturing Process Key Characteristics (MKC)
- Assembly Key Characteristics (AKC)

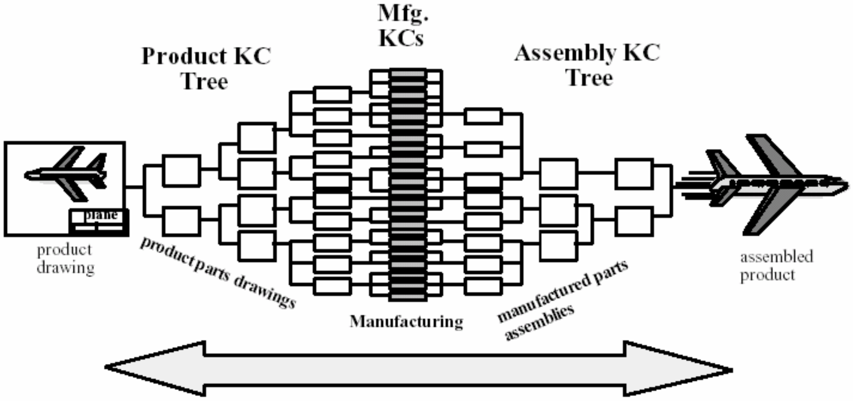


Figure 20: The Key Characteristics Concept, Lee and Thornton (1996)

The KC-method is further developed by Thornton (1999) to contain a mathematical framework for KC-management.

The KC-method focuses on structuring a product by managing the product's critical parameters coupled to the requirements on its performance, function, and form as well as its manufacturing system's critical parameters that can affect the realization of the product's critical parameters. The method provides a possibility to control an important aspect of the coupling between products and manufacturing systems. A delimitation of the method is that MKCs and AKCs are not unambiguously coupled to products, manufacturing processes or manufacturing systems.

3.3.2.2 Design of Experiments and Taguchi Method

When developing complex products and/or manufacturing systems, the relationship between product features and manufacturing process capabilities might be difficult to identify. Juran (1988) claims that establishment of relationships between multiple variables of a complex process and the associated product features, requires designed experiments.

Bergman (1992) presents the concept of designed experiments. The main idea is that in a designed system, a set of variables, i.e. system input (e.g. manufacturing process variables) impact on system output (e.g. product feature values). By designing a set of experiments with planned changes in input variables, it is possible to deduce cause-effect relationships in a system. Understanding of the relationship between inputs and outputs of a system might provide the ability to optimize the system performance in terms of maximizing or minimizing system output. In a designed experiment various system inputs are combined and the system output is measured for every system input combination. Even the interplay between two or more inputs might impact the system output, i.e. when the effect of an input depends on some other input's value.

Since the number of system inputs might be very large it is often not possible to perform the so-called "full factor" experiments. In such a case the "reduced factor" experiments are performed.

Taguchi (1993) applies the concept of designed experiments to create products and manufacturing processes insensitive to variation by elucidating the relationship between input signals (system inputs), noise factors, and output response (system output). The function of a robust system that is insensitive to variation must not be affected by noise factors, such as aging or environment. Taguchi proposes usage of two orthogonal arrays, i.e. system input array and noise factor array, which show how the relationship between various system inputs and noise factor impact on system output.

3.3.3 Design For Manufacturing

The relationship between a product and its manufacturing system is sometimes termed manufacturability, which is a qualitative measure that refers to the ease with that a product can be manufactured. Various manufacturability management methods, which are often called DFM or DFA (DFM(A) = Design For Manufacturing (Assembly)) have been developed and presented in Magrab (1997), Subramaniam and Ulrich (1998), Eskilander (2001), and Boothroyd et al. (2002). These manufacturing process-specific methods focus on highlighting certain product and manufacturing system properties that should be controlled in order to minimize manufacturing time and -cost and maximize manufacturing quality.

Manufacturability can be managed through applying various constraints when designing products and manufacturing systems. These constraints might be applied as input to the design activity or might appear during the execution of the design activity. In previous case experiences from earlier projects are formalized in design rules and used as design guidelines, while in latter case the frequent mapping between both design objects must be performed in order to be able to at all times consider the manufacturability issue.

When starting a design activity, not only generic manufacturing process constraints are to be considered as input constraints. A product and its manufacturing system might be on the different levels of completeness. Fagerström et al (2002) describe four different situations:

- new product and new manufacturing system,
- new product and old manufacturing system,
- old product and new manufacturing system,
- old product and old manufacturing system.

3.3.4 Modular Systems

A module platform is an expression of the company's development strategy, focused on short- and long-term profit maximization through, among other things, reuse of design object modules, mass-customization of products, and separation of module-development activities. Module platforms can be developed using the modularization methodology such as Modular Function Deployment™ (MFD™), presented by Erixon (1998). Although there are numerous methods that cover embodiment of technical solutions in modular architectures, the approach taken by Erixon (1998) is a rare attempt to modularize from the strategic rather than technical point of view. MFD starts from identification of customer needs and their systematization through application of Quality Function Deployment (QFD), it then goes on defining the technical solution according to the identified requirements by utilizing function-means trees (by Suh (1990)) and the concept selection method (by Pugh (1998)).

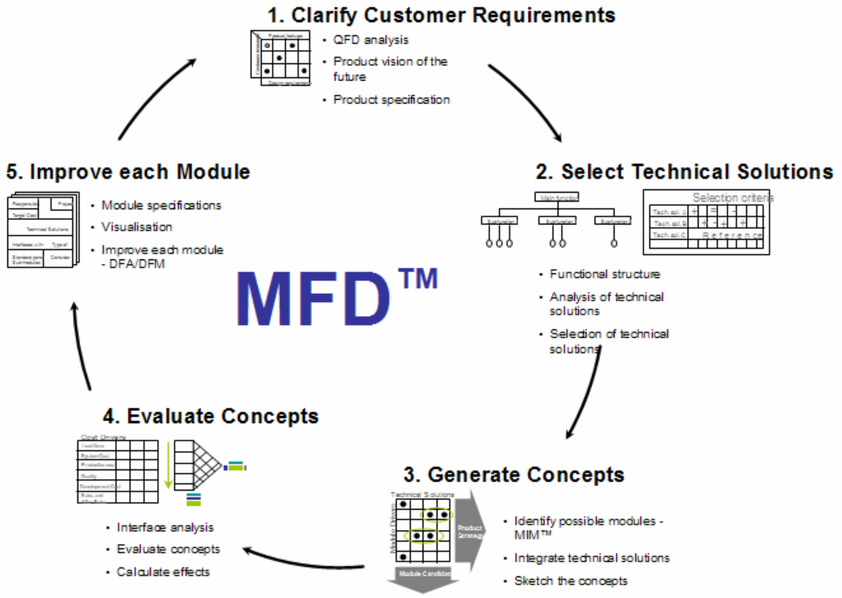


Figure 21: Modular Function Deployment™, Erixon (1998)

When a preferred technical solution concept is created a modular embodiment structure is defined. Here, MFD utilizes a unique concept of MIM (Module Identification Matrix), where a set of strategic module drivers is identified. These module drivers are reasons why a technical solution or a set of technical solutions should be embodied as a separate module. The module drivers cover various aspects on the developed technical system: development and design, variance, manufacturing, quality, purchasing, and after-sales. After the modules are identified, they are evaluated through analyzing e.g. interface complexity, assortiment complexity, and variant flexibility. Finally, the developed modules are improved by applying methods like DFMA.

From the manufacturing point of view, modularity in both product and manufacturing system space is an important mean for enhanced reusability. The need to reuse manufacturing systems has been emphasized by Fagerström et al. (2002). As stated in Section 3.3.3, according to Fagerström et al. (2002), the communication between product and manufacturing system development processes can be divided into four different situations. The first situation occurs if there is a new product and a new manufacturing system to be designed. Here, the design decisions concerning the manufacturing system and the product can be regarded as mutual constraints. The second situation occurs if there is a new product and an already existing manufacturing system. In this case is it important that the product designers take the manufacturing system modules and possible manufacturing system configurations into account. Here, the manufacturing system module platform can be regarded as constraint on the product design. The third situation is the opposite of the previous one, and occurs if the product exists and a new manufacturing system is to be designed. In this case it is important that the manufacturing system designers have good knowledge about the product modules and possible product configuration. Here, the product module platform can be regarded as a constraint on the manufacturing system design. The fourth situation occurs if both the product and the manufacturing system exist. The design perspective is in this case concerned with design object improvements in form of redesign.

3.4 Manufacturing System Design Activities

3.4.1 Integrated Product and Manufacturing System Design

A manufacturing system is designed by carrying out various design activities. Sohlenius (2001) argues that the best product and manufacturing system design (correct quality and high design productivity) is achieved if manufacturing system design is integrated into product design process. He also points out that, since a manufacturing system is a technical system that is similar to any physical product, manufacturing system design follows the same problem solving principles as product design.

Wu (1994) presents a problem solving oriented manufacturing system design framework that encompasses following activities:

1. analysis of situation,
2. setting objectives,
3. conceptual modeling (functional requirements, organization of functions, analysis of control systems),
4. detailed design (selection of production technology, organization and layout of production technology, development of manufacturing information system),
5. evaluation and decision.

There is the reason to believe that this broad problem solving oriented design framework as presented by Wu is applicable on designing any technical system, i.e. both products and manufacturing systems.

Product and manufacturing system designs are often integrated using the development project models based on the stage-gate philosophy as described in Chapter 1. The stage-gate models for integrated product and manufacturing system design presented by e.g. Andreasen and Hein (1987), McGrath (1996), and Ulrich and Eppinger (2000), are based on similar problem solving principles as those utilized by Wu (1994).

3.4.2 Specific Activities in Manufacturing System Design

Traditionally, there are some specific activities that are performed by manufacturing system designers. When performing these activities a manufacturing system designer considers issues e.g.:

- the product that is going to be manufactured,
- manufacturing technologies (processes and resources) and their ability to create desired product properties,
- manufacturing system design principles about e.g. manufacturing process and workshop layout, batching and manufacturing resource resetting, process control or inventory management.

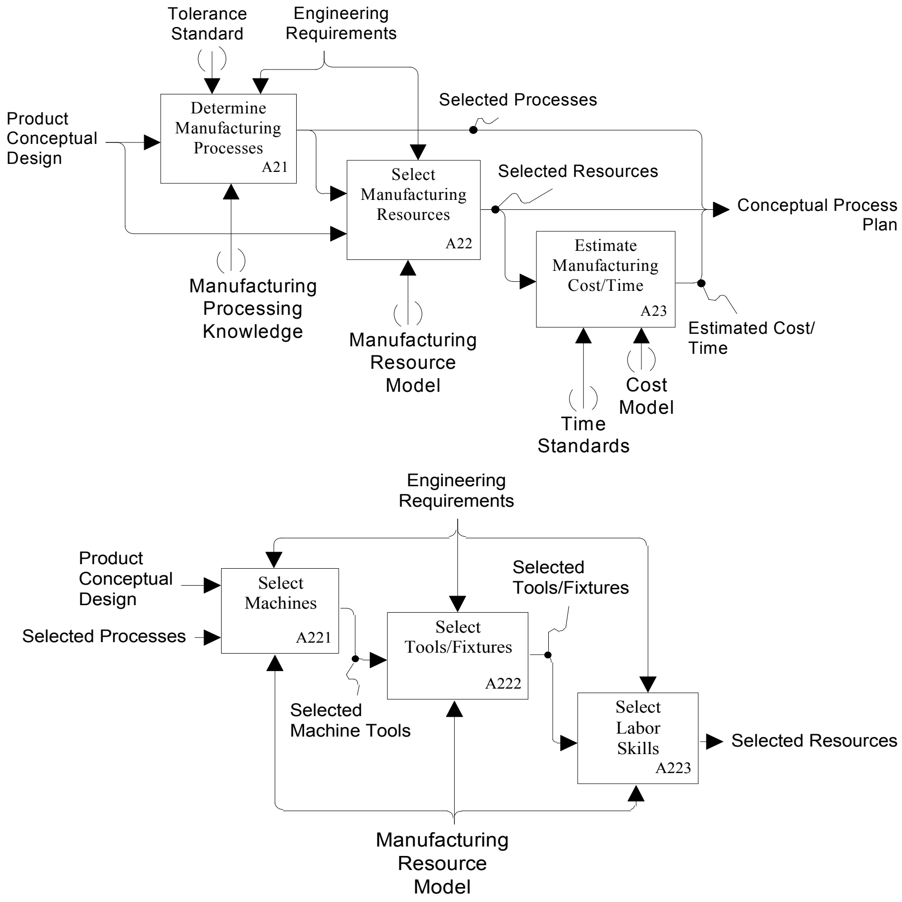


Figure 22: Conceptual Manufacturing System Design according to Feng and Song (2000)

Mårtensson (2000) determines manufacturing system design process to be consisted of the following activities:

1. product part analysis,
2. manufacturing process selection,
3. manufacturing process grouping,

4. workshop layout determination,
5. manufacturing resource behaviour determination,
6. product part handling determination.

Feng and Song (2002) present an activity model containing some necessary activities that must be performed during the conceptual design of a manufacturing system, cf. Figure 22.

3.4.3 Operations Design

Many of the activities, which are specific for manufacturing system design, are supported by methods developed and used within the area of operations management. Noori and Radford (1995) define operations as the production of goods and services, the set of value-added activities that transform inputs into outputs. Waller (1999) defines operations management as the effective planning, organizing and control of all the resources and activities necessary to provide the market with tangible goods and services. An important area of operations management is thus planning, i.e. operations design.

Various authors, present the methodology used in the area of operations design, e.g. Andersson et al (1992), Askin and Standridge (1993), Krajewski and Ritzman (2002), Noori and Radford (1995), Olhager (2000), Slack et al (1998), Waller (1999), and Wild (1995). Most of these authors present an almost identical set of methods, which can be applied on some typical manufacturing system design problems. Some of these methods will be discussed in following paragraphs.

Slack et al (1998) summarize operations design in a chart presented in Figure 23.

The design of products and services follows general problem-solving method, while design of processes, although executed in parallel with product design, is executed by modeling through application of a set of special methods for network design, design of layout and flow, process technology design and job design.

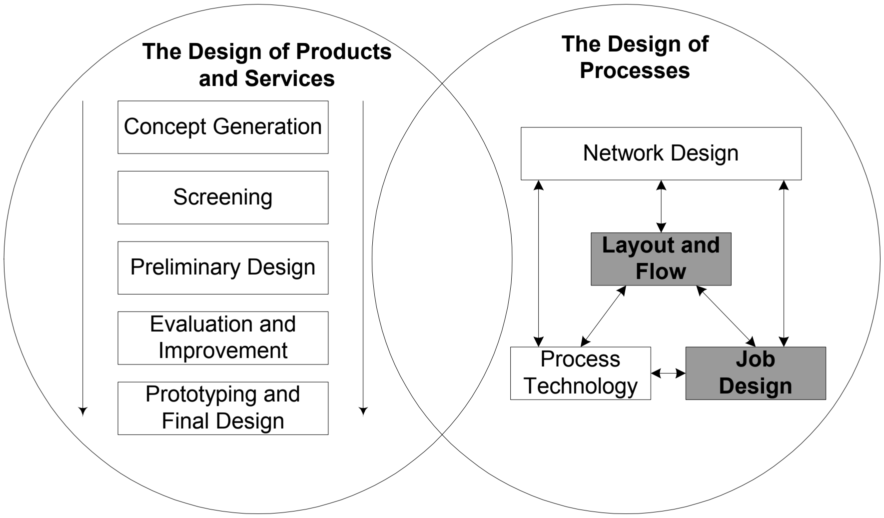


Figure 23: Operations design framework, after Slack et al (1998).

3.4.3.1 Design of Operations Networks

According to Slack et al (1998), which is also backed by most of the other mentioned authors within the field of operations design, manufacturing network design is based on market demand forecasts and is concerned with:

- configuration of the supply network by deciding on the amount of vertical integration in the supply chain (e.g. in- and outsourcing decisions).
- deciding on location of manufacturing facilities based on a myriad of influencing factors.
- long-term capacity management by balancing economies and diseconomies of scale as well as applying capacity-leading and capacity-lagging strategies.

3.4.3.2 Design of Process Technologies

Design of process technology is concerned with choosing the resources that are going to support execution of the chosen processes. Operations design literature only present common process technologies and does not provide methods for performing the technology selection. Waller

(1999) presents a typical set of process technologies such as manufacturing automation technologies (NC, robots, CAM, FMS, AGV, AS&RS, CIM), information technologies (EDI, LAN, WAN, Ethernet, Client/Server, ISDN, Internet) and artificial intelligence technologies (expert systems, rule-based systems, neural networks and fuzzy logic). Traditional manufacturing process technologies, such as machining, casting or welding are not discussed in the operations design literature.

3.4.3.3 Layout Design

Methods for design of layout and flow and methods for job design is the part of process design methodology that is especially focused by the members of operations design community.

According to Krajewski and Ritzman (2002), layout design involves decisions about the physical arrangement of economic activity centers (resources) within a facility. Slack et al (1998) claim that the layout design activity should be executed according to the following procedure:

1. Selection of process type (project, jobbing, batch, mass, continuous) based on volume-variety characteristics (cf. Figure 14)
2. Selection of layout type (fixed position, process, cell, product)
3. Detailed design of layout (the physical position of all transforming resources and the flow of the operations transformed resources)

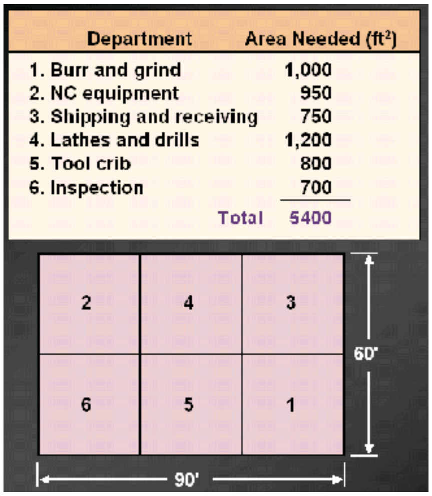
According to Noori and Radford (1995), in a process layout, similar pieces of equipment or functions are grouped together (e.g. all milling machines in same physical location), while in a product layout, the pieces of equipment required to make a particular product are grouped together (e.g. an automobile assembly line). Noori and Radford also discuss cell layout, which they call group technology layout (cf. Section 3.3.1.1), where the pieces of equipment required to make a set of products with similar shapes or similar operational requirements are grouped together. Fixed position layouts are according to Noori and Radford characterized by the fact that equipment is brought to the fixed object that is being processed (e.g. a house).

The layout types that are most often discussed are process and product. Cell layout is often regarded as being integrated into product and/or process layout and fixed position layout is not so frequently applied in manufacturing.

3.4.3.4 Process Layout Design

Krajewski and Ritzman (2002) present strategies for designing process and product layouts. Similar strategies are also presented by most of the other authors. According to Krajewski and Ritzman the process layout design should be created by performing following activities:

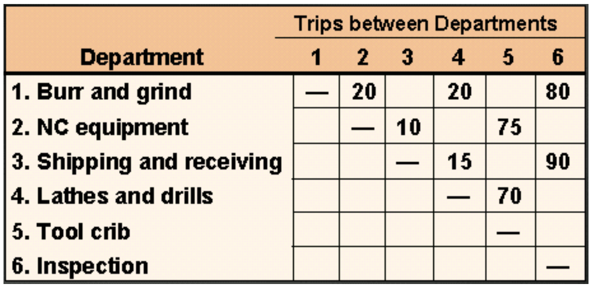
1. Gather information
   a) Estimate space requirements by department.
   b) Create a block plan that allocates space and indicates placement of each department. A block plan should fit building geometry.



Department	Area Needed (ft^2)
1. Burr and grind	1,000
2. NC equipment	950
3. Shipping and receiving	750
4. Lathes and drills	1,200
5. Tool crib	800
6. Inspection	700
Total	5400

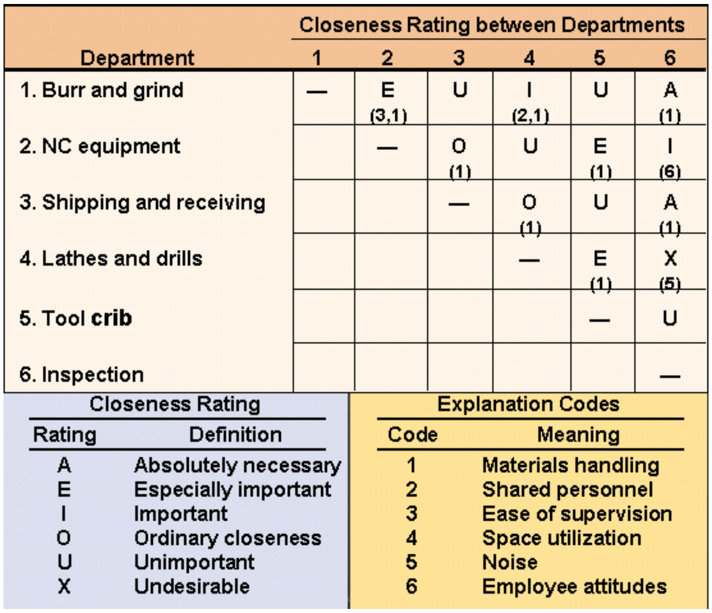
Figure 24: A block plan, adapted from Krajewski and Ritzman (2002)

   c) Find the closeness factors by creating a trip matrix which shows the number of trips between each pair of departments per unit of time. Alternatively, a relationship chart (REL chart), which shows qualitative proximity importance judgments, can be used.



Department	Trips between Departments					
	1	2	3	4	5	6
1. Burr and grind	—	20		20		80
2. NC equipment		—	10		75	
3. Shipping and receiving			—	15		90
4. Lathes and drills				—	70	
5. Tool crib					—	
6. Inspection						—

Figure 25: A trip matrix shows that e.g the number of trips between dep. 3 and 6 is 90 per day, adapted from Krajewski and Ritzman (2002)



Department	Closeness Rating between Departments					
	1	2	3	4	5	6
1. Burr and grind	—	E (3,1)	U	I (2,1)	U	A (1)
2. NC equipment		—	O (1)	U	E (1)	I (6)
3. Shipping and receiving			—	O (1)	U	A (1)
4. Lathes and drills				—	E (1)	X (5)
5. Tool crib					—	U
6. Inspection						—

Closeness Rating

Rating	Definition
A	Absolutely necessary
E	Especially important
I	Important
O	Ordinary closeness
U	Unimportant
X	Undesirable

Explanation Codes

Code	Meaning
1	Materials handling
2	Shared personnel
3	Ease of supervision
4	Space utilization
5	Noise
6	Employee attitudes

Figure 26: A REL chart shows that closeness between e.g. dep. 3 and 6 is absolutely necessary because of materials handling reasons, adapted from Krajewski and Ritzman (2002)

2. Develop a block plan
   a) Create a new block plan based on closeness requirements identified in trip matrix and/or REL chart.
   b) Evaluate new layout by calculation and comparison of desir-

ability scores for layout alternatives. Desirability score is estimated by multiplying each load (e.g. amount of trips between two departments) by the distance traveled and summing over all of the loads. A layout alternative with lower desirability score is more cost effective.

3. Design a detailed layout

    a) Use trip matrix, including material flow rates, transportation costs, and initial block layout to find a feasible detailed layout by applying a heuristic CRAFT-method (CRAFT = Computerized Relative Allocation of Facilities Technique). Working from an initial block plan CRAFT evaluates all possible paired exchanges of departments until a design with greatest reduction of the total desirability score is found.

3.4.3.5 Product Layout Design

Now, how should a product layout be arranged? According to Slack et al (1998) a product layout designer needs to decide on following:

- What cycle time is needed (based on the volume demand and the manufacturing time available)?
- How many stages (stations) are needed (based on the work content)?
- How should the task-time variation be dealt with?
- How should the layout be balanced?
- How should the stages be arranged?

The product layout design is according to Krajewski and Ritzman performed by establishing a flow using a precedence diagram, which allows visualization of immediate predecessors, and allocation of flow elements to different stations (composed of resources).

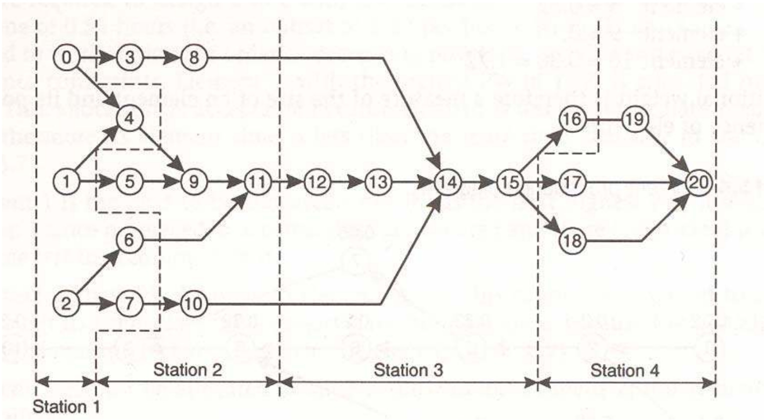


Figure 27: A precedence diagram, Wild (1995)

The goal is to create a balanced flow where every workstation process material, with the processing cycle-time that is similar for all the work-stations in the system, so that all stations are maximally utilized while costs for work-in-progress (e.g. queues, stocks) are kept at the minimum.

In product design, the stations can be arranged in linear shape, U-shape or serpentine shape (cf. Figure 28).

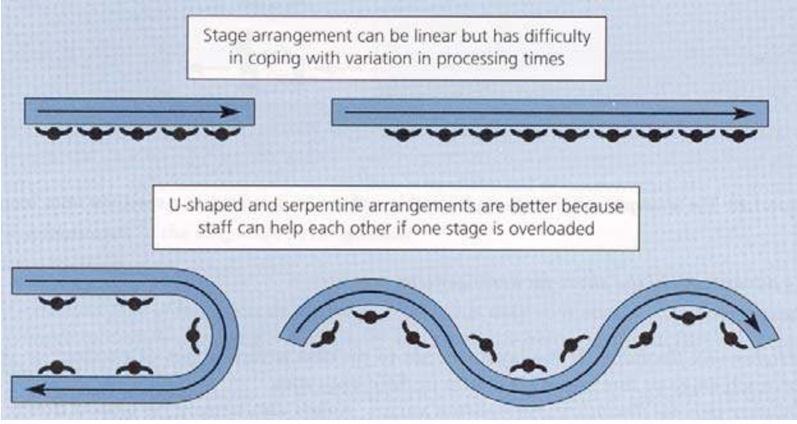


Figure 28: The arrangement of stations, Slack et al. (1998)

3.4.3.6 Cell Layout Design

According to Askin and Standridge (1993), when designing cell group layout three major activities need to be performed:

1. Part coding

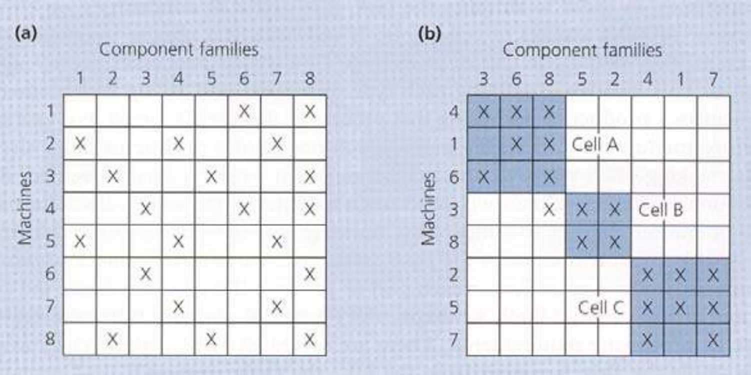
   In this activity the part shape is represented with a code that is used to categorize shape elements (features) in order to be able to easier match part's process requirements with resource's process capability. Various coding systems are used, among which Opitz is the most used one.

2. Assigning parts to machines (resources)

   Resources that execute the manufacturing processes that are capable of creating the desired part features are selected.

3. Assigning machines (resources) to groups (cells)

   Selected resources that are assigned to create all the relevant parts are assigned to cells. Here, various methods might be applied, among which Production Flow Analysis (PFA) is the most popular one.



(a)

Component families

Machines	1	2	3	4	5	6	7	8
1						X		X
2	X			X			X	
3		X			X			X
4			X			X		X
5	X			X			X	
6			X					X
7				X			X	
8		X			X			X

(b)

Component families

Machines	3	6	8	5	2	4	1	7
4	X	X	X					
1		X	X	Cell A				
6	X		X					
3			X	X	X	Cell B		
8				X	X			
2						X	X	X
5				Cell C		X	X	X
7						X		X

Figure 29: Production Flow Analysis (PFA), Slack et al (1998)

In PFA, part requirements and process grouping are examined simultaneously. From a matrix where part-resource relationship is inserted a resource that produce fewest parts is selected as a key resource. A subgroup of all the parts that visit the key resource along with all the resources required by these parts is formed. If this new subgroup can be divided into two or more disjoint sets new subgroups are formed. In addition, if a resource is included in a subgroup due to just one part type, then this resource is excluded from the subgroup. The grouping procedure continues until all parts and resources are assigned to subgroups. The procedure is finished by combining subgroups into groups of desired size, i.e. subgroups with the greatest number of common resources form new groups.

3.4.3.7 Job Design

Slack et al (1998) refer to job design as activity which influences the relationship between people, the technology they use, and the work methods employed by the operation.

The most central part of the job design is method study. According to Wild (1995), the method study consists of seven steps:

1. Select the job to be studied
2. Record the existing work method and all other relevant facts.

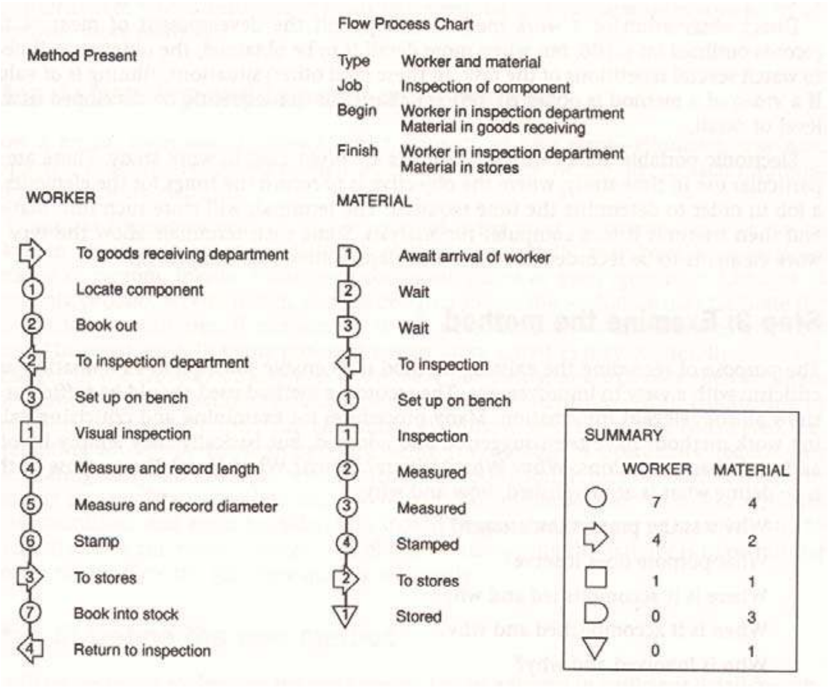
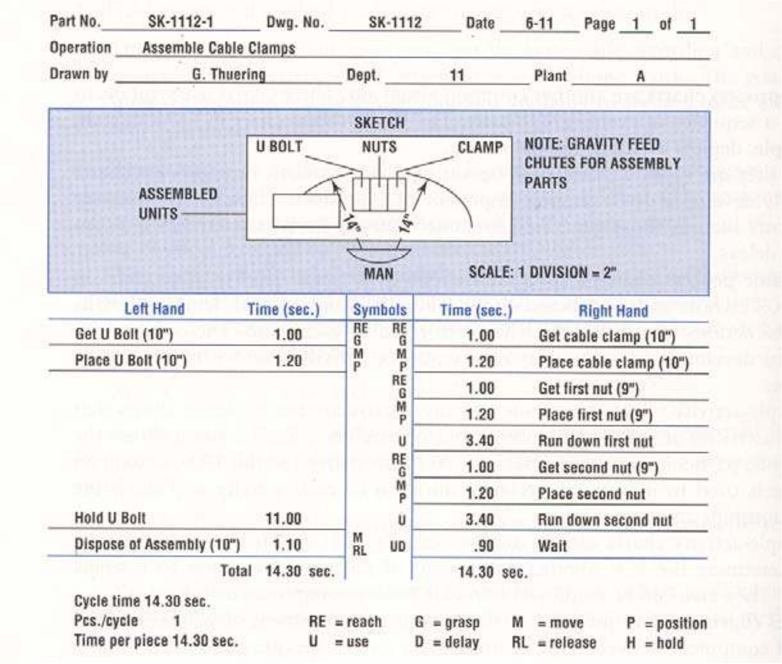


Figure 30: Worker and material flow process chart, Wild (1995)

The existing work method is most often captured in a process chart. A process chart may capture the material transition or the tasks performed by a worker. Process charts are sometimes also used for capture of overall manufacturing process.

Worker tasks are sometimes subdivided into left- and right-hand tasks and are viewed in an operator process chart. Standardized work measurement systems, e.g. MTM, can be utilized to capture the work content.



Part No. SK-1112-1 Dwg. No. SK-1112 Date 6-11 Page 1 of 1
Operation Assemble Cable Clamps
Drawn by G. Thuering Dept. 11 Plant A

NOTE: GRAVITY FEED CHUTES FOR ASSEMBLY PARTS

SCALE: 1 DIVISION = 2"

Left Hand	Time (sec.)	Symbols		Time (sec.)	Right Hand
Get U Bolt (10")	1.00	RE G	RE G	1.00	Get cable clamp (10")
Place U Bolt (10")	1.20	M P	M P	1.20	Place cable clamp (10")
			RE G	1.00	Get first nut (9")
			M P	1.20	Place first nut (9")
			U	3.40	Run down first nut
			RE G	1.00	Get second nut (9")
			M P	1.20	Place second nut
Hold U Bolt	11.00		U	3.40	Run down second nut
Dispose of Assembly (10")	1.10	M RL	UD	.90	Wait
Total	14.30 sec.			14.30 sec.	

Cycle time 14.30 sec.
Pcs./cycle 1
Time per piece 14.30 sec.

RE = reach
U = use
G = grasp
D = delay
M = move
RL = release
P = position
H = hold

Figure 31: Operator process chart, Noori and Radford (1995)

3. Examine the method by defining what is accomplished, how, where, when, by who, and why is it done in the current way.
4. Develop and improve work method by eliminating unnecessary activities and rearranging the sequence of activities in order to simplify allover process execution.
5. Define the new method and describe it by using a process chart.

6. Install the new method.
7. Maintain the new method.

Job design method can be used reactively, i.e. improvement of an existing job design, and proactively, i.e. creation of a completely new job design.

3.4.4 Manufacturing System Design Using IDEF-Methodology

Manufacturing system design activities can be supported by a set of methods that belong to the IDEF-methodology. IDEF stands for ICAM Definition, where ICAM is an acronym for U.S Air Force program for Integrated Computer Aided Manufacturing. IDEF-methodology consists of ten methods that together comprise a structured framework for enterprise modeling and analysis. Among the ten IDEF-methods, IDEFØ and IDEF3 are best suited to aid the manufacturing system design activities by simply representing manufacturing system information in two different views, i.e. function view and process view.

3.4.4.1 IDEFØ

IDEFØ is a method designed to model the decisions, actions, and activities of an organization or system, NIST (1993). The method is based on an established graphical language SADT (Structured Analysis and Design Technique).

IDEFØ-diagrams consist of boxes that represent an activity or a function, inputs that are transformed into outputs, controls that determine the way inputs are transformed into outputs, and mechanisms that are guided by controls in transforming inputs into outputs. An IDEFØ-diagram consists of between three and six activities/functions. An Activity/Function is further decomposed into IDEFØ-diagrams on lower levels, representing inner structure of the activity and creating a hierarchical description of a modeled system.

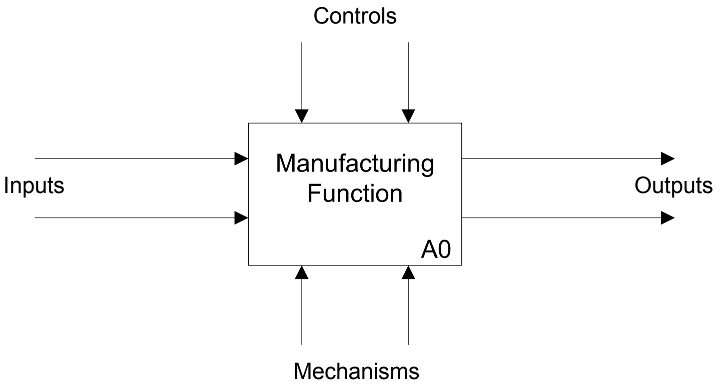


Figure 32: An IDEFØ-element, adapted from NIST (1993)

3.4.4.2 IDEF3

The IDEF3 Process Description Capture Method provides a mechanism for collecting and documenting processes, Mayer et al. (1995). IDEF3 captures precedence and causality relationships between process operations (Units of Behavior – UoB) as well as the relationship between a process and the object that it transforms from an initial into a desired state. UoBs are represented by boxes, object states are represented by circles, and transitions by arrowed transition arcs. IDEF3-diagrams are decomposed in same manner as IDEFØ-diagrams in order to allow representation of process hierarchies.

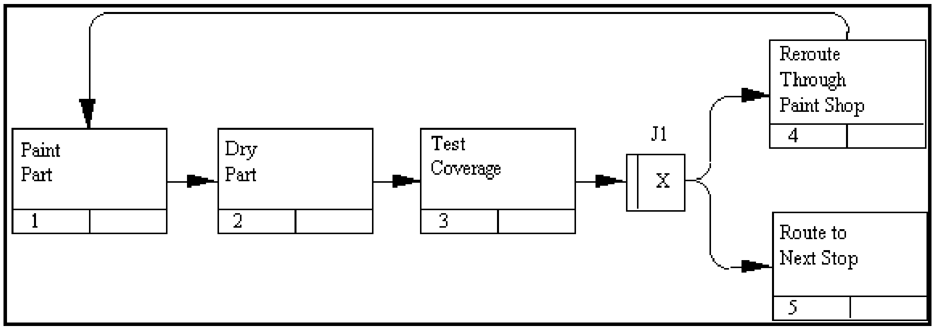


Figure 33: Example of an IDEF3 Process Description Diagram, Mayer et al. (1995)

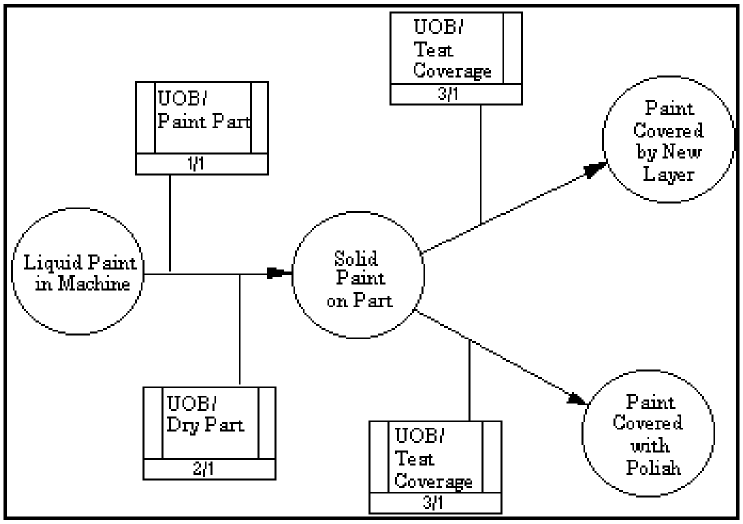


Figure 34: Example of an IDEF3 Object State Transition Network Diagram, Mayer et al. (1995)

3.4.5 Computer Aided Manufacturing System Development Tools

During the last two decades a great number of simulation and digital prototyping (SDP) tools for computer aided manufacturing system development has been presented. Tools like CAD (Computer Aided Design) and Digital Mock-Up (DMU) have improved manufacturing engineering organizations' capability to in early stages of the development process visualize and analyze (e.g. DFMA-analysis) the proposed product concepts. CAD is also used for graphical design of manufacturing workshops and for design of manufacturing tools and fixtures.

Various simulation tools have also been introduced. Tools for simulation and programming of industrial robots, PLCs, and CNC-machines, together with graphical ergonomics simulators for simulation of manual workplaces, provide a powerful platform for virtual development of automated and manual manufacturing stations. Furthermore, Discrete Event Simulation (DES) tools are applied for modeling whole manufacturing lines.

Figure 35: Software Tools for Manufacturing System Development, Delmia Corp.

Today it is also possible to import manufacturing stations models from e.g. ergonomics or robot simulation software into a DES-model and thereby enable the possibility to model, visualize, virtually run, and analyze manufacturing systems from an overall process level to a detailed technology level. However, this method of moving models between different software tools is, due to the absence of appropriate and accepted information exchange standards, still possible either within a single software package or between few predefined software packages.

4 DEVELOPMENT PROCESSES

4.1 Business Processes

The business processes are referring to the unique ways in which an organization coordinates and organizes its operations to produce valuable products and/or services (Laudon and Laudon (1998)). The operations of an organization include various, directly or indirectly, value-adding processes which involve creation, communication and the utilization of material, information and knowledge.

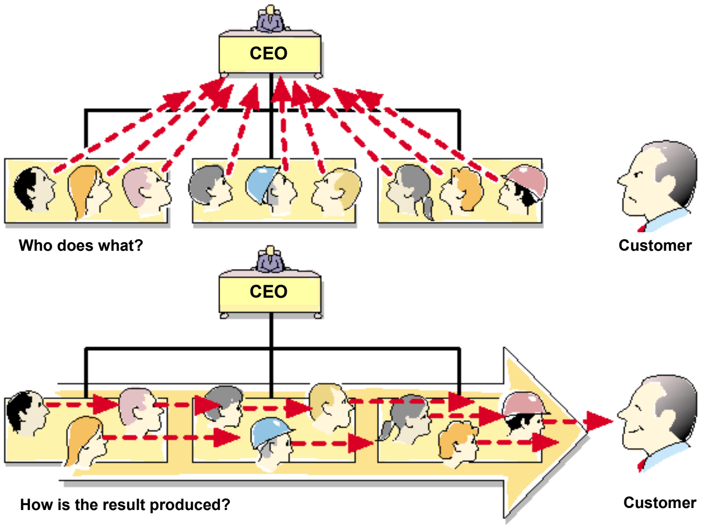
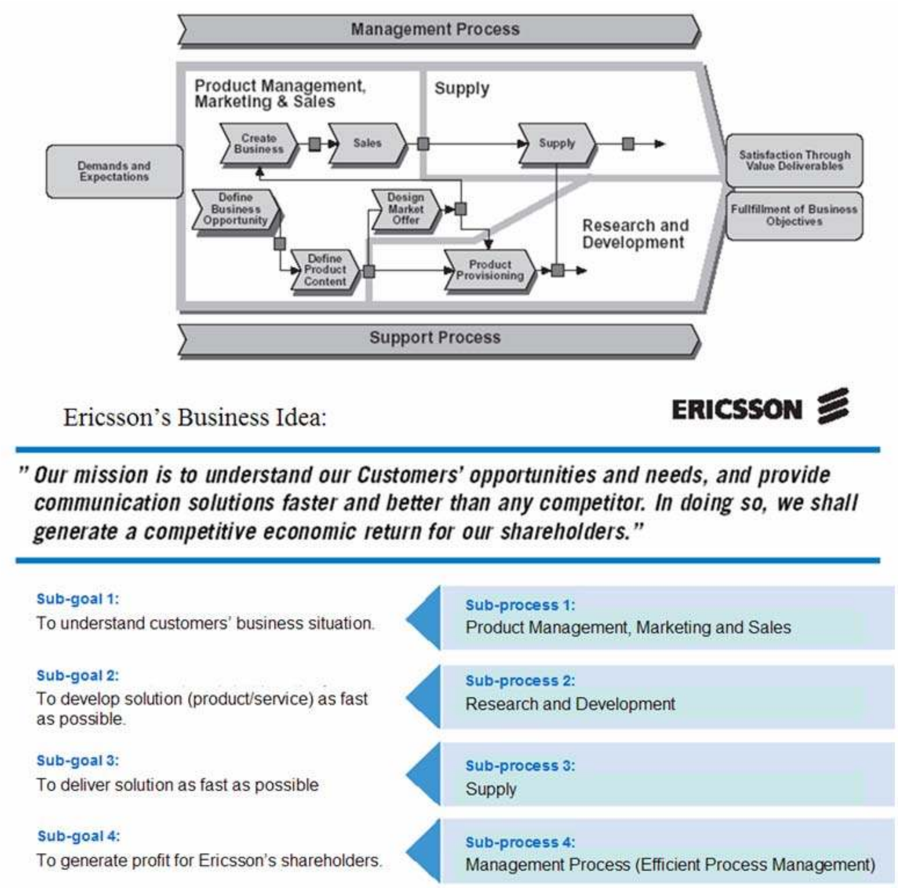


Figure 36: Functional vs Process Organization, adapted from Aganovic and Jonsson (2001)

Different ways of organizing the operations in a business process have evolved over the decades, for instance, the functional organization and the process organization of which the latter is the most recent evolved. Whereas the functional organization focus on *who does what,* the process organization focus on *how is the result produced*. In a process organization the customer demands are better understood and, thus, easier satisfied. In addition, unnecessary operations can be cut while streamlining the core value-adding business processes (Aganovic and Jonsson (2001)). However, even if the process organization is applied, the enterprise must still have an understanding of the functions that are needed to execute the set of processes.



Ericsson's Business Idea:

" Our mission is to understand our Customers' opportunities and needs, and provide communication solutions faster and better than any competitor. In doing so, we shall generate a competitive economic return for our shareholders."

Sub-goal 1: To understand customers' business situation.	**Sub-process 1:** Product Management, Marketing and Sales
Sub-goal 2: To develop solution (product/service) as fast as possible.	**Sub-process 2:** Research and Development
Sub-goal 3: To deliver solution as fast as possible	**Sub-process 3:** Supply
Sub-goal 4: To generate profit for Ericsson's shareholders.	**Sub-process 4:** Management Process (Efficient Process Management)

Figure 37: Core Processes at Ericsson Corporation, adapted from Aganovic and Jonsson (2003)

According to Rentzhog (2000), business processes are usually divided into two categories:

- *Core Processes* fulfill enterprise's overall business idea. Core processes mirror core operations of an enterprise – its source of life!
- *Support Processes* help core processes to deliver correct results (management, HR,…).

The kernel of an enterprise's operations is consisted of core processes. In order to be able to act as an engine that carries the enterprise towards sustained profitability the core processes should be based upon the enterprise's business idea, its vision, and strategies for achieving the goals and eventually coming closer to the vision. Figure 37 shows an example of correspondence between a business idea and the specified core processes.

4.2 The Development Process

Industrial companies deploy some kind of development process, e.g. product development and/or manufacturing system development. The development process is usually regarded as a core business process. The execution of the development process is most often carried out in a project manner, i.e. every new product introduction or new manufacturing system implementation is a new project. Therefore, the development process descriptions may be regarded as project control models for development projects.

A development process is usually divided into a set of sub-processes. In these sub-processes, the product and its manufacturing system are defined. Figure 38 shows some examples on how such a division could be carried out, and in Section 4.3 a number of development process models is presented and discussed. What can be said about development processes in general is that they always involve analysis and synthesis activities, which are two inseparable modes of action within the development work.

The key driver of the analysis and synthesis within the sub-processes is the development decision-making. This decision-making is supported by various development methods and tools, which, in the case of manufacturing system development, have been discussed in Section 3 and will be further discussed in Section 4 and in Sections 7 and 8.

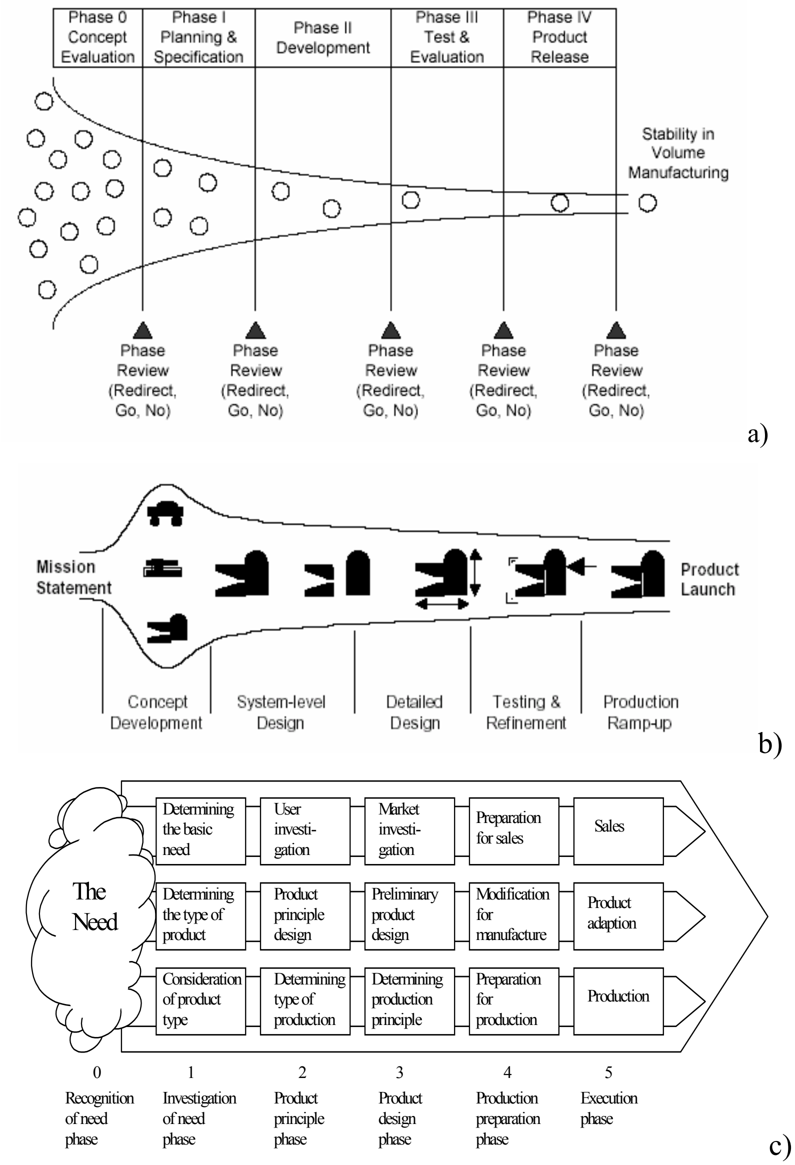


Figure 38: Examples of development process models: a) stage-gate model according to McGrath (1996), b) development process model according to Ulrich and Eppinger (2000), and c) integrated product development process according to Andreasen and Hein (1987)

In addition, another type of decision-making occurs in the interface between two sub-processes. This decision-making handles the question if the previous sub-process has been satisfactorily completed and if the project can move on to the next sub-process or not. Such a decision-making approach is presented in the *Phase Review Model* by McGrath (1996). In this model, three optional outcomes of the decision are identified: *go*, *no* and *redirect*. Here, *go* means that the objectives of the previous phase (sub-process) are fulfilled and the next phase (sub-process) can be initiated, *no* means that the process is terminated and will not be continued and *redirect* means that the objectives of the previous phase (sub-process) are not fulfilled and, consequently, some rework has to be done. The point where decision-making occur between two stages is often referred to as a gate. This type of model is often called a *stage-gate* model.

4.3 Sub-processes within the Development Process

In this section, a general set of development sub-processes, based on several existing development process descriptions, is presented. Four theoretical product development process models (i.e. Andreasen and Hein (1987), Cooper (1993), McGrath (1996), Ulrich and Eppinger (2000)), as well as three product development process models that are currently employed at various manufacturing enterprises, (i.e. Ericsson (2001), Carlsberg (1997), Scania (1998)) have been reviewed. In addition to these models, the supply process model developed by the Supply Chain Council, SCOR (2001), is also reviewed.

What is to be remembered is that this general set of sub-processes is a result of analysis, a least common denominator for the reviewed development process models, and a categorization framework[2]. It is developed to only present existing process models in a comprehendible way and it is not to be regarded as a development process model in its own right.

---

[2] The sub-processes have been analyzed in collaboration with Jonas Fagerström at KTH Production Engineering. The work has also been presented as a conference paper, Fagerström et al. (2001).

4.3.1 General set of Sub-processes: Categorization Framework

Two basic stages of the development process, each consisting of three sub-processes, have been identified and defined. However, it should be noted that the interfaces between these sub-stages are not unambiguous. Therefore they have been classified according to their main characteristics.

Stage 1 – DEVELOPMENT: In this stage the design objects, i.e. the product and its manufacturing system, are developed. The knowledge in an enterprise is transformed into the models of the design objects. The sub-stages of this stage are controlled by various stakeholder requirements.

Sub-process 1.1 – Preparation: In this sub-process the organization of the project and the project outline are determined. Market needs are investigated and recognized. These needs are then organized and a formal requirement structure is established.

Sub-process 1.2 – Synthesis: In this sub- process the synthesis of the design objects is carried out. The design object concept is first synthesized from the formal requirements. Thereafter, the synthesis on the system level is carried out and the design object architecture is established. Finally, the syntheses on the detail level, where modules and components of the design object are determined.

Sub-process 1.3 – Analysis: In this sub-process the design objects are more thoroughly analyzed and their conformance towards the stakeholder requirements is checked. The results of the analysis can thereafter be used as a basis for further synthesis in the current or other projects. This validation sub-process is the last step of the development stage.

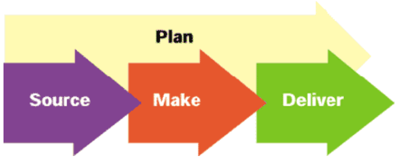


Figure 39: The basic SCOR-model, SCOR (2001)

Stage 2 – REALIZATION: In this stage the design objects, i.e. the product and its manufacturing system, are realized, using the design object models created in the development stage as a blueprint. Here, the product development project is ordering the prototype manufacturing, the installation of the manufacturing system, and the verification of the manufacturing process. Furthermore, the products ordered by early customers are made and delivered in this stage. The definition of this stage and its sub-stages is based on the Supply-Chain Operations Reference (SCOR) model (SCOR (2001)). The SCOR-model provides standard descriptions for the processes within the supply chain, and identifies the performance measurements and supporting tools suitable for each process.

Sub-process 2.1 – Sourcing: In this sub-process the physical instances, that is, material, components and modules of the design object are inserted. The processes, in which the supply sources are identified, are triggered and carried out. Finally, deliveries of physical instances of the design object are planed, transferred, received and verified.

Sub-process 2.2 – Making: This sub- process involves the processes that must be implemented in order to transform components and modules to a specific configuration of the design object. Some of the main processes that are carried out are planned, realized and verified.

Sub-process 2.3 – Delivering: In this sub-process all order management steps, from processing customer inquiries and quotes to routing shipments, are encompassed. This is the last sub-stage of the realization stage and, consequently, also of the innovation process.

Virtual Stage – Planning: This virtual stage is embedded in both the development stage and the realization stage. The planning activities are executed in all the sub-stages. The interaction between sub-stages and between stages is also planned in this virtual stage.

4.3.2 The Reviewed Development Process Models

The table below shows how the reviewed development process models fit into the corresponding generic sub-process structure, i.e. the categorization framework.

	Development			**Realization**		
		P	**L**	**A**	**N**	
General Sub-processes	**Preparation** Investigate market need Recognize need Formalize requirement	**Synthesis** Concept synthesis System synthesis Detailed synthesis	**Analysis** Concept analysis System analysis Detailed analysis	**Source** Supply chain execution	**Make** Verify	**Deliver** Verify
Andreasen & Hein (1987)	Recognition of need Investigation of need	Product principle Product design	Production preparation	Execution	Execution	Execution
Ulrich & Eppinger (2000)	Planning	Concept development System design Detailed design	Testing and refine	Production ramp up	Production ramp up	Production ramp up
McGrath (1996)	Concept evaluation Planning and specification	Planning and specification Development	Test and evaluation	Product Release	Product Release	Product Release
Cooper (1993)	Preliminary investigation Detailed investigation	Development	Test and validation	Full product and market launch	Full product and market launch	Full product and market launch

Ericsson (2001)	Pre-study Feasibility study	Specification Design integration and verification	System verification Process verification	Customer acceptance Production ramp up	Customer acceptance Production ramp up	Customer acceptance Production ramp up
Carlsberg (1997)	Idea evaluation Preliminary study	Development Planning for launch	Verification	Production Launch	Production Launch	Production Launch Completion and follow up
Scania (1998)	Initialization Pre study	Feasibility Development	Feasibility Development	Realization	Realization	Realization

The reviewed development process models focus primarily on product development activities. All of them involve manufacturing aspects, but the awareness of the manufacturing system as a separate design object is not to be regarded as very significant. Every new configuration of the manufacturing system, within or outside of an existing manufacturing system, is a system of its own and is therefore to be treated as a separate design object. However, manufacturing system is usually treated as an aspect of the product rather than a separate technical system that need to be developed and implemented.

Development process models seldom implement the decision-making methods and tools related to manufacturing system development; the primary focus lies on decision-making methods and tools for product development and project management. Furthermore, even in cases where the manufacturing system development is treated separately, the low awareness about the manufacturing system as a separate design object is demonstrated by the fact that manufacturing system implementation activities are not included in the process model. Only in Scania (1998) there is awareness that a manufacturing system is not implemented until a physical instance of a virtual manufacturing system model is installed and approved for operation.

5 DEVELOPING MANUFACTURING SYSTEMS IN THE CONTEXT OF ENGINEERING DESIGN THEORY

5.1 Engineering Design Theory

Engineering Design Theories (EDT) offer frameworks for systematic synthesis and analysis of technical systems. These frameworks encompass mechanisms for structuring design objects as well as certain rules for how to carry out synthesis and analysis of a design object.

5.2 Engineering Design Theory by WDK-school

Since the beginning of 1980s, a group of mainly European engineering scientists has been developing a theory body for engineering design. This group is today known as Design Society, but during the last two decades they have conducted their meetings under the label Workshop Design Konstruktion – WDK. Their work has resulted in the compilation of rather heterogeneous set of theories into two major theoretical systems: Theory of Technical Systems and Theory of Domains.

5.2.1 Theory of Technical Systems

The Theory of Technical Systems (TTS), presented by Hubka and Eder (1988) classifies human knowledge about technical systems into an ordered set of statements about a technical system's nature, regularities of conformation, origination, development and various empirical observations.

According to the TTS, a transformation system has the purpose to transform its operands (materials, energy or information) from an original state into a desired state. This transformation is carried out in a transformation process consisting of sub-processes that alter one or several properties of the operand.

A transformation system consists of technical, living (e.g. human), information, and/or management systems (cf. Figure 40). If a transformation process is executed in a technical system it is then denoted as a technical process.

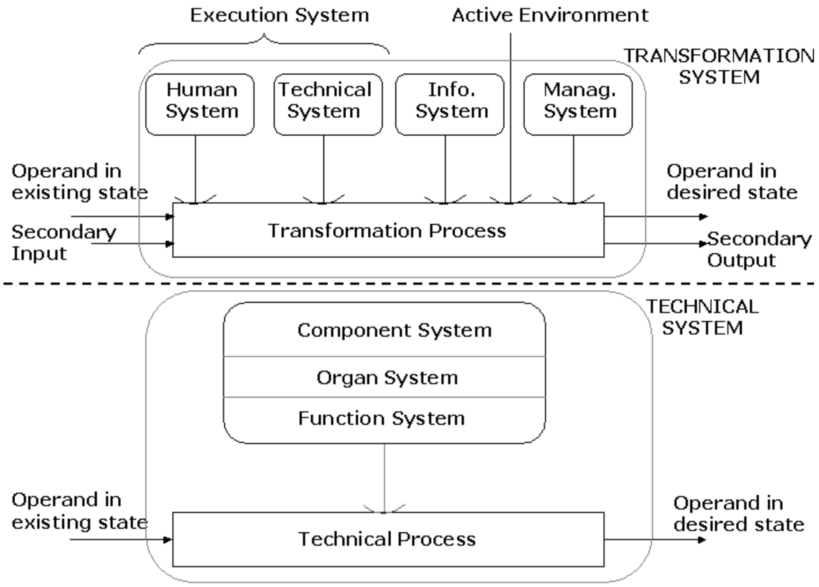


Figure 40: Transformation system model and technical system model, adapted from Hubka and Eder (1996)

The technical system must produce effects that are necessary for carrying out the technical process and thus the appropriate transformation of the operand. These effects mirror the functions of the technical system. The function system produces a set of effects needed to carry out technical processes of the technical process system.

The active units, which produce the effects within a technical system, are called organs. Organs are also referred to as function carriers or technical concepts. The organ system is concretized in the constructional system. Here, the organs are distributed among the physical components with specified spatial relationships.

Besides structural rules, expressed through four system models (technical process, function, organ, and components), the TTS also comprises a framework for classification of system properties. Here the properties of technical systems are classified into three major groups, where each group is divided into subgroups. The three groups are: external properties, internal properties and design properties.

5.2.1.1 Using Theory of Technical Systems in Manufacturing Systems Design

The TTS as presented by Hubka and Eder (1988) considers the life phase aspects in the development of technical systems. This initiative is delimited to the design of one general technical system without considering the design of its life phase systems such as manufacturing system, distribution system or destruction system.

Hubka and Eder (1996) continue their work and elaborate a special TTS for plant design. Plants are here regarded as technical systems of the highest levels of complexity. They consist of machines, down to mechanisms and components. The plant design theory regard a manufacturing plant as a technical system and is superficially exploring issues that are specific for plant design projects (e.g. plant planning project stages, industry branches, types of production, plant location, environmental regulations, plant layout). However, the structural relationship between a plant and products, which it is aimed to produce, is not discussed. Furthermore, clarification of relationship between the plant's technical system and the plant's human system is also out of scope for the special TTS for plant design.

Jansson (1993) utilizes the TTS to create a framework for management of product structures throughout product development and manufacturing processes. A product's structure is here regarded as a major factor that impacts manufacturing process productivity and quality, and thus customer satisfaction. Jansson splits the component system into physical structure and logical structure and identifies relationship between these two product structures and manufacturing structuring principles Jansson uses his extension of the TTS to support the selection of manufacturing strategy and to enhance manufacturability of products, while manufacturing system design, i.e. synthesis of manufacturing processes and resources, is not directly supported.

Hubka and Eder (1988) present a technical system as a part of a transformation system where technical systems operate by interacting with human systems, information systems, and management systems. Focus of the TTS lies on managing various design perspectives of a technical system without considering other collaborating systems. According to the discussion in section 3.1, a manufacturing system consists resources that may belong to any subsystem in a transformation system. This leads to the conclusion that a manufacturing system is in the context of TTS regarded as a transformation system. As presented in the TTS, the relationship between various transformation subsystems is not formalized and it is not discussed whether structuring of “non-technical” subsystems follow the same pattern.

5.2.2 Theory of Domains

The concept of system models of the TTS is further developed and depicted as the more homogeneous total system view in the Theory of Domains (ToD).

The ToD, presented by Andreasen (1980) is a theoretical foundation for mechanical design based on four technical system perspectives:

- *The Process System*, which is contained of processes, i.e. transformations of objects (material, energy, signals) in space and time based on various technological principles.
- *The Function System*, which is contained of functions, i.e. abilities to create desired effects that enable the transformation.
- *The Organ System*, which is contained of organs, i.e. entities that carry the functions and thus create the effects.
- *The Constructional System*, which is contained of physical components and assemblies thereof that embody (realize) the desired organs.

These four perspectives are called the domains. In every domain, a system model can be expressed on various levels of complexity and abstraction.

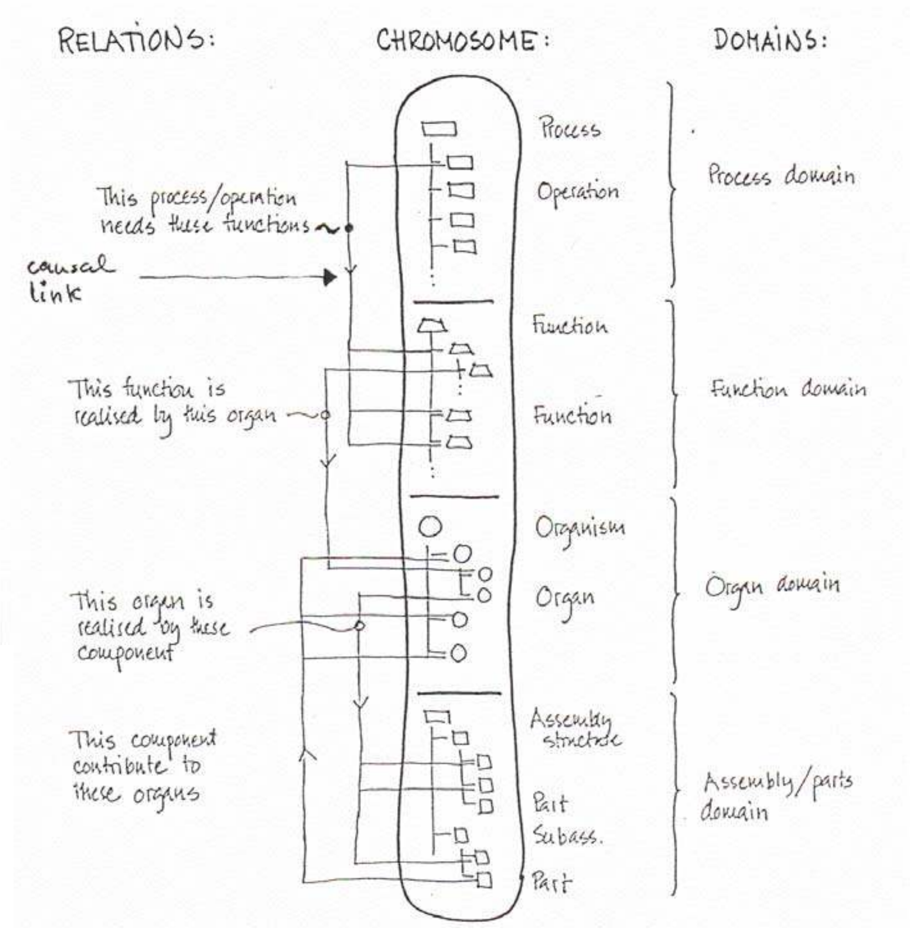


Figure 41: The Product Chromosome Model, Andreasen (1992)

Andreasen (1980) explicitly defines various elements of the ToD in 52 term definitions, 29 axioms and 10 laws. Definitions are formulated in collaboration with professor V. Hubka and are also used as a foundation of TTS.

The domains are interrelated by causal relationships, specified in Figure 2. These relationships can generally be expressed as a general relation between structures of functions and means where decomposition of the domain systems is carried out by zigzagging between the domains. A function desired in domain A is realized by means in domain B, and a mean in domain B exists in order to realize the corresponding function in domain A.

The domain structure can be utilized as the basic structure for computer aided product modeling. This structure contains the generic data about a product and is regarded as the product chromosome (cf. Figure 41).

When synthesizing a technical system an engineering designer, either deliberately or not, makes decisions about the technical process that the system is going to be able to execute, functions that the system is going to have, organs that are going to carry the functions, and physical components that are going to embody the organs. Understanding the structural models of the ToD and the relationship between them gives to an engineering designer the ability to make conscious decisions through creation of four structural models of a technical system capturing the design intent and history. Andreasen (1980) presents a foundation for synthesis algorithm according to the ToD. Andreasen (1980) claims that mapping between domains according to the synthesis algorithm is too complex to be used as a basis for a synthesis method. Therefore, Andreasen proposes application of simplified mapping. For example, the process system model should consist of working processes only, i.e. processes that alter operand properties, while other processes, i.e. processes that enable working processes, are represented in the function system model only.

Recently, a new approach to the ToD has been presented. Hansen and Andreasen (2002) present an extension to the original ToD, where the function domain has vanished as a structure of its own and the function has come to be seen as a behavior of its organ (function-carrier), i.e. functions inherit the organ structure.

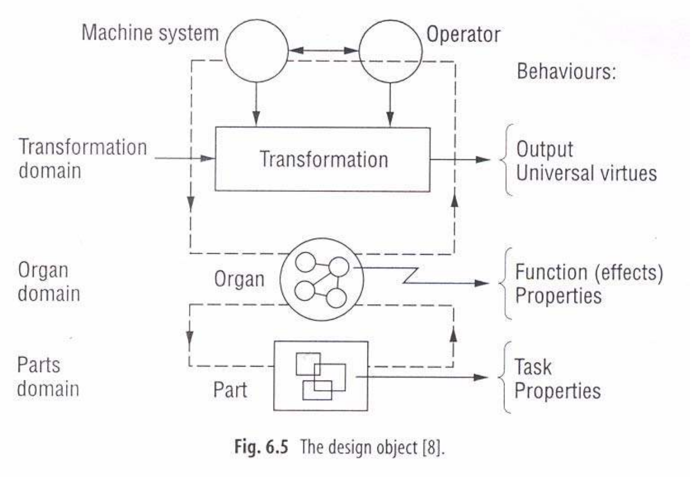


Figure 42: New Theory of Domains, Hansen and Andreasen (2002)

5.2.2.1 Using Theory of Domains in Manufacturing Systems Design

The ToD is generally applicable for modeling of technical systems. Andreasen (1992) extends product's chromosome model by incorporating the structure of a manufacturing process that is going to manufacture a product's parts and assemblies.

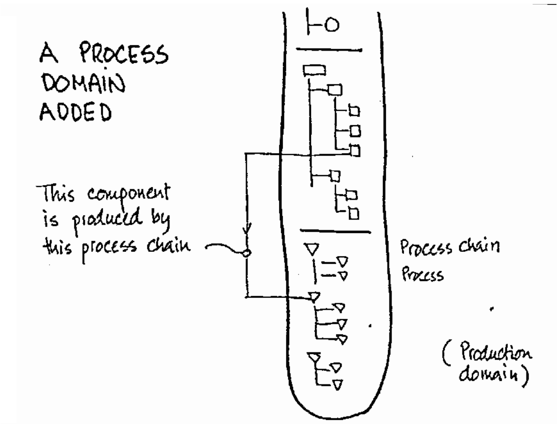


Figure 43: Manufacturing process structure in the product chromosome model, Andreasen (1992)

A new domain, manufacturing process domain is thus proposed. This new domain specifies the sequence of manufacturing operations while not representing the manufacturing system and its resources.

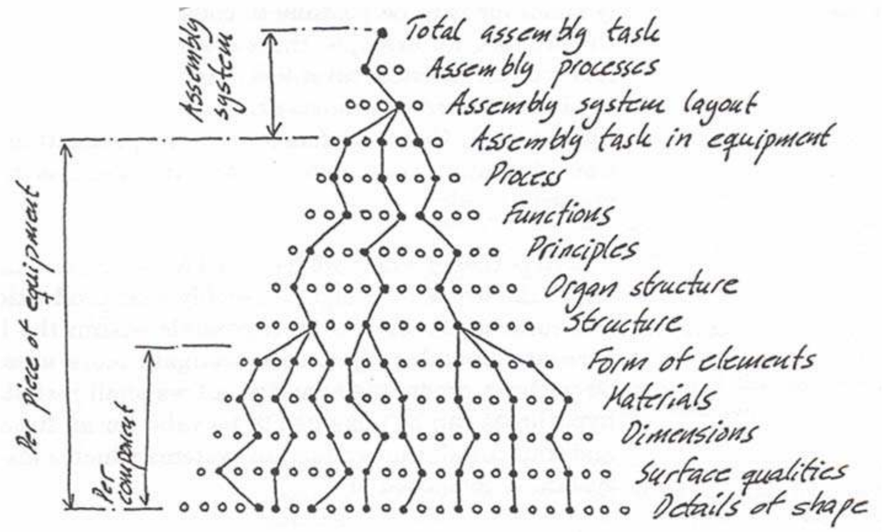


Figure 44: Design degrees of freedom in flexible assembly system design, Andreasen and Ahm (1988)

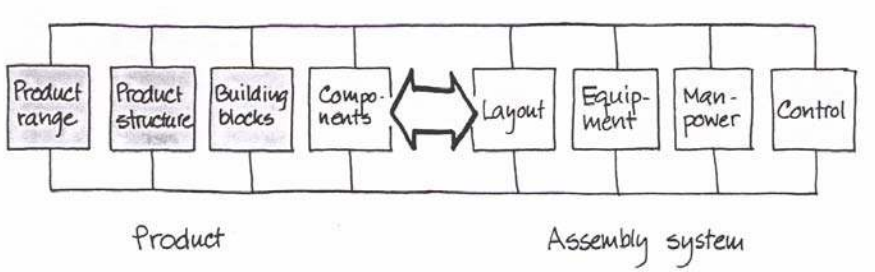
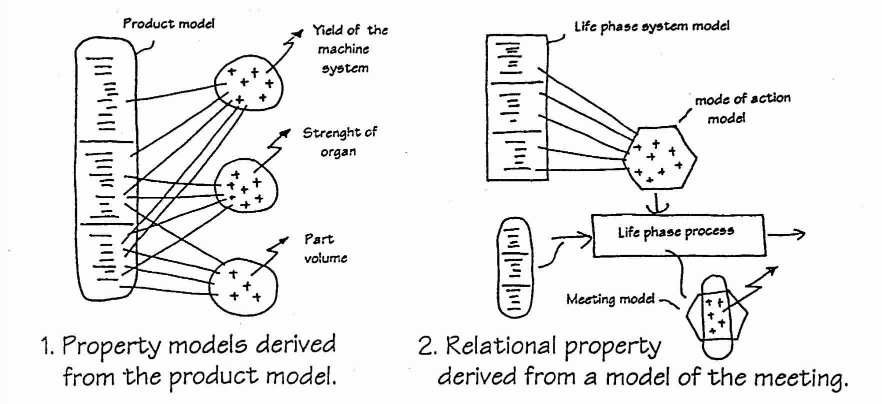


Figure 45: The different views on a product and its assembly system are gradually defined, Andreasen and Ahm (1988)

Andreasen (1992) takes a total life- cycle aspect on product modeling by introducing the notion of product life phase systems. During its lifetime, a product interacts with life-phase systems such as a manufacturing system, distribution system or destruction system. These systems are developed and/or configured concurrently with the product.

Mortensen and Andreasen (1996) continue discussion about interactions between a product and its life-phase systems by introducing the "meeting theory", where relations between two design objects, synthesized into two separate chromosomes, are called meetings (cf. Figure 46). Although it is clear that the product and the manufacturing system are two separate technical systems that, due to high interdependency, need to be developed in harmony with each other, some deeper elucidation of the relationship between a product and its manufacturing system is not in the scope of the original ToD.



1. Property models derived from the product model.

2. Relational property derived from a model of the meeting.

Figure 46: Meeting between a product and a life-phase system, Mortensen and Andreasen (1996)

Olesen (1992) presents the concept of dispositions, where decisions made during product design dispose controls on the manufacturing system design activity. Manufacturing system design activities do, in same manner, impact on product design. The concept of dispositions is a perspective on concurrent engineering based on the ToD. Both product and its manufacturing system are synthesized by the decomposition in four system models: process, function, organ, and component; i.e. a product and its manufacturing system are defined by two separate chromosomes. Dispositions are based on the relationship between different system models that describe a product and its manufacturing system. Four levels of coupling can be identified: range, concept, structure, and component. However, even if this approach by Olesen deals with products and their manufacturing systems as two separate technical system types, the manufacturing control system is regarded as a technical system of its own. Olesen claims that the synthesis must be carried out in three chromosomes representing product, manufacturing system, and manufacturing control system. Manufacturing control system is thus in Olesens approach not regarded as a manufacturing resource type that carries a manufacturing system function of controlling the inherent flow of materials and information between e.g. machines or between machines and humans.

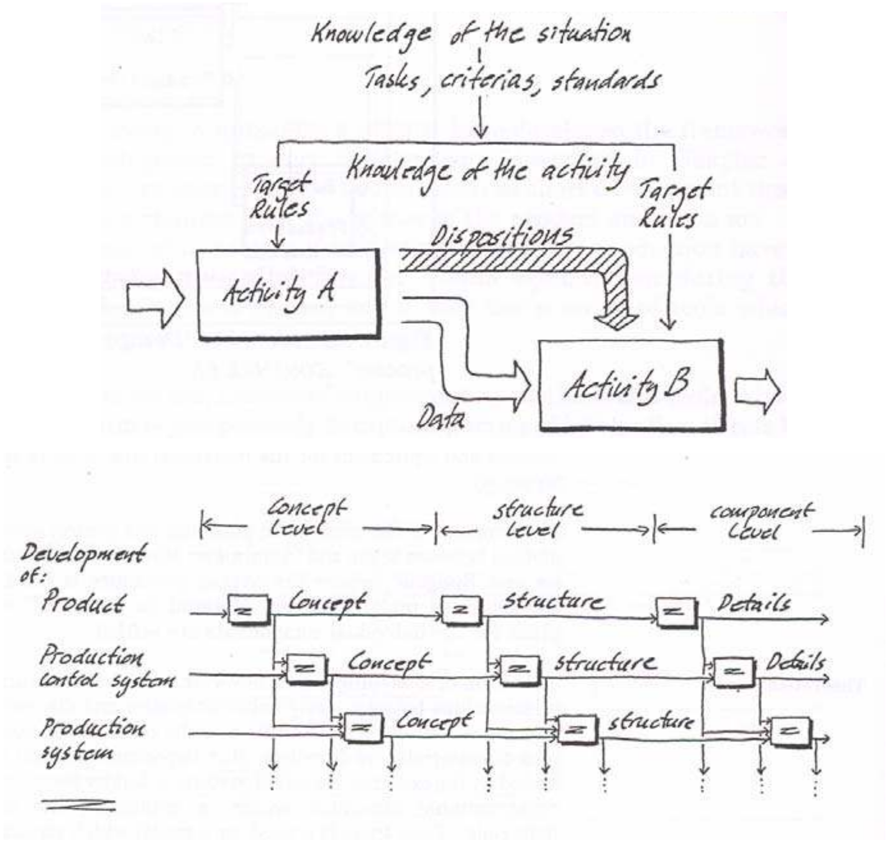


Figure 47: The concept of dispositions, Olesen (1992)

5.3 Axiomatic Design Theory

The concept of domains and zigzagging is also adapted in the Axiomatic Design Theory, introduced by Suh (1990). The Axiomatic Design Theory (ADT) has been under developed by professor N. P. Suh and his colleagues at Massachusetts Institute of Technology since late 1970s.

The ADT is in its structure similar to the ToD; it relies on the concept of domains where a design object is deployed in four domains (cf. Figure 48):

- the customer domain, which is characterized by the Customer Attributes (CA)
- the functional domain, which is characterized by Functional Requirements (FR), according to CAs
- the physical domain, which is characterized by Design Parameters (DP), that satisfy FRs
- the process domain, which is characterized by Process Variables (PV), that control DPs.

The domain on the left (e.g. the functional domain) relative to the domain on the right (e.g. the physical domain) represents “what we want to achieve” whereas the domain on the right represents the design solution, “how we want to do it”.

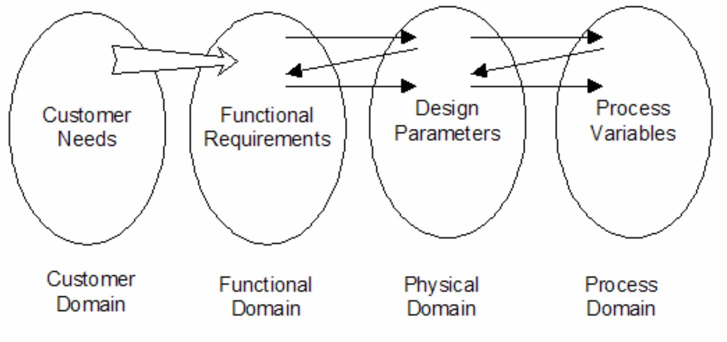


Figure 48: The Axiomatic Design Domains

FRs, DPs and PVs must be decomposed into a hierarchy until a complete detailed design is created or until the design is completed. The decomposition, and the creation of the design hierarchies, is conducted by “zigzagging” between the domains. The designer maps from the “what” domain into the “how” domain and then comes back to the “what” domain in order to generate the next level in the design structure of the "what" domain.

The design solution is continuously synthesized during the decomposition process by application of the design axioms. Two axioms are used as the fundamental decision criteria:

- *The Independence Axiom*: Maintain the independence of the functional requirements.
- *The Information Axiom*: Minimize the information content of the design.

The relationship between domains is in the ADT expresses as:

- {FR}=[A]*{DP}
- {DP}=[B]*{PV}

where [A] and [B] are design matrices that contain the relationship space for vectors that are representing FRs, DPs, and PVs. The design matrix is for good design diagonal (uncoupled design, see the Independence Axiom) and for acceptable design triangular (decoupled design).

$$[A] = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ 0 & 0 & x \end{bmatrix} \quad [A] = \begin{bmatrix} x & 0 & 0 \\ x & x & 0 \\ x & 0 & x \end{bmatrix} \quad [A] = \begin{bmatrix} x & x & x \\ x & x & 0 \\ x & x & x \end{bmatrix}$$

Figure 49: Uncoupled, decoupled and coupled design matrix

The Information Axiom is used when choosing among different design solution alternatives. The meaning of the axiom is that in order to increase the possibility to succeed with the design, the designer must choose the solution alternative with less information content and/or work on the reduction of the information content in the chosen solution. Most information reduction strategies are concerned with reducing the variance of DP's and PV's.

The two axioms of the ADT give a base for development of a wide theoretical foundation. The latest presentation of the ADT by Suh (2001) contains theorems and corollaries based on axiom 1 and 2.

5.3.1.1 Using Axiomatic Design in Manufacturing Systems Design

In the ADT as presented by Suh (1990), the manufacturing system design is taken into account by the determination of the PVs. When a DP for a product is chosen the designer must determine a PV that controls the DP. Suh formulates a theorem about manufacturability, which claims that if a product is to be regarded as manufacturable, the multiplication of the design matrix [A] by the design matrix [B] must yield either a diagonal or triangular matrix, i.e. if either [A] or [B] represent a coupled design, the product cannot be manufactured. However, A PV is a product-centric capability requirement for a manufacturing system but it is not defining all its properties. Suh indeed recognizes the manufacturing system as a separate technical system with its own set of FRs and DPs, but the elucidation of coupling between manufacturing system's FRs and DPs and product's FRs, DPs, and PVs is not achieved neither by Suh (1990) nor by Suh (2001).

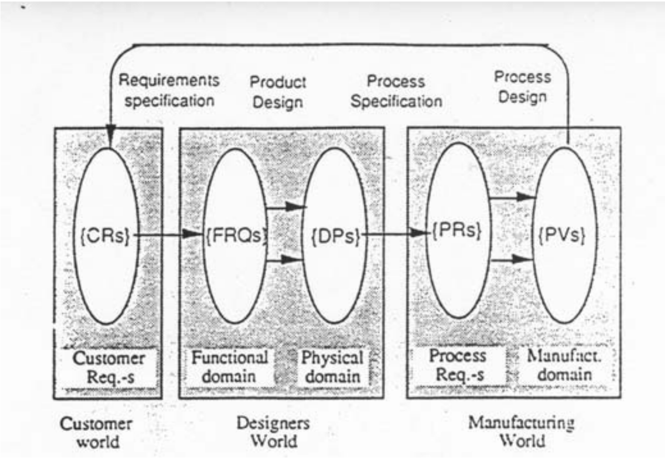


Figure 50: The introduction of process requirements, Sohlenius (1992)

Sohlenius et al. (1992) tries to enhance the coupling between products and manufacturing systems by introducing an additional domain called a "process function domain". This new domain is inserted between the physical domain and the process domain. It contains the manufacturing process requirements that are set by the product. In this new setting, the PVs in the process domain are the properties of the manufacturing processes proposed in order to realize the process requirements (PR) set in the process function domain.

Vallhagen (1996) takes an approach based on an application of the ADT on large systems design, which was originally proposed by Suh (1995). Here, the process domain is replaced by a "manufacturing world" that consists of representations of different subsystems in a manufacturing system. These subsystems: parts manufacturing system, material handling system, assembly system, integration and control system, and human factors system, execute different sub-processes in the manufacturing system. Vallhagen (1996) uses the extension proposed by Sohlenius (1992) and represent every of these five subsystems by a set of PRs and the corresponding PVs. By applying this approach one creates a heterogeneous and complicated manufacturing system description where direct coupling between DPs and PVs as well as between PVs that represent different subsystems is difficult to maintain. This means that the approach presented by Vallhagen is a theory that does not treat a product and its manufacturing system as equal technical systems and does not present a comprehensive mechanism for representation of the relationship between a product and its manufacturing system.

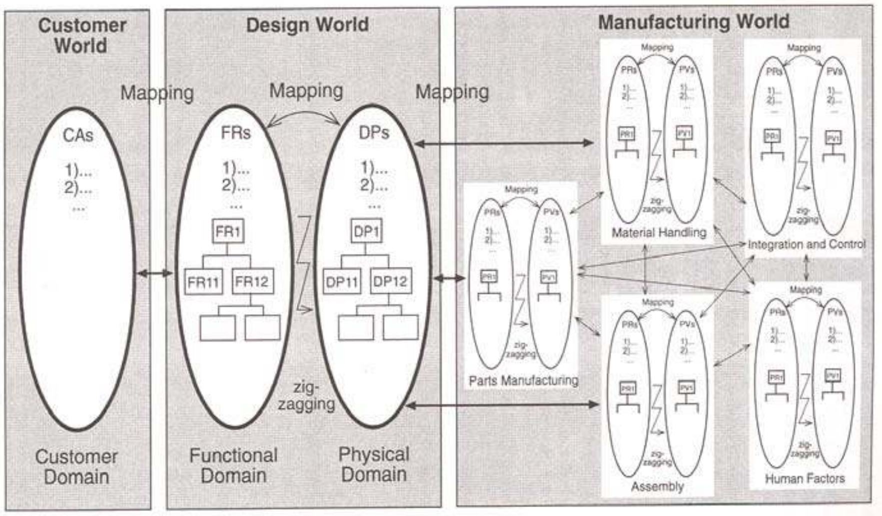


Figure 51: The manufacturing world, Vallhagen (1996)

Sohlenius (2000) proposes a further extension of the work presented in Sohlenius (1992) for the manufacturing system development in the context of concurrent engineering. This extension, besides manufacturing processes, takes even the manufacturing resources into consideration by keeping the original ADT-domains as a description of the product and adding a set of ADT-domains that represent the manufacturing system (cf. Figure 52). The process domain here constitutes, together with business requirements (BR), the functional domain (manufacturing requirements-MR) of the manufacturing system structure. Manufacturing parameters (MP) are DPs for manufacturing system and manufacturing installation (MI) are its PVs. However, because of the lack of relationship details, the structural coupling between products and manufacturing systems still remains unclear.

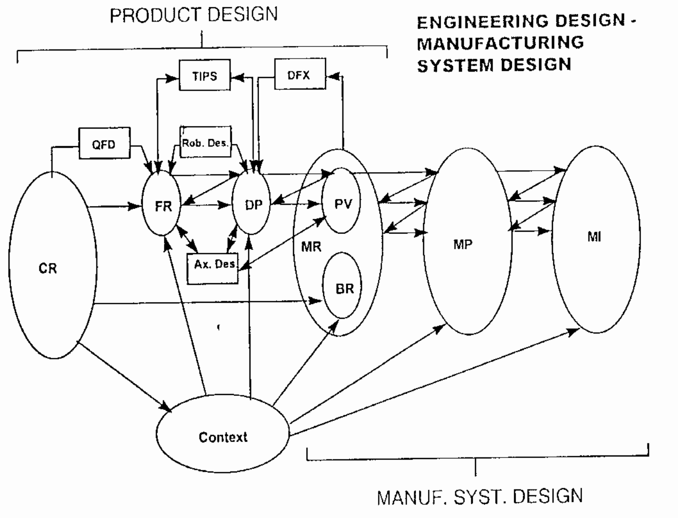


Figure 52: A manufacturing system design framework, Sohlenius (2000)

Similar approach is taken by Almström (2001), who proposes a framework where product-DPs are translated into process-FRs (Sohlenius (1992) calls these PRs) that are realized by process-DPs (Sohlenius (1992) calls these PVs). Manufacturing processes described with process-DPs are then executed by manufacturing resources that are described in a novel "system domain". In this new domain a manufacturing system structure is presented in a heterogeneous manner. Manufacturing system is presented as consisted of an information system, resource system, and organisation system. Almström (2001) takes here a heterogeneous system approach that is similar to that of Vallhagen (1996) and that share the same weaknesses. The reasoning of Almström is even weaker than that of Vallhagen in describing the relationships between different manufacturing system views/subsystems.

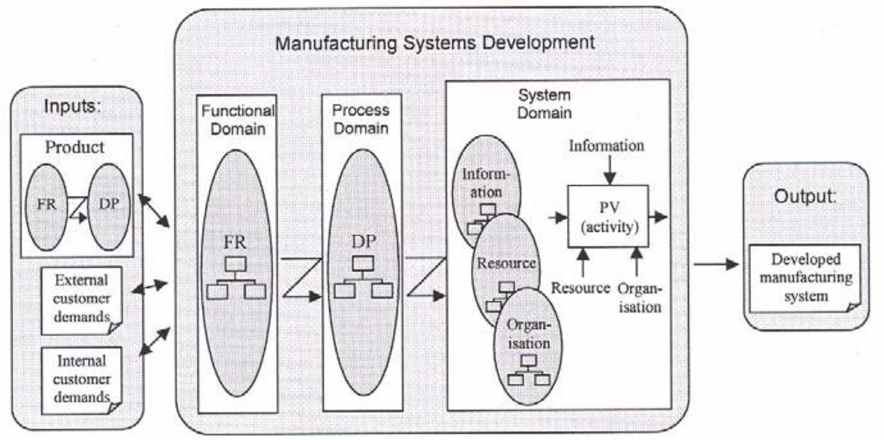


Figure 53: Introduction of a system domain, Almström (2001)

The relationship between products and manufacturing systems in the context of the ADT has also been discussed by Mårtensson and Fagerström (2000). Here, the process domain with its PVs is regarded as bi-directional communication platform where product development and manufacturing system development meet each other. From the product development point of view the process domain is utilized for selecting appropriate manufacturing processes to generate the product and control its DPs. The product solution space here is constrained by the capabilities of a manufacturing system. The manufacturing system can either be under development or already existing. From the manufacturing system development point of view the PVs in the process domain are either important input constraints, or FRs for the manufacturing system design that determine what processes the manufacturing system must be able to execute. Mårtensson and Fagerström have also proposed that the choice of certain manufacturing process and PV impacts directly on product's functional domain by introducing new (end-customer independent) FRs and thus new DPs.

Fagerström et al (2002) offer a view that is on a high conceptual level, and thus does not contain any details, but that demonstrates a comprehensive fundamental idea that does not violate the simplicity of the original theory. Here, a product as well as its manufacturing system are both represented with a set of original ADT-domains that contain CNs, FRs, DPs, and PVs. These two sets of domains are related through constraints that they impose on each other. Any decision in a product domain constrains the solution space in manufacturing system domains and vice versa. By applying this idea it might be possible to utilize strengths of original theory, treat a product and its manufacturing system as equal technical systems in order to maintain simplicity of the theory, and develop a constraint-based framework for representation of the relationship between two design objects.

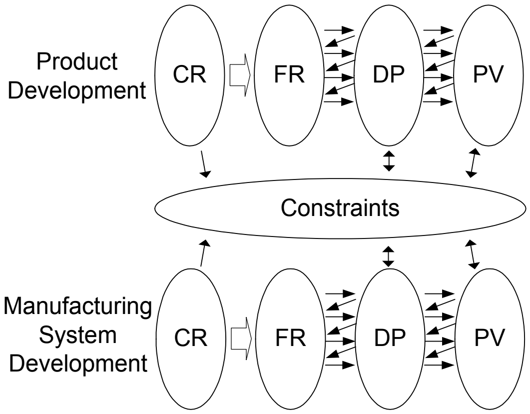


Figure 54: Product and manufacturing system designers communicate through constraining each other, Fagerström et al (2002)

6 INFORMATION MANAGEMENT FOR MANUFACTURING SYSTEMS DESIGN

6.1 Product Data Management

When developing the product and its manufacturing system the developers use many different computer applications in order to support a specific development task. All data that describes models of products and manufacturing systems are manipulated by, and shared between, these different applications.

These data are stored in and retrieved from different *central* databases. These central databases are central in logical sense but are physically distributed across different servers and are managed using some systems for product data management (PDM).

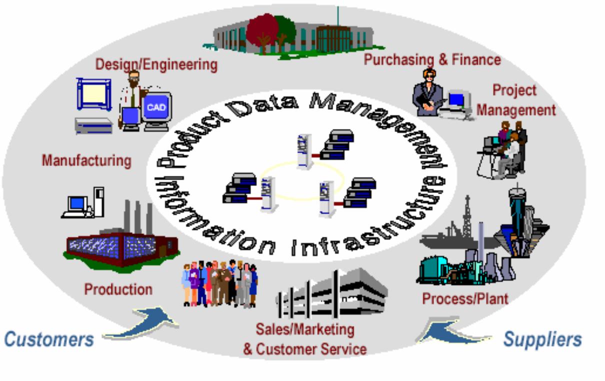


Figure 55: Product Data Management, CIMdata (1997)

PDM systems keep track of the masses of data and information required to design, manufacture or build, and then support and maintain the products. In addition to product data the PDM-systems are able to manage the processes and workflows that are used to modify and control the product (CIMdata (1997)).

6.2 Product Data Management and Digital Manufacturing

PDM-systems were first introduced for data management in CAD/CAE-intensive product development activities. Lately, the manufacturing engineers started to use more complex CAM/CAPE applications to conduct manufacturing system development activities.

This, in combination with increased understanding of relationship between the product and the manufacturing system development activities, as well as the relationship between different manufacturing system development activities, calls for the PDM-systems for manufacturing system data management. A number of system vendors have perceived this need and a number of system solutions for Digital Manufacturing (DM) have emerged on the market.

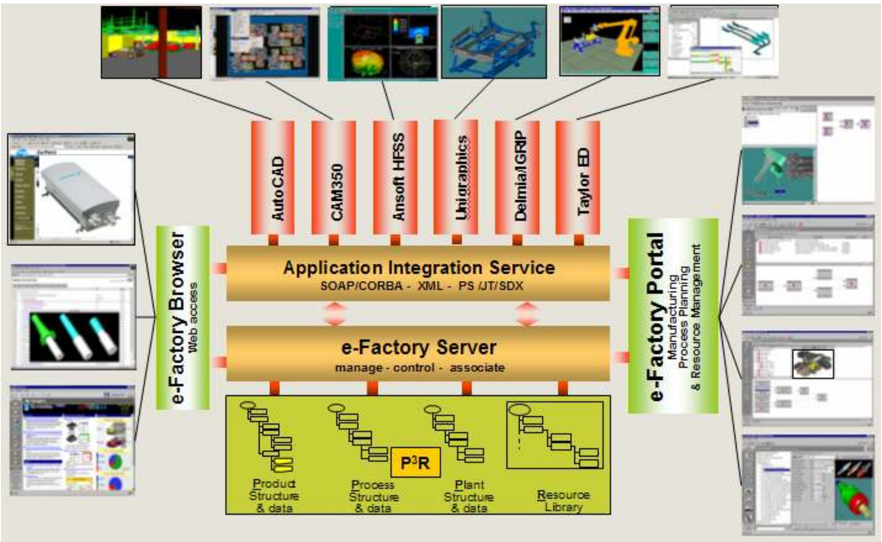


Figure 56: A commercial Digital Manufacturing platform, adapted from UGS PLM Solutions

The domain of DM as defined in this thesis has been under constant transition during the last three decades. Early works, presented by for example Kjellberg (1982) and STU (1986), in the 1980-ies witnesses about the high ambition level in the DM-research community. However, at that time, the possibilities for practical realization of these ideas were limited because of rather low information technology level. In the mid-

1980-ies, first commercial applications emerged and by beginning of the 1990-ies, the works presented by Kimura (1993) and Onosato and Iwata (1993) have emerged. During the 1990-ies the amount of commercial DM-applications have constantly increased and the first manufacturing system development data management solutions were generated by the research society. Nowadays, the commercial DM-concepts are beginning to establish as strong engineering information systems.

6.3 Digital Manufacturing of Today

The definition of DM that is used in this thesis is an expression of current market offer: DM is an information system that enables the execution of the process for collaborative development of products, manufacturing systems and manufacturing processes.

The environment that is based on the DM-concept is used for development of virtual models of manufacturing systems and processes without interference with physical manufacturing systems.

DM consists of authoring applications (e.g. CAM, plant layout, process planning, discrete event simulation, robotics simulation and programming, ergonomics analysis) collaboration applications (e.g. web-based digital mock-up and visualization tools) and data management systems (e.g. PDM) (cf. Figure 56).

6.4 Conceptual Requirements for Digital Manufacturing Platforms

Four conceptual requirements, for information systems in extended enterprises are outlined in Al-Timimi and MacKrell (1996): interoperability, portability, longevity and extensibility. An additional requirement for these information systems is scalability.

6.4.1 Interoperability

Different applications must, while executing in parallel, be able to share information in order to ensure that all users work on the latest set of information. The means for this is for all involved systems to have a common definition of the semantics of the information they create, manipulate and manage.

In addition, to achieve interoperability on a team level, it is necessary to have a common definition of the work processes involved, i.e. a common definition of the workflow, and the flow of information between these processes.

Common definitions of the information and the workflow provide a possibility to implement a information management mechanism that can support execution of workflows for concurrent development of products and manufacturing systems.

6.4.2 Data Portability

Information that describes products and manufacturing systems, must be possible to exchange and share between the applications that belong to the Digital Manufacturing platform. The information need to be described in an application independent way. Portability is one of the means for interoperability.

6.4.3 Longevity

The information should outlive the application and the computer platform on which it was created. This is an important requirement to be fulfilled in order to increase possibility to speed new product development by reusing pre-existing designs.

Furthermore, the systems (products and resources) that are described often need to be maintained, and thus the information is needed, after the system that created the information ceased to exist, sometimes several decades afterwards, e.g. systems in the aeronautical and automotive industry. To achieve longevity, the data semantics must be application- and version- independent.

6.4.4 Extensibility

The information need to cover all thinkable properties of the described object (product and manufacturing system) in order to allow for extended application functionality. However, this may be difficult or, in fact, impossible to achieve. Hence, the information model must be developed in such a way that it is easy to extend to fulfill additional information requirements.

This is of great importance in order to have solutions for information representation that allows for changes in design and modeling techniques, and therefore have ability to take advantage of new development tools and technologies.

6.4.5 Scalability

The implemented Digital Manufacturing-solution must be prepared for continuously increased number of users.

6.5 Digital Manufacturing Architecture

6.5.1 Three-Tier Architecture

All three types of commercial DM-solutions are based on the three-tier architecture principle. According to Larman (1998) the three vertical tiers of this information system architecture are: presentation, application logic, and storage. This separation of the tiers enables information model transparency by decoupling the information model in the application logic tier from the application processing (Johansson and Rosén (1999)). The application tier communicates with the back-end storage layer.

The three-tier architecture enables scalability of the information system by offering a possibility to continuously broaden each tier of the system. The application logic tier can for instance be distributed on several physical network nodes where access to the software objects, in and between the network nodes, is managed by distributed object technologies such as CORBA or DCOM.

This architecture can be illustrated with PDM-systems architecture. CAD-systems and other applications are in the application tier while the meta-database is in the application logic tier. The network file servers that are consisting the referenced application files are operating in the storage tier (Aganovic (2001)).

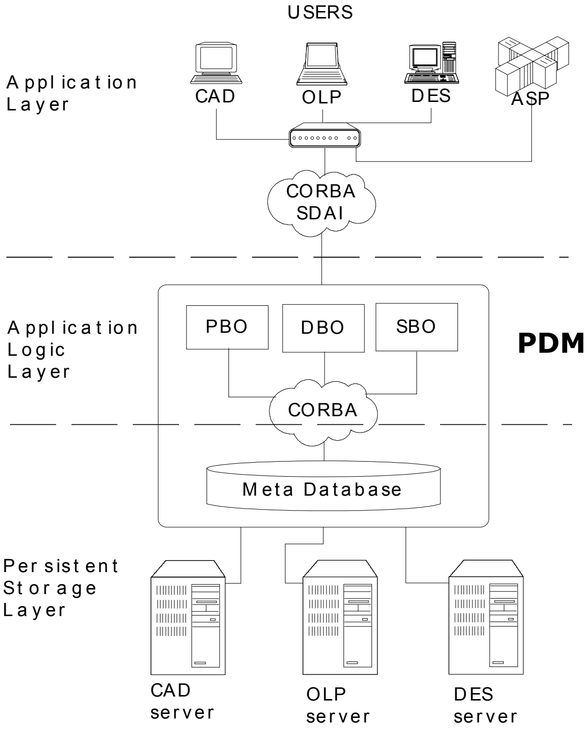


Figure 57: An example of a three-tier architecture, adapted from Aganovic (2001)

All three DM-solution types are built on the three-tier architecture supported by either CORBA or DCOM and thus are able to fulfill the requirement on scalability.

6.5.2 Solution Type 1

This solution provides a common information platform, without external referencing, to share information between the own applications, see Figure 58. However, the lack of workflow capability in combination with a proprietary information model limits the interoperability to a minimum, i.e. no workflow control and no, or limited, interoperability for 3rd part applications.

Furthermore, the proprietary information model, in combination with the lack of standardized interfaces such as STEP, precludes data portability.

It also limits the ability to comment on the longevity of data and the extensibility of the information model. An assumption that can be made, however, is that both longevity and extensibility is limited due to the lack of transparency in the solution.

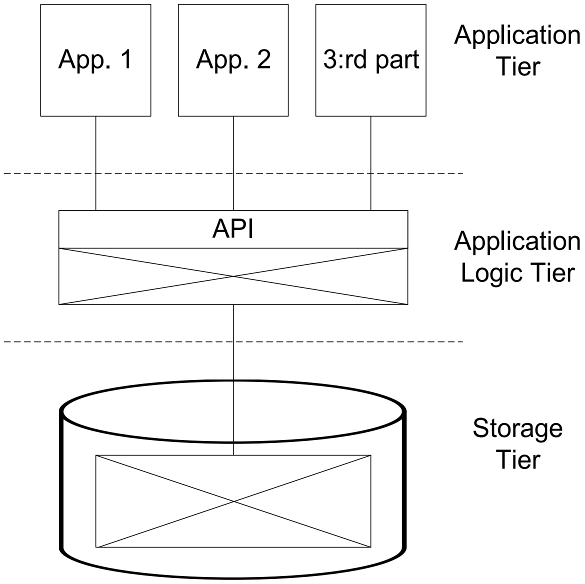


Figure 58: Simplified architecture of solution type 1.

6.5.3 Solution Type 2

This solution provides a common information platform, with external referencing and workflow capability, to share information between the own applications, see Figure 59. In similarity to Solution type 1, the information model of Solution type 2 is proprietary. This provides interoperability for own applications, in terms of workflow control and sharing of data, but it also imposes limited interoperability for 3rd part applications.

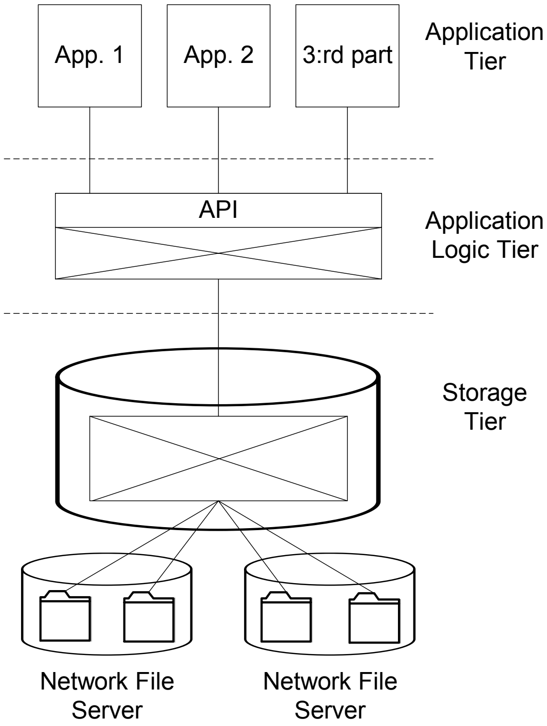


Figure 59: Simplified architecture of solution type 2.

Solution type 2 has, for the same reasons as Solution type 1, no data portability, and no, or limited, data longevity and information model extensibility.

6.5.4 Solution Type 3

This solution provides a common information platform, with external referencing and workflow capability, to share information between the own and 3rd part applications, see Figure 60. In contrast to the two former solutions, Solution type 2 has an open, or partly open, information model. This, in combination with workflow capability, provides interoperability for own and 3rd part applications.

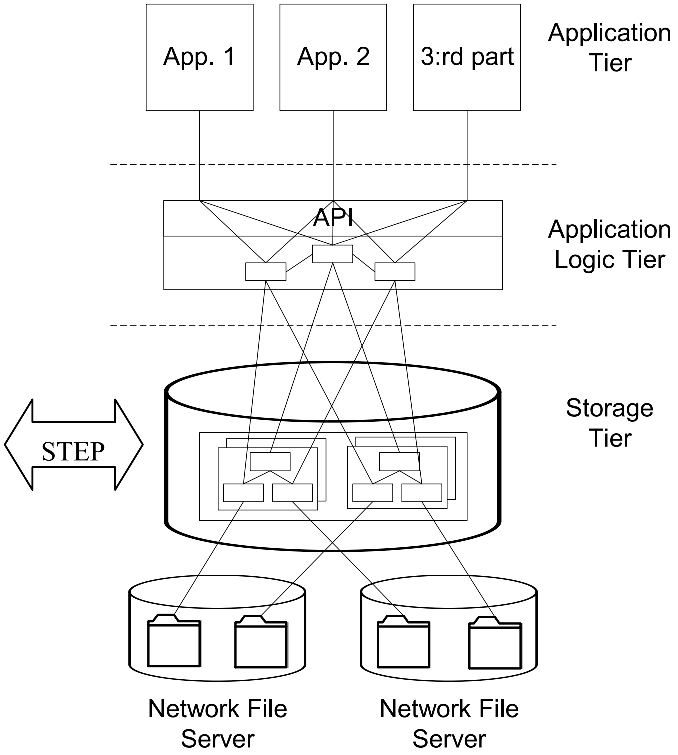


Figure 60: Simplified architecture of solution type 3.

In addition, the open information model, complemented with a STEP interface to part of the open information model, provides the means for data portability. An open information model does not automatically mean data longevity and information model extensibility. It provides, however, transparency to the solution that simplifies migration of data if a change in the information model should occur.

An interface based on an international standard, such as STEP, also imposes stability and, thus, longevity. Even though the internal model changes, the standardized interface remains the same, at least until a major revision of the standard occurs, which usually occur at a much lower pace.

6.6 Semantic Web

The Internet of today is suited for human browsing and searching of textual content. As masses of information grow this model becomes inadequate. In order to more efficiently manage the potential of the World Wide Web (W3), a model that supports integrated and uniform access to information sources and services suited for intelligent applications for information processing is needed. This model require standard mechanisms for data interchange and semantics handling (Decker et al. (2000)).

Semantic Web is an initiative by W3-consortium (W3C) that is set up in order to develop a foundation for the next generation of Internet. This new W3 will enable computers to "comprehend" semantic documents and data and thus execute various tasks by utilizing "services" given by the "resources" on the Internet (Berners-Lee et al. (2001)).

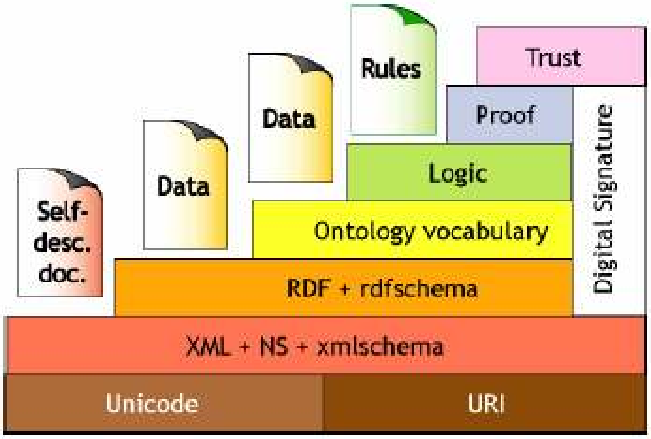


Figure 61: The Semantic Web vision, Berners-Lee (2001)

These resources and their mutual relationship are described using the RDF. RDF, Resource Description Framework, is a standardized foundation for processing metadata. It provides interoperability between applications that exchange "computer-comprehendible" information on the Internet. RDF is not considering a particular application domain or defining its semantics. The semantics of an application domain is defined in its RDF-schema.

RDF is utilizing eXtensible Markup Language (XML) for syntax-representation. XML is a standardized markup language for defining and representing documents that contain structured information.

RDF is a first step towards an environment where different experts and organizations can publish their services on the Internet. These services are then utilized by other organization in, for example, the development of a product or a high-order service. Technical properties of RDF are explained in more detail in Section 6.7.3.2

Besides Semantic Web with RDF, a couple of different web-service platform development efforts are underway in the research and development community. Web-Service Description Language (WSDL) (Christensen et al. (2001)) and Universal Description, Discovery and Integration (UDDI) (UDDI (2002)) are two of these initiatives. WSDL and UDDI complement each other as well as the RDF, and are continuously subjected to the concept harmonization discussions.

6.7 Information Models

When conducting the development activities within an industrial organization an engineer use various methods and tools to make development decisions. In order to be able to make decisions, he/she need certain information as input into the decision-making process. When a decision is made he/she have produced a certain amount of output information, which is usually used as either input to some other decision-making activity within the development process or it is stored in a design repository to be used as representation of the designed object, e.g. a structural model of a manufacturing system. This information flow through the development process is supported with computerized information management systems, e.g. PDM-systems.

6.7.1 Information and other related concepts

Nielsen (2003) provides an explanation of difference between information and other related concepts, i.e. data, knowledge, and competence. According to Nielsen, data is the set of symbolic representation of abstract or real-world concepts. When put in a certain context, data is interpreted in a meaning and thereby becomes the information. When information is understood by a person it becomes a knowledge, which when operationalized by that person, is regarded as competence. Information systems provide therefore the information needed for making competent decisions.

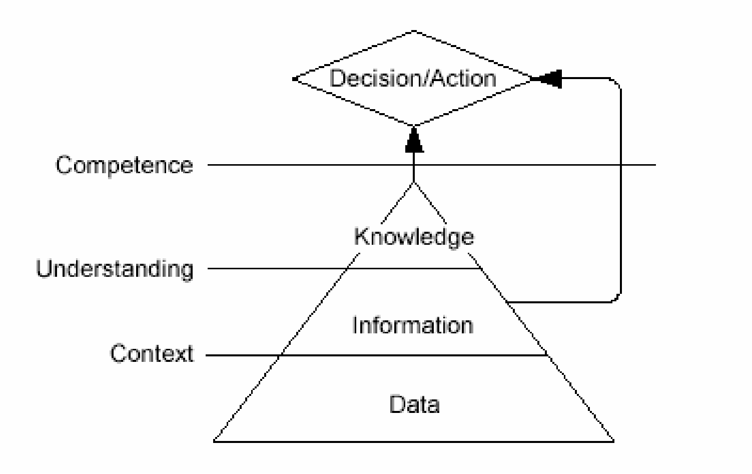


Figure 62: The relationship between data, information, knowledge and competence, Nielsen (2003)

6.7.2 The nature of information model(ing)

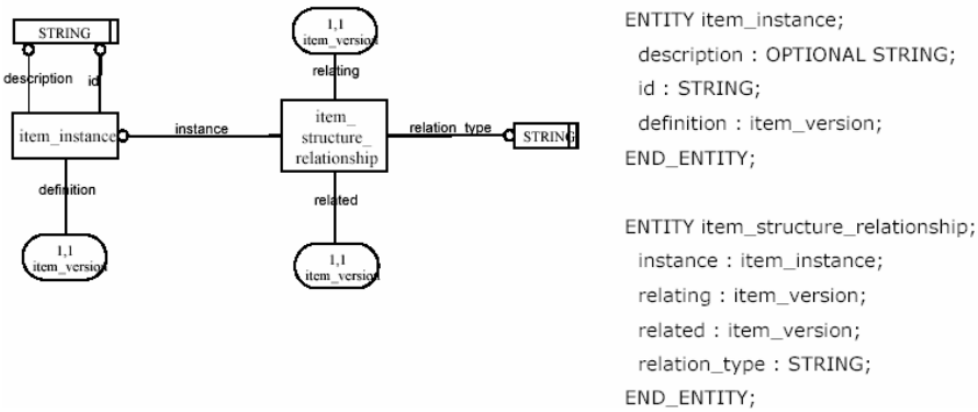
A certain domain of operation, e.g. manufacturing system development, that needs to be supported with a computerized information management system must be represented in a formal way. That means that all relevant information elements associated with the domain that is to be represented must be defined and their mutual relationship must be clarified. Given a certain purpose and a viewpoint, the representation of the domain must be unambiguous. This kind of representation is made through information models. According to Nielsen (2003), an information model is a formal model of data and its interpretation rules.

An information model is created in an information modeling activity, which according to Schenck and Wilson (1994) aims to *formulate descriptions of the real world information so that it may be processed and communicated efficiently without any knowledge of its source and without making any assumptions.*

6.7.3 Representation of information models

6.7.3.1 EXPRESS

Information models can be represented using different information modeling "languages". The most well-known information modeling language is UML, the Unified Modeling Language (Booch et al. (1999)). Other well-known languages are e.g. EXPRESS (Schenck and Wilson (1994)) and Entity-Relationship (Chen (1976)).



```
ENTITY item_instance;
  description : OPTIONAL STRING;
  id : STRING;
  definition : item_version;
END_ENTITY;

ENTITY item_structure_relationship;
  instance : item_instance;
  relating : item_version;
  related : item_version;
  relation_type : STRING;
END_ENTITY;
```

Figure 63: Graphical and lexical representation in EXPRESS, Nyqvist (2003)

Whereas the UML is a pure graphical modeling language, EXPRESS contains both graphical (EXPRESS-G) and lexical representation of information elements (cf. Figure 63). Lexical representation of EXPRESS is directly computer-interpretable, which is considered to be a great strength compared to UML (Johansson (2001)).

Moreover, since EXPRESS is a part of the STEP-standard, i.e. ISO10303-11, (cf. Section 6.8) all the implementable information models within STEP are defined in EXPRESS.

Figure 64 shows a set of basic modeling primitives in EXPRESS-G.

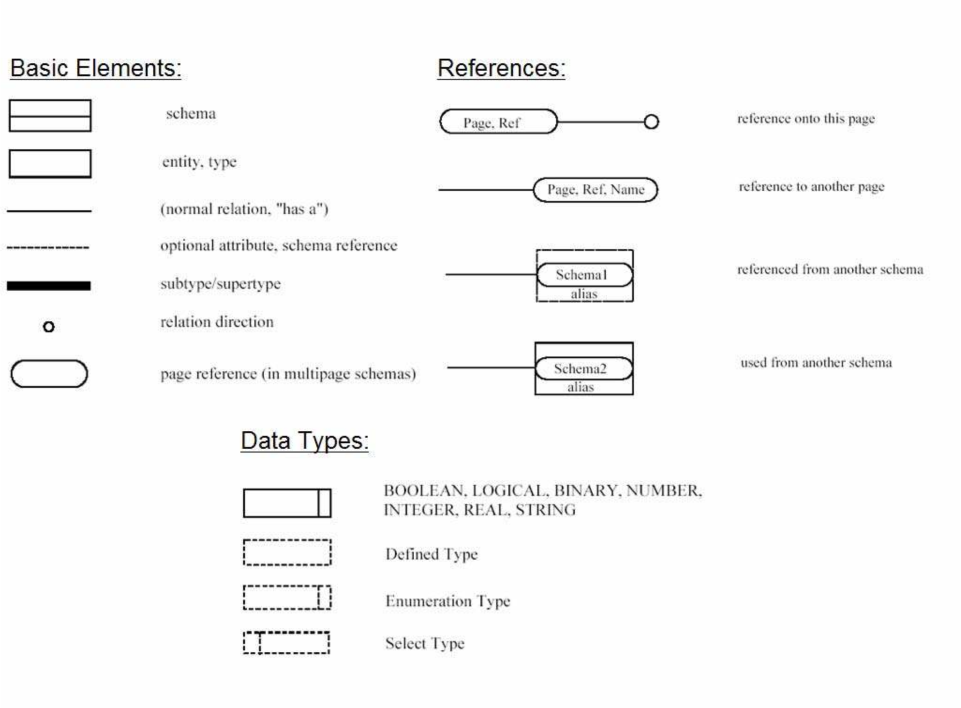
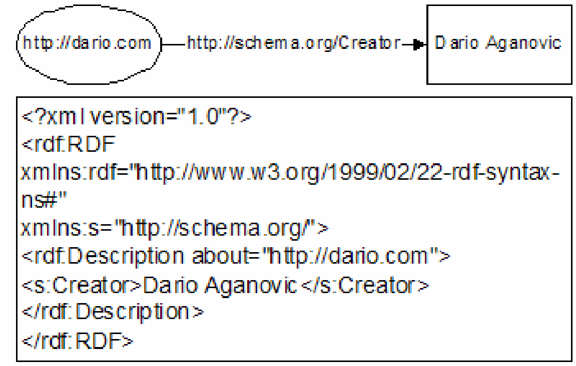


Figure 64: Basic modeling primitives in EXPRESS-G, adapted from Celander (1999)

6.7.3.2 RDF

As already stated in Section 6.6, RDF can be utilized for information management within, and modeling of, Internet-based application domains. Due to its object-oriented nature, RDF provides the possibility to regard Internet as distributed software that has the capability of world-wide distributed information storing and processing. Utilization of RDF-based information management is a way of applying the concept of web-services.

RDF's primary mission is to describe resources on the web, i.e. to manage the meta-data. Every information management resource on the Internet can be represented in a RDF-statement. A RDF-statement always contains a resource, its properties and property values. A statement is, thus, always consisted of a subject (resource), a predicate (property), and an object (value), cf. Figure 65 (Lassila and Swick (1999)).



```
<?xml version="1.0"?>
<rdf:RDF
xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-
ns#"
xmlns:s="http://schema.org/">
<rdf:Description about="http://dario.com">
<s:Creator>Dario Aganovic</s:Creator>
</rdf:Description>
</rdf:RDF>
```

Figure 65: Resource http://dario.com (subject) has property http://schema.org/Creator (predicate) with value Dario Aganovic (object)

RDF is not considering a particular application domain or defining its semantics. The semantics of an application domain is defined in its RDF-schema. RDF-schemas provide means to define property domains and ranges, as well as class hierarchies. RDF-schemas are stored on Internet and are accessed by intelligent software agents when they attempt to interpret certain resource's RDF-information. Figure 66 shows general class hierarchy for RDF-schemas. Figure 67 shows the general constraints for RDF-schemas

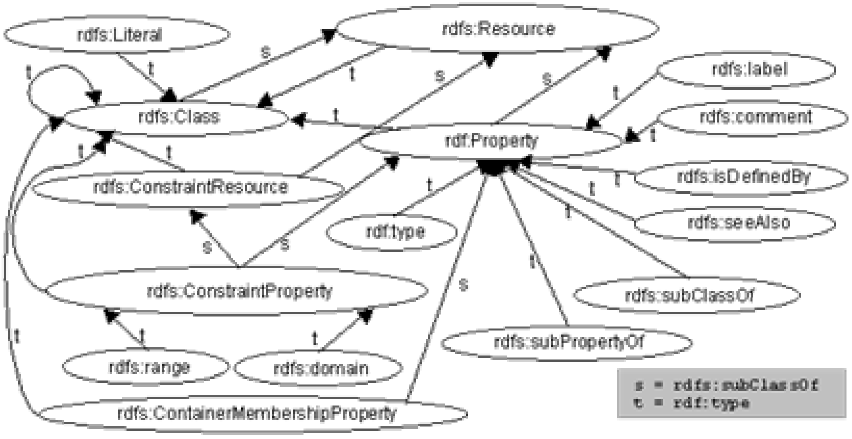


Figure 66: Class hierarchy for RDF-schema, Brickley and Guha (2000)

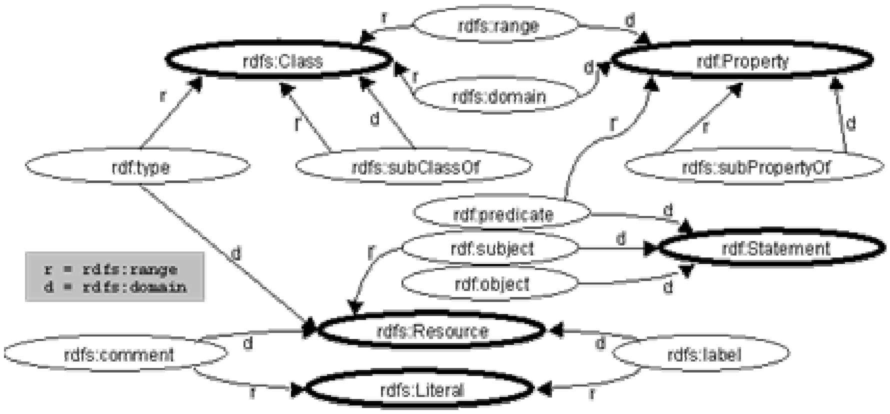


Figure 67: Constraints in RDF-schema, Brickley and Guha (2000)

RDF-statements and RDF-schemas can, like EXPRESS-models, be represented both graphically and lexically. The graphical representation utilizes the concept of directed labeled graphs (DLG) and the lexical representation utilizes the XML-syntax (cf. Figure 65). It is important to stress that XML is a standard mechanism to represent structured data, while RDF provides mechanisms to give meaning to it (Ding et al. (2002)).

6.8 Standardized Information Models: ISO 10303-STEP

ISO 10303 or STEP (Standard for Exchange of Product model data) is an international standard for the computer-sensible representation and exchange of product data (ISO (1994)). One objective with STEP is to provide a standard mechanism for achieving product data extensibility, longevity, portability and interoperability. All STEP mechanisms are application independent. STEP is consisted of several components:

- *Description methods* define the information content of an application by utilizing the data definition language EXPRESS (Part 11).
- *Integrated resources* contain a common set of information building blocks for all application areas. This mechanism enables e.g. mechanical and electrical design view to be represented together.
- *Application protocols (AP)* are formal specifications of the information requirements for a particular industrial application

area. In *Application Interpreted Model (AIM),* application protocols use the integrated resources to represent the information requirements for the application area.

- *Implementation methods* provide rules for mapping of information models built with the description methods into a selected implementation, e.g. clear text encoding is specified in ISO 10303-21 (Part 21), *Standard Data Access Interface* (SDAI) is specified in ISO 10303-22 (Part 22), C++ binding to SDAI is specified in ISO 10303-23 (Part 23), and XML representation of EXPRESS schemas is specified in ISO 10303-28 (Part 28).
- *Conformance testing* specifies how various STEP-implementations should be tested in order to be regarded as STEP-conformant to a certain level.

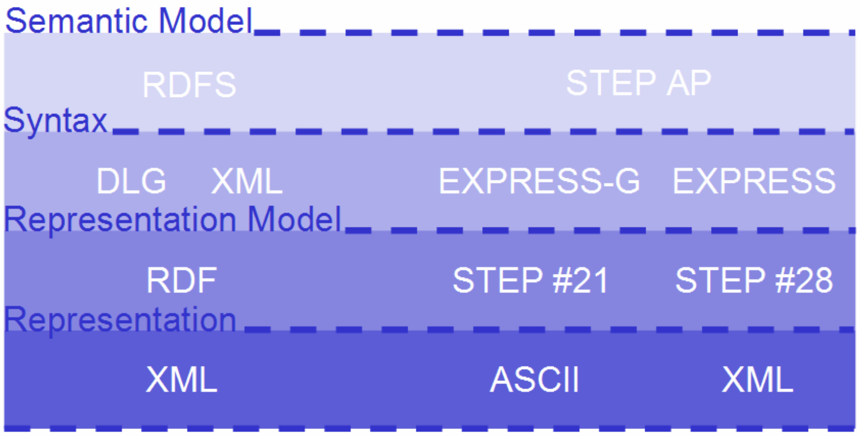


Figure 68: A comparison between Sematic Web (left) and STEP (right)[3]. Application Protocols of STEP contain the information that can be represented as RDF-schema (RDFS) using the syntax and representation models of the Semantic Web.

6.8.1 STEP AP214

STEP's application protocol AP214 covers information requirements for automotive mechanical design processes but is applicable on mechanical products in general. Figure 69 shows the kernel of AP214 structure.

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[3] This figure was developed in collaboration with Johan Nielsen at KTH Production Engineering

AP214 contains hundreds of entities but the ones depicted in Figure 69 are the most significant ones.

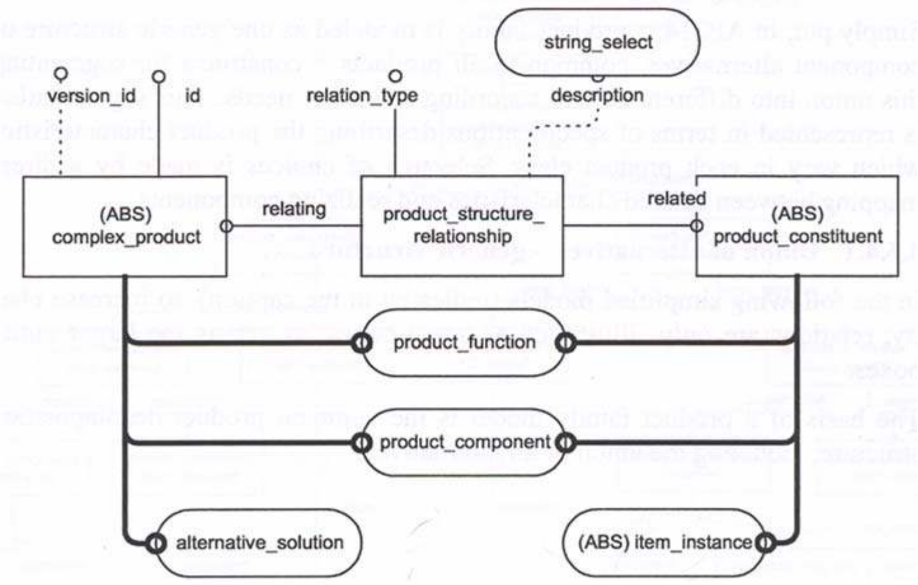


Figure 69: AP214 Structure kernel, Sivard (2001)

Behavior of a product is represented by the entity *product_function*. The behavior, i.e. the function, is carried by a *product_component*, i.e. the principle technical solution, which is an element in a conceptual product structure. The physical entity that realizes the technical solution is *item_instance*. Functions and technical solutions are of type *complex_product*, but are also its constituents, i.e. *product_constituent*. The realization, decomposition, and specialization relationship between the entities is managed through the *product_structure_relationship* entity.

This structure kernel is utilized for management of product as well as manufacturing system structures. The relationship between these structures is managed through AP214 process planning mechanism (cf. Figure 70)

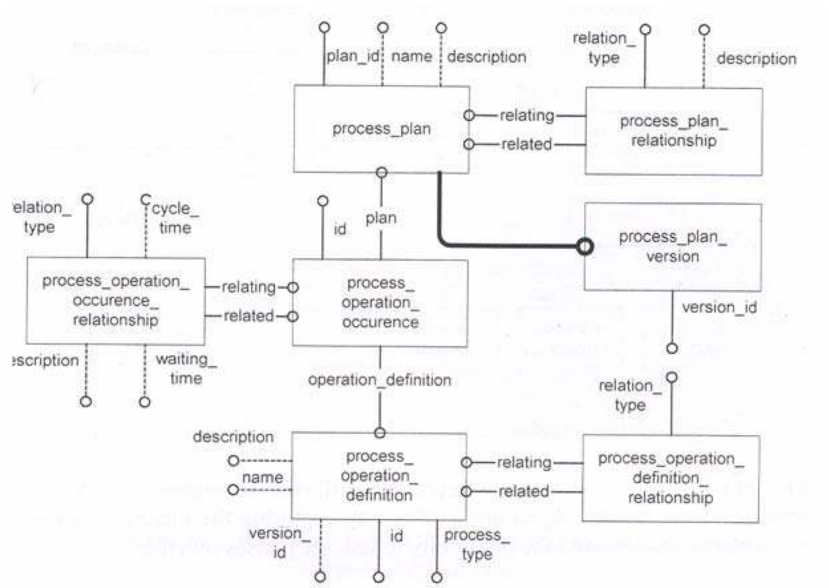


Figure 70: Process planning mechanism in AP214, Johansson (2001)

6.8.2 STEP AP233

STEP's application protocol AP233 covers information requirements for systems engineering (SE) processes in general.

According to Sedres (2001): *AP233 acts not only as a simple exchange standard, but:*

- *Captures the semantics of SE information*
- *Supports exchange of overlapping data between different classes of tools (i.e. CAD and workflow tools)*
- *Facilitates traceability and management of systems engineering information across different tools and SE environments*
- *Opens up the possibility of creating meaningful central data repositories.*

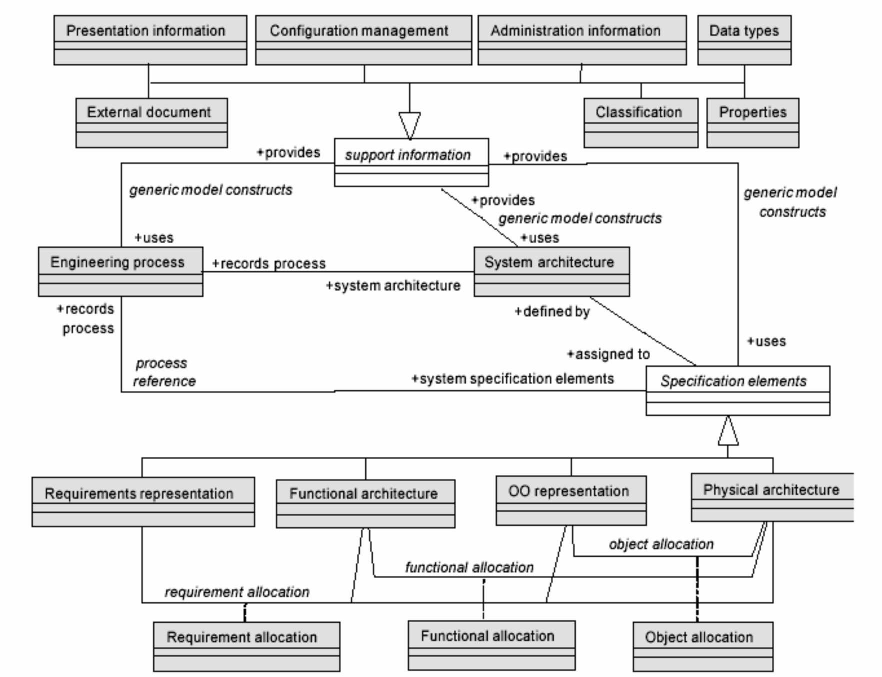


Figure 71: AP233 architecture

Figure 71 shows the AP233 architecture. It is important to stress that AP233 is yet not an official part of STEP, but a working draft (nr. 5) published by ISO as publicly available specification PAS 20542 (ISO (2001))

Despite the fact that is born in aerospace industry, AP233 is not delimited to any specific industry branch since it is developed to be generic, i.e. to be able to represent all kinds of systems, e.g. electromechanical consumer products, energy plants, vehicles, defense products, manufacturing systems, and software (Sedres (2001)).

In the area of integrated product and manufacturing system development the most interesting parts of the AP233-structure would be these that represent the system architecture, functional architecture, physical architecture, requirements representation, and system properties. These different representation entities are utilized when modeling systems from different perspectives.

Although it has a great potential to provide significant benefits if used for development data information management within the field of integrated product and manufacturing system development, there is the lack of research on application of AP233 in this field.

6.9 Information Models for Manufacturing System Development

Within the research community there have been numerous attempts to create information models that capture information requirements within the fields of product and manufacturing system development. Most of the created development information models focus on representing product information and several of them are based on engineering design theory.

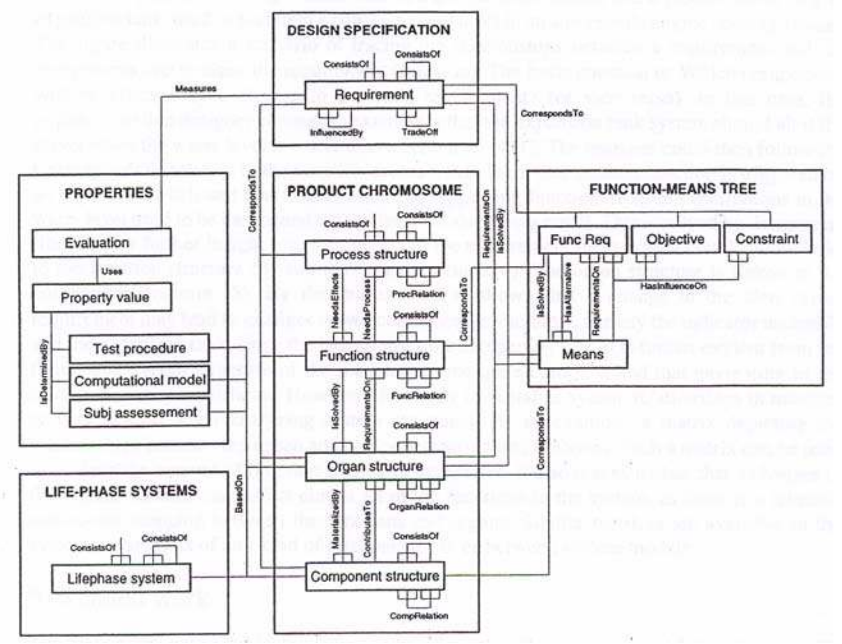


Figure 72: An Entity-Relationship diagram for product models, Malmqvist and Schachinger (1997)

Malmqvist and Schachinger (1997) present an information model based on the Theory of Domains as presented by Andreasen (1992). This information model is aimed to be used as a blueprint for creation of engineering databases for product development.

Schmekel (1992) digs deeper into the engineering design theory and creates an information model based on a merger between the engineering design theory as presented by Pahl and Beitz (1996) and the Axiomatic Design theory as presented by Suh (1990). The parameters presented by Suh, i.e. functional requirements and design parameters, are regarded as quantitative characteristics of qualitative structural building blocks of Pahl and Beitz's theory. The focus of Schmekel's theory and the corresponding information model is on product development without consideration of manufacturing issues.

The information model presented by Szykman et al. (2000) and Hirtz et al. (2002) is an appropriate representative for a common group of development information models. Szykman and Hirtz present results from the Design Repository project by NIST (the National Institute of Standards and Technology), where a web based engineering database and artifact modeling tool is created. Here, the taxonomy of engineering design as presented by Pahl and Beitz (1996) has been used to create an information model that captures a set of common functions and common means that realize them. The ambition with this information model is to provide fundaments for creation of experience databases to support product development activities.

Sivard (2001) creates an information model based on Axiomatic Design theory as presented by Suh (1990) in order to support the development of product families. This information model is also harmonized with STEP AP214 in order to be able to provide a platform for development activities within the extended enterprises. A similar approach is taken by Storga (2002), who base his product development information model on the Theory of Domains and harmonize it with STEP AP203. Storga also proposes an infrastructure for web-services based on the presented information model.

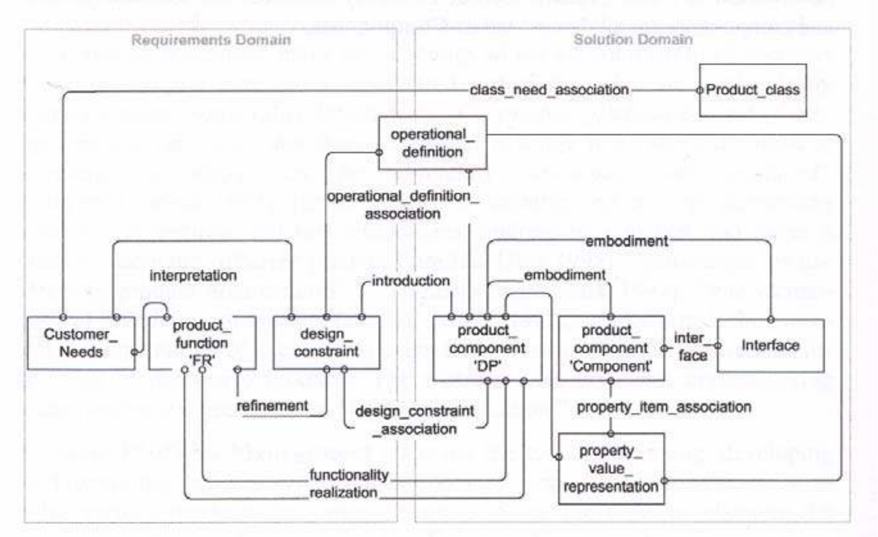


Figure 73: An information model based on Axiomatic Design theory and harmonized with STEP AP214, Sivard (2001)

Johansson (2001) is one of the few researchers who present an information model for concurrent development of products and manufacturing systems. Johansson's work resulted in official additions to STEP AP214 to, besides product development with consideration of certain manufacturing issues, even cover manufacturing system development. This information model is not built upon the theoretical base of engineering design theory, but is a result from a number of industrial case studies and collaboration within STEP standardization group. The correspondence between Johansson's information model and the engineering design theory was never assessed.

Nielsen (2003) extends this work by further elucidating the relationship between products and manufacturing systems within the domain of manufacturing process modeling. Nielsen's information model is not (yet) a part of the official STEP AP214 specification.

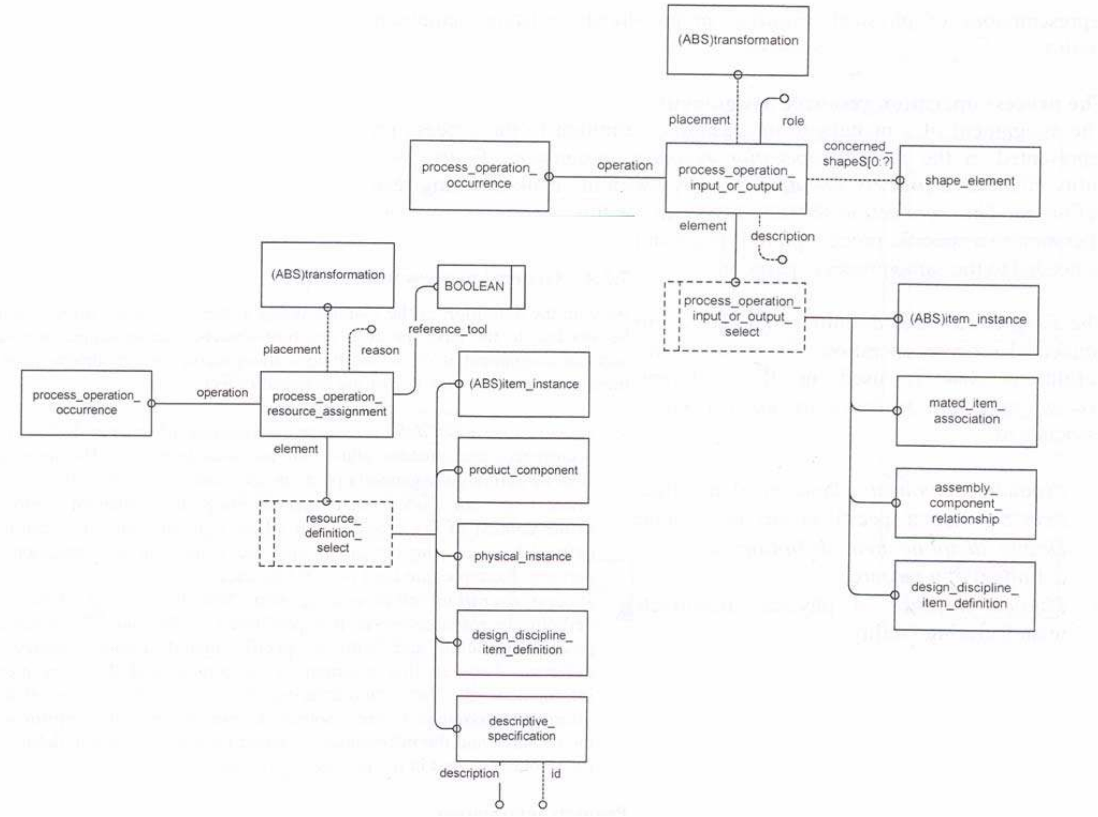


Figure 74: Process to product association (top right) and process to manufacturing resource association (down left), Johansson (2001)

Bernard and Perry (2003) present a concept of informational integration between products, manufacturing technologies, and manufacturing processes aimed to support the process planning activity. This approach does not treat products and manufacturing systems as separate design objects with different structural views, but focuses on describing a possible relationship mode between a chunk of material and processes and machines that transform it into a product.

There are numerous information models that aim to represent a manufacturing system structure from the engineering design theory point of view. One of them is Gabbar et al. (2003), who presents a generic object-oriented model for manufacturing plants that focuses to describe a static structure of a plant, i.e. machines, humans, and information objects, its behavioral model, i.e. what happens within a plant and when things happen, and its functional model, i.e. how do things happen. The weakness of this kind of approach is that it focuses on describing a manufacturing system without explicitly considering the manufactured product.

Part III: Research Results

In this part, the main research results are presented. The research aimed at answering following research questions:

1. *Which are the main characteristics of the relationship between a product and its manufacturing system in the context of manufacturing system development based on concurrent engineering philosophy?*
2. *How can the development tasks, where various methods and tools are utilized for gradual creation of detailed manufacturing system structure models, be coordinated during the manufacturing system development process?*
3. *How can the methodological framework for manufacturing system development be utilized in creation of systems for development information management in extended enterprises?*

First, five industrial case studies are presented. The findings from these case studies are, together with the findings from the literature study presented in Part II, utilized in the creation of a manufacturing system development theory. The theory consists of a development process, a toolbox and a set of hypotheses describing the nature of the development relationship between the design objects, i.e. a product and its manufacturing system, as well as the relationship between different views on the design objects. The theory is validated on an industrial case study. A conceptual information model, based on the theory is also presented.

7 INDUSTRIAL CASE STUDIES

7.1 Case Study 1: Design of a Manufacturing System for Multi-Carrier Power Amplifier (MCPA)

Multi-Carrier Power Amplifier (MCPA) is a key component in third-generation mobile telecommunications systems, WCDMA. The manufacturer, Ericsson Corporation describes MCPA:

The Multi Carrier Power Amplifier (MCPA) is an ultra linear wideband power amplifier.

The use of the MCPA in WCDMA is derived from the fact that a complex wideband radio frequency signal needs to be transmitted over the air interface.

The fact that the MCPA has a bandwidth greater than a single WCDMA carrier enables a number of carriers to be combined at low signal level before amplification. This is a cost effective method of avoiding the need of one power amplifier per carrier.

Figure 75: MCPA

This case study is divided into two sub-cases (A and B) where various aspects on MCPA manufacturing system design in the context of concurrent engineering are studied.

7.1.1 Case Study Data for Sub-case A: Development Project Control Model

This case study is performed at departments for mechanical design, PCB-design (Printed Circuit Board), RF-design (Radio Frequency), industrial engineering, and project management, at Ericsson in Stockholm-Kista during the period between January and April 2001.

7.1.1.1 Question

How is the development project for a telecommunication system product and its corresponding manufacturing system coordinated?

7.1.1.2 Proposition

Product and manufacturing system development projects at a telecommunications system development company are coordinated by rigorous utilization of a formal project control model, which fosters simultaneous product and manufacturing system design as well as efficient and effective decision-making.

7.1.1.3 Sources of Evidence

- Documentation:
    - Product and manufacturing system design process description
    - Design instructions
    - Project management instructions
    - Drawings
    - CAD- and simulation models
- Focused interviews:
    - Two project managers
    - Mechanics Designer
    - PCB-Designer
    - RF-Designer
    - Industrial Engineer – Mechanics

- Industrial Engineer – Printed Circuit Boards
- Industrial Engineer – Test
- Test Designer

7.1.2 Case Study Report for Sub-case A

7.1.2.1 Development Project Control Model at Ericsson

By the time the case study was performed the staff at Ericsson used two different, but synchronized, project models for controlling the product design activities and manufacturing system design activities, respectively. These two models are today merged into a single stage-gate model depicted in Figure 76.

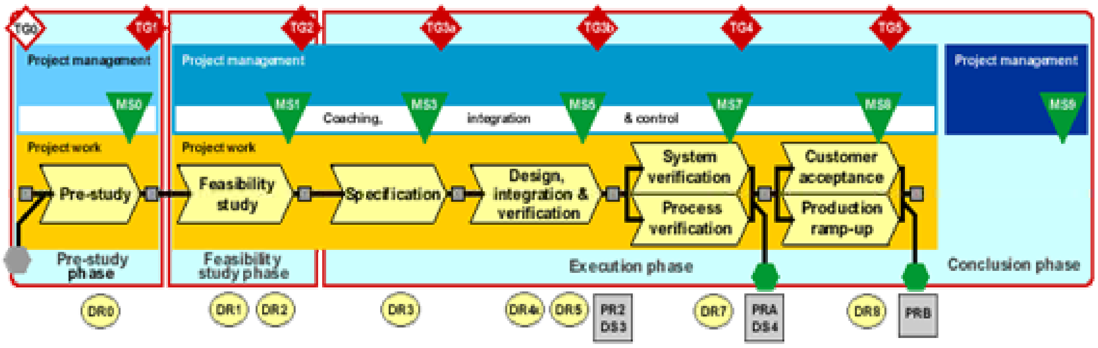


Figure 76: Project control model at Ericsson

Every design activity begins with a pre-study (stage 1), where business opportunities are stated and examined and some product concepts are presented. Thereafter, the project is planned in the feasibility study stage (stage 2). By this time, the manufacturing system designers are involved in the project. Specification (stage 3), which follows the two preparatory stages, is a first execution stage in a product design project. In this stage, requirement specifications for a product and its manufacturing system are developed. The supply chain is here represented by a preliminary supplier list. Requirements specifications are deployed into a product and a manufacturing system design during the design, integration and verification stage (stage 4). This stage is followed by the system and process verification stage (stage 5), where a product and its manufacturing system concept are verified against requirement specifications. Stages 3-5 are iterated several times creating product and manufacturing system increments of gradually higher level of detail and correctness. When a product and a manufacturing system concept with satisfactory properties have emerged a step from virtual and single physical prototypes is taken into customer acceptance and production ramp-up (stage 6). During this stage, certain corrections may lead to requirements redefinition and/or, hopefully minor, product and manufacturing system design changes. When product and manufacturing system properties are regarded to be stable the product design project is concluded (stage 7).

7.1.2.2 Utilization of the Development Project Control Model

The project control model is a general framework than needs to be applied to every single project. The manner of application depends on the type of the project. Although the project control model provides guidelines for how the different applications should be carried out, the project managers apply the parts of the project control model, which is according to their subjective opinion best suited to the project. The project control model contains a wide range of procedures and guidelines, which are more often applied in large than small projects. Since WCDMA-unit is a novel organization, the project control model is used more rigorously in projects run by a well-established GSM-unit than the MCPA-project run by the WCDMA-unit. Generally, the project control model is utilized in stages 1-3, while through stages 4-7 an ad-hoc project control is applied. A possible reason for this practice is project control model rigidity combined with too optimistic time schedules. These utilization patterns contribute to a lower productivity of the product design process than possible and to a lower product design quality.

Although Ericsson executes certain product and manufacturing system design activities in collaboration with external suppliers, the project control model does not contain formal support for supplier participation in the design activities. The only support provided by the project control model is the specification of external technology provisioning activities focused on traditional sourcing rather than co-development.

Ericsson's products are designed gradually by development and realization of product increments. Furthermore, different product development units are responsible for developing different product subsystems. In order to be able to create appropriate system, the coordination between subsystem increments must be carried out. This coordination requires plain requirements management and change management routines. Functional requirements on products and manufacturing systems as well as means of realization of these requirements must therefore be managed. Unfortunately, project control model do not entirely support incremental product and manufacturing system development since requirements cannot be traced across the system boundaries, i.e. between products and manufacturing systems as well as between different product subsystems.

Cross-functional collaboration is a major focal point of the project control model on its highest level. Unfortunately, detailed guidelines for project task execution do not foster cross-functional collaboration with same emphasis. The quality of collaboration between product and manufacturing system designers depends on designers' personal interest in intersystem issues rather than clear procedural instructions provided by guidelines, such as design review guideline. In design review guidelines participation of manufacturing system designers in product design review is recommended but not required. First product design review is carried out by the end of stage 4 on a physical product prototype. Furthermore, cross-functional manufacturing system reviews are not formalized and product designers are not required to participate manufacturing system design activities. Nevertheless, due to modest geographical distance between product design and manufacturing system design departments, some individuals take initiative to visit their colleagues across functional borders to discuss dependency between product and its manufacturing system. Furthermore, change requests resulted from the design reviews are either seldom implemented or implemented after the development project is completed; in a design rationalization project.

By the time this case study was completed an improved product design review guideline was implemented in the project control model. This guideline requires cross-functional participation in DMU-based design reviews that must be carried out as soon a conceptual virtual prototype is developed. In some cases it is possible to do such a design review during the stage 1.

Since the development and realization of in-production test software and test equipment is a time-critical activity, the manufacturing system designers need a test requirements specification at a very early stage. While manufacturing system designers require this specification at latest immediately after the stage 1 has been concluded, the product designers are unable to present it before the stage 3 has come to an end. The project control model is ambiguous in this respect; the specification is to be delivered sometimes between the beginning of stage 2 and the end of stage 3. However, a more intensive information exchange between product designers and manufacturing system designers is required in order to be able to develop test system with right quality at right time.

A critical success factor in every product design project is that senior management, which continuously reviews the project and admits the gate passage has all the information necessary for making the specified decisions. It has been demonstrated that all the necessary information is most often not presented due to the inability of the project management and project participants to coordinate the information flow. However, due to the tight time schedules, senior management feels forced to admit the project to pass the gate even if all decision support information is not presented. In general, problems with information flow management are believed to have a negative impact on all project execution levels regarding both product design process productivity and product design quality.

The collaboration between product designers and manufacturing system designers is identified as critical success factor and is therefore constantly improved. However, the collaboration within functional areas is regarded to be another critical success factor that has not attracted much attention. A manufacturing system, for instance, is a complex system designed by applying a vast range of perspectives and adherent tools used by a great number of engineers with different professional interests. Coordination of various manufacturing design activities is considered to be a neglected area, which must be improved and formalized in a project control model in order to improve efficiency and effectiveness of overall product design process.

7.1.2.3 Conclusions

- Product and manufacturing system design activities at Ericsson are coordinated by partial utilization of a formal project control model. Project control model should contain clear guidelines for application on a number of “standard” project-types. Project control model must contain as few as possible relevant documents in order to be regarded as a tool and not a straitjacket.

- Project control model do to some extent foster simultaneous product and manufacturing system design. Both product and manufacturing system designers must participate in product design reviews. Manufacturing system design reviews, executed by both product and manufacturing system designers should be introduced.
- Design reviews must start, and requirements specification must be developed, early in the project (stage 1) in order to avoid unnecessary iterations.
- Co-development support for collaboration with external suppliers should be implemented in order to improve development process performance in the extended enterprise.
- Project control model do not foster efficient and effective decision-making. Information flow management must be improved so that decision can be based on facts rather than assumptions. Requirements traceability across system boundaries must be improved.
- Coordination of various manufacturing design activities must be improved and formalized in a project control model in order to improve efficiency and effectiveness of overall product design process.

7.1.3 Case Study Data for Sub-case B: Manufacturing System Design Process

This case study is performed at industrial engineering department of Ericsson’s Stockholm-Kista manufacturing plant during the period between November 2001 and January 2002.

7.1.3.1 Question

How are manufacturing system development activities within the industrial engineering department at a telecommunication systems development company carried out, related, and coordinated?

7.1.3.2 Proposition

Manufacturing system development at a telecommunications systems development company include following coordinated activities: manufacturability analyses, manufacturing process design, factory layout design, design of manufacturing operations, design of manufacturing resources, as well as manufacturing system validation.

7.1.3.3 Sources of Evidence

- Documentation:
    - Manufacturing system design process description
    - Design instructions
    - Project management instructions
    - Drawings and CAD-models
    - Manufacturing system specifications
    - Design review reports
- Focused interviews:
    - Project Manager
    - Systems Engineer – Manufacturing
    - Industrial Engineer – Mechanics
    - Industrial Engineer – Printed Circuit Boards
    - Industrial Engineer – Test
    - Test Designer
    - Prototype Manufacturing Engineer
    - Quality Engineer

7.1.4 Case Study Report for Sub-case B

7.1.4.1 Design Structure Matrix

Manufacturing system design at Ericsson is mapped using the DSM-method (Design Structure Matrix) presented by Eppinger (2001). Interviewees were asked to describe activities that they are responsible of carrying out as well as to state which inputs are required in order to be able to carry out these activities. Interviewees were exhorted to disregard the formal guidelines in the development project control model when discussing the issue and to instead focus on mediating a true image of their work tasks. The resulting DSM is presented in Figure 77.

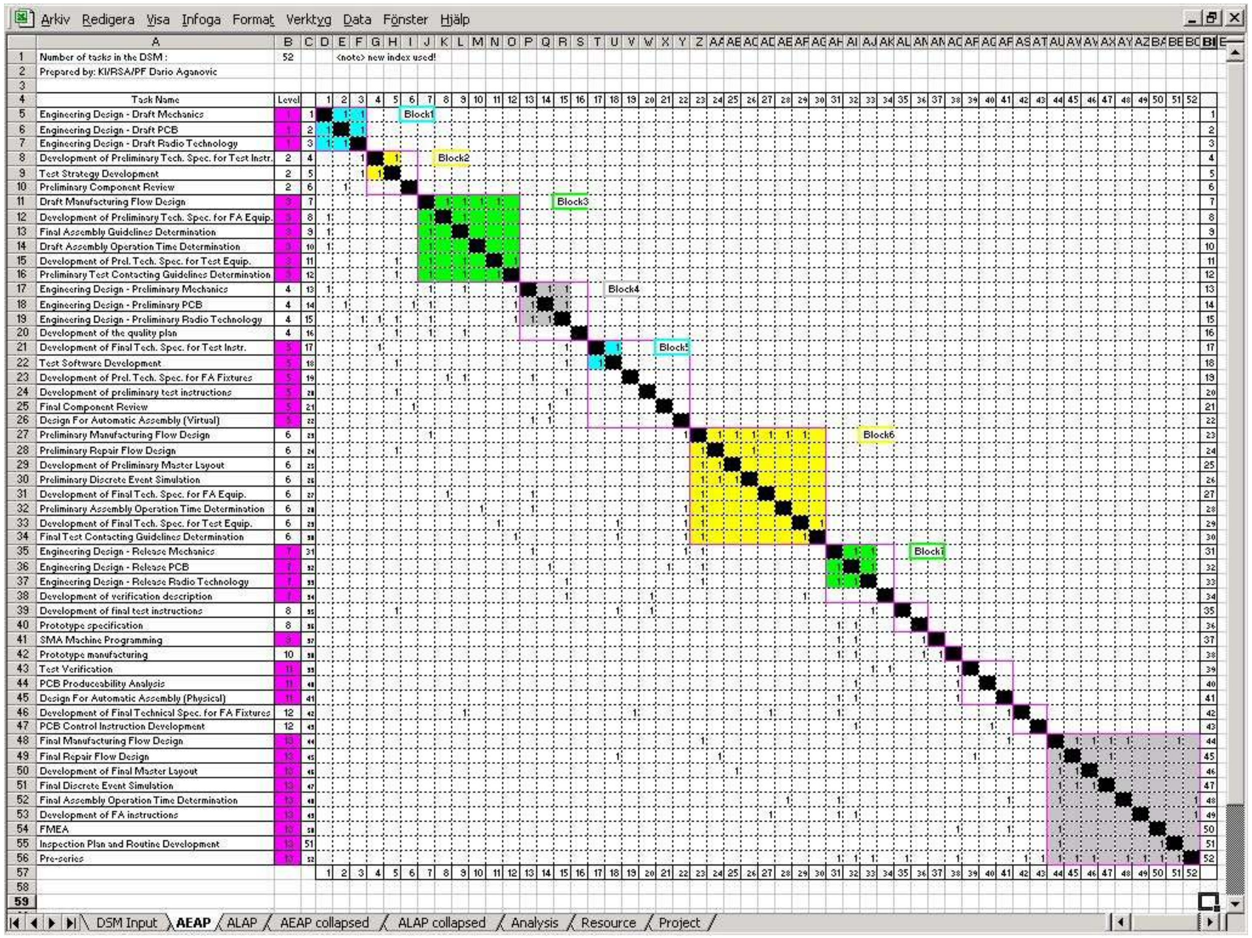
7.1.4.2 The Findings

From a manufacturing system designer's point of view, manufacturing system design process is divided into three stages, i.e. specification, development, and verification. Every of these three stages begins with collecting appropriate product model from product designers. These three stages are re-executed every time a product increment is designed. Sometimes, unsatisfactory results discovered during the validation phase lead to iteration of these three stages.

In first stage a draft product model is collected from mechanics-, PCB, and RF-designers. This model (RF-model) is used by the test developer for development of test strategy and development of preliminary technical specifications for test instruments. PCB preparation engineer is using the product model (PCB-model) to carry out a preliminary component review. Manufacturing system engineer and mechanics preparation engineer use product model (mechanics) to develop draft manufacturing process specification, preliminary technical specifications for final assembly equipment, final assembly guidelines, and preliminary assembly operation times. Concurrently, test industrial engineer is utilizing test strategy, final assembly guidelines, and draft manufacturing process specification to create preliminary technical specifications for test equipment (excluding test instruments) and preliminary test contacting guidelines. During the course of specification work a manufacturing system model consisted of various guidelines and specifications is communicated to product designers.

The next stage is the development stage, which begins with collection of a preliminary product model. During the same time the quality coordinator is developing a quality plan. Test developer is using previously created test strategy and preliminary test instrument specification along with the product model (RF-model) to create final test instrument specification and to develop in-production test software. Test developer is also responsible of creating preliminary test instructions. While test developer is involved with these tasks and PCB preparation engineer is working on final component review, mechanics preparation engineer uses preliminary technical specification for final assembly equipment along with final assembly guidelines to create preliminary technical specifications for final assembly fixtures. He is also responsible for carrying out a Design For Assembly (DFA) analysis. DFA-analysis is carried out together with product designers using a virtual product mechanics model. Thereafter, manufacturing systems engineer begins to work on specifying preliminary manufacturing process specification, preliminary repair process specification, preliminary factory layout, and final technical specifications for final assembly equipment. Manufacturing systems engineer uses a discrete event simulation tool as an aid in e.g. dimensioning and balancing the manufacturing line. Mechanics preparation engineer and manufacturing systems engineer work together in determining preliminary assembly operation times. Concurrently, test industrial engineer is creating final technical specifications for test equipment (excluding test instruments) and final test contacting guidelines. During the course of development work a manufacturing system model consisted of various guidelines and specifications is communicated to product designers.

The last stage in a manufacturing system development process cycle is verification, which begins with collection of a released product model. Test developer initiates this stage by starting development of verification instructions and final test instructions. At the same time, prototype-manufacturing engineer uses product model to specify the prototype, to develop NC-code for surface mounted assembly machines, and to manufacture the prototype. This prototype is then used by test developer for test verification, by PCB preparation engineer for PCB manufacturability analysis, by mechanics preparation engineer for DFA-analysis, and by quality coordinator for failure mode and effect analysis (FMEA). PCB preparation engineer carries then on working with PCB inspection instructions while quality coordinator develops an overall inspection plan. Mechanics preparation engineer creates final technical specifications for final assembly fixtures and final assembly instructions.



Number of tasks in the DSM : 52

Prepared by: KI/RSA/PF Dario Aganovic

	Task Name	Level	
5	Engineering Design - Draft Mechanics	1	1
6	Engineering Design - Draft PCB	1	2
7	Engineering Design - Draft Radio Technology	1	3
8	Development of Preliminary Tech. Spec. for Test Instr.	2	4
9	Test Strategy Development	2	5
10	Preliminary Component Review	2	6
11	Draft Manufacturing Flow Design	3	7
12	Development of Preliminary Tech. Spec. for FA Equip.	3	8
13	Final Assembly Guidelines Determination	3	9
14	Draft Assembly Operation Time Determination	3	10
15	Development of Prel. Tech. Spec. for Test Equip.	3	11
16	Preliminary Test Contacting Guidelines Determination	3	12
17	Engineering Design - Preliminary Mechanics	4	13
18	Engineering Design - Preliminary PCB	4	14
19	Engineering Design - Preliminary Radio Technology	4	15
20	Development of the quality plan	4	16
21	Development of Final Tech. Spec. for Test Instr.	5	17
22	Test Software Development	5	18
23	Development of Prel. Tech. Spec. for FA Fixtures	5	19
24	Development of preliminary test instructions	5	20
25	Final Component Review	5	21
26	Design For Automatic Assembly (Virtual)	5	22
27	Preliminary Manufacturing Flow Design	6	23
28	Preliminary Repair Flow Design	6	24
29	Development of Preliminary Master Layout	6	25
30	Preliminary Discrete Event Simulation	6	26
31	Development of Final Tech. Spec. for FA Equip.	6	27
32	Preliminary Assembly Operation Time Determination	6	28
33	Development of Final Tech. Spec. for Test Equip.	6	29
34	Final Test Contacting Guidelines Determination	6	30
35	Engineering Design - Release Mechanics	7	31
36	Engineering Design - Release PCB	7	32
37	Engineering Design - Release Radio Technology	7	33
38	Development of verification description	7	34
39	Development of final test instructions	8	35
40	Prototype specification	8	36
41	SMA Machine Programming	9	37
42	Prototype manufacturing	10	38
43	Test Verification	11	39
44	PCB Produceability Analysis	11	40
45	Design For Automatic Assembly (Physical)	11	41
46	Development of Final Technical Spec. for FA Fixtures	12	42
47	PCB Control Instruction Development	12	43
48	Final Manufacturing Flow Design	13	44
49	Final Repair Flow Design	13	45
50	Development of Final Master Layout	13	46
51	Final Discrete Event Simulation	13	47
52	Final Assembly Operation Time Determination	13	48
53	Development of FA instructions	13	49
54	FMEA	13	50
55	Inspection Plan and Routine Development	13	51
56	Pre-series	13	52

Figure 77: DSM of the manufacturing system design process at Ericsson

Mechanics preparation engineer works together with manufacturing system engineer in determining final assembly operation times. Manufacturing system engineer develops final manufacturing process specification, final repair process specification, and final factory layout. These final specifications are developed and verified by using the discrete event simulation tool. The verification phase is concluded with preseries manufacturing or/and initiation of a new specification phase.

Manufacturing system design activities within these three stages are related by the information flow between them. Information exchange pattern and activity dependency pattern for manufacturing system design activities at Ericsson is depicted in DSM in Figure 77.

7.1.4.3 Conclusions

- Manufacturing system design activities at Ericsson are divided into three stages: specification, development, and verification. These three stages are re-executed because of new product increment or iteration due to unsatisfactory results.
- Activities within three stages of manufacturing system design include: (i) manufacturability analyses (mechanics, PCB, and RF), (ii) manufacturing process design (including repair process), (iii) factory layout design, (iv) design of manufacturing operations (assembly and test), (v) design of manufacturing resources (assembly and test), (vi) manufacturing system verification (based on physical prototype), and (vii) quality plan development (including inspection routines).
- Manufacturing system design involves a great number of activities executed by engineers within various functional departments with different perspectives on the manufacturing system using different product models (different views, same master model). Information exchange pattern shows great complexity.
- Manufacturing system design engineers work without formal collaboration methodology on the task level (cf. Section 6.1.2.3); i.e. they coordinate their activities ad-hoc. This is likely to lead to long development lead times due to the lack of synchronization as well as unsatisfactory development decisions based on assumptions rather than facts.

7.2 Case Study 2: Development of an Assembly System for Bias-T

7.2.1 Case Study Data

This case study is performed at industrial engineering department of Ericsson's Stockholm-Kista manufacturing plant during the period between December 2001 and February 2002.

7.2.1.1 Question

- How are structures of a telecommunication product and its assembly system related when fitted into the framework provided by the Theory of Domains?
- Does the information management standard STEP AP214 have all the necessary mechanisms to represent telecommunication product and its assembly system structured according to the framework provided by the Theory of Domains?

7.2.1.2 Proposition:

- Both product and its assembly system are represented by the four system models of the ToD. Relationship between a product and its assembly system is expressed in relationship between the system models. The assembly system model has following characteristics:
    - Process model is a description of an assembly sequence for a product.
    - Function model is a description of assembly system capability in terms of assembly processes, e.g. soldering.
    - Organ model is a description of assembly system concept in terms of conceptual function carriers, e.g. robot.
    - Component model is a detailed description of the physical embodiment of the assembly system.
- STEP AP214 can represent all the domain structures for both

products and their manufacturing systems by applying its product representation structure for representing the manufacturing system and by utilizing the process planning mechanism to handle the relationship between the two structures.

7.2.1.3 Sources of Evidence:

- Documentation:
    - Bill of material
    - Drawings
    - Assembly and test instructions
- Open-ended interviews:
    - Industrial Engineer
    - Test Designer
- Physical Artifact:
    - Bias-T

7.2.2 Case Study Report

7.2.2.1 The Product: Bias-T

Bias-T (Figure 78) provides direct current power (DC) to the antenna low noise amplifier (LNA) in the GSM mobile communications networks. Bias-T receives the DC and the radio frequency signal (RF), injects the DC on the low-potential RF, and provides the high-potential RF to the LNA. Both Bias-T and LNA are mounted in the antenna tower.

The active component in the product is the printed board assembly (PBA). The PBA is screwed in the chassis and the connectors are soldered to the board. A seal is placed between the chassis and the cover that is screwed in the chassis. PBA is thus encapsulated with the chassis and the cover, while interfacing the LNA as well as the DC- and the RF-sources through the connectors.

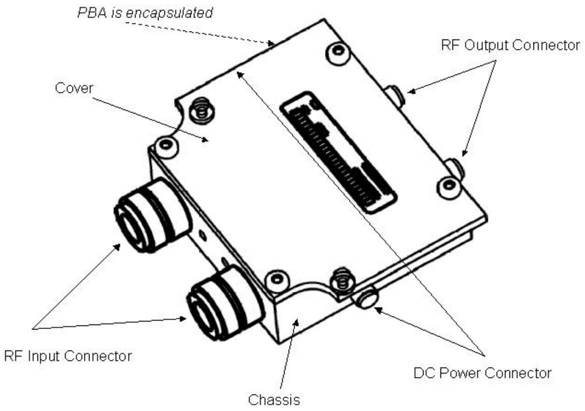


Figure 78: Bias-T

7.2.2.2 The Decomposition of the Product

The product, Bias-T, has only one service, that is to receive the DC and the RF-signal, combine them, and provide the result to the tower mounted LNA. The desired functionality of the product is expressed in the process sequence (PPx-PPy) that is shown in Figure 79.

In order to be able to provide the service the product must contain a set of basic functions that can be combined into the desired process. These basic functions depicted in the function tree (PFx-PFy) are resulting from the desire to handle the DC and the RF-signal as well as from the environmental constraints. These constraints are specifying that the product have to be mounted in the antenna tower. The environmental constraints here are for example, mounting surfaces, temperature variation, and NOx in the atmosphere. These constraints are together with the natural desire to spatially contain physical functionality carriers determining the requirement on the encapsulation function.

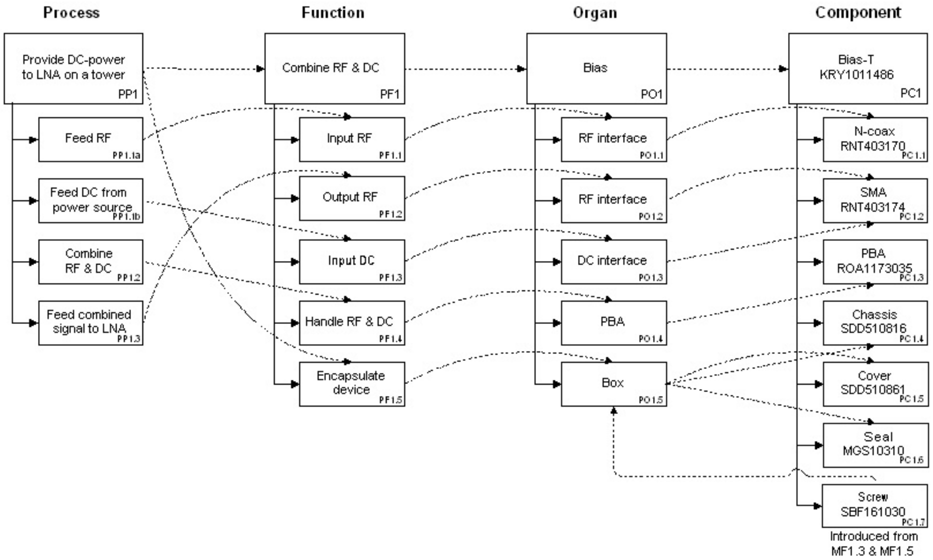


Figure 79: Bias-T decomposition

The functions are realized by the organs depicted in the organ tree (POx-POy). These organs are technical solutions to the functional requirements and can be represented in for example, the circuit diagrams or printed board schemas.

The organs are realized by the components in the component tree (PCx-PCy). These components are either standard components or components tailored in order to materialize a specific organ that realizes a special functionality. In this work the printed board assembly is considered to be a “black box” that is materializing the organ responsible to realize the main functionality of the product, namely DC-RF combination.

7.2.2.3 The Decomposition of the Assembly System

Bias-T is produced in a manufacturing system that is executing a manufacturing process specified in a process structure (MPx-MPy) in the Figure 80. This process is a product-centric description of the sequence of subprocesses that must be executed in order to successfully assemble the Bias-T product. Since the process description is product centric, the subprocesses that are connected with fixturing and transport of the product between the assembly subprocesses are not included in this study.

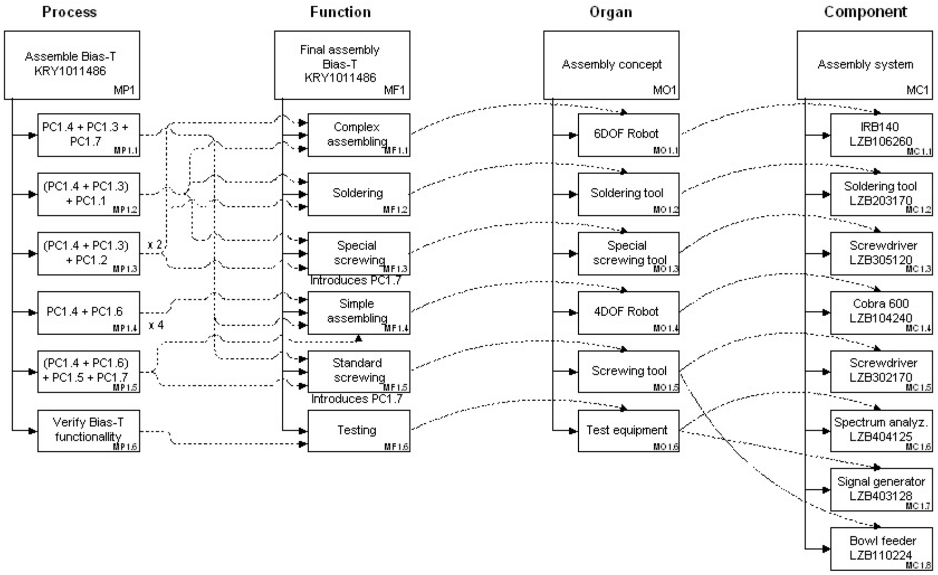


Figure 80: Decomposition of the Bias-T Assembly System

In order to be able to provide the service, the manufacturing system must contain a set of basic functions that can be combined into the desired manufacturing process. These basic functions are depicted in the function tree (MFx-MFy).

The choice of the functions is affecting the product design. Since the product is chosen to be assembled by screwing a new component, the screw, is introduced in the component tree. Naturally, the other components in the product are also affected by, for example, the introduction of needs for screw-holes in the printed board, the chassis and the cover.

The functions are realized by the organs depicted in the organ tree (MOx-MOy). The functional need is satisfied by choice of automatic handling, automatic screwing, and automatic soldering as assembly solutions. The organs are realized by the components in the component tree (MCx-MCy). These components are either standard assembly resources or resources tailored in order to materialize a specific organ that realizes a special functionality. It is important to remark that the spatial properties of the assembly resources and the products are highly coupled.

7.2.2.4 Generalization of the Decomposition in the ToD-based Information Model

In this section some general conclusions are drawn from the decomposition of Bias-T and its manufacturing system and presented as an information model expressed in UML. This UML-model is a conceptual model that is not containing software classes, attributes, methods and association multiplicity. The model consists only of the information entities and the associations between them.

Most of the information entities are specializations of an abstract entity called *Chromosome*. This entity has some general characteristics that are inherited by its child-entities. These characteristics are associations with the entities *Constraints* and *Design Specification* as well as the capability to get decomposed into a hierarchy of its own. This decomposition capability is represented as a self-aggregation association. The entities *Constraints* and *Design Specification* as well as their associations with *Chromosome* is described by Andersson (2001) and Malmqvist and Schachinger (1997).

The entities derived from the chromosome entity are:

- Group 1: *Product Process*, *Product Function*, *Product Organ*, and *Product Component*
- Group 2: *Manufacturing Process*, *Manufacturing Function*, *Manufacturing Organ*, and *Manufacturing Component*.

The associations between the entities inside of each group are described by Malmqvist and Schachinger (1997) as associations between entities *Process*, *Function*, *Organ* and *Component*.

There is, however, very important relationship between a product and its manufacturing system. This relationship that is identified in section 5.1 is here represented by associations between the entities that are representing different technical systems. These associations can be divided in three groups, where each group is containing two associations:

- Group A: System-level associations
    - *Is Determining* **-** a product is determining manufacturing processes that need to be executed in order to generate the product.

    - *Is Constraining* - a manufacturing process that is possible to achieve is putting constraints on product design.
- Group B: Detail-level associations
    - *Influences On* - a manufacturing function influences a product by for example introducing new components, as in the case of screwing.
    - *Influences Choice Of* - a product influences the choice of manufacturing functions by for example setting the demands on highest soldering temperature that is allowed, which in turn affects choice of the soldering technique.
- Group C: Detail-level Spatial Associations
    - *Is Handled By* – a product is physically handled by manufacturing resources, which means that the spatial relationship between the product and the manufacturing resource must be considered.
    - *Is Handling* - a manufacturing resource is physically handling the products, which is setting demands on, for example, product dimensioning if re-use of the manufacturing resources is demanded by the stakeholders.

Furthermore, there is a dependency relationship between manufacturing functions and product organs. For example, the determination of the screwing process as a fastening method is introducing a screw in the product structure (*Influences On*), which in turn is demanding screw-holes to be introduced. These holes can, when exactly dimensioned, be regarded as product components but are as technical concepts introduced in the organ domain. The choice of screw and hole dimensions is setting requirements on choice of the screwing equipment (*Is Handled By*).

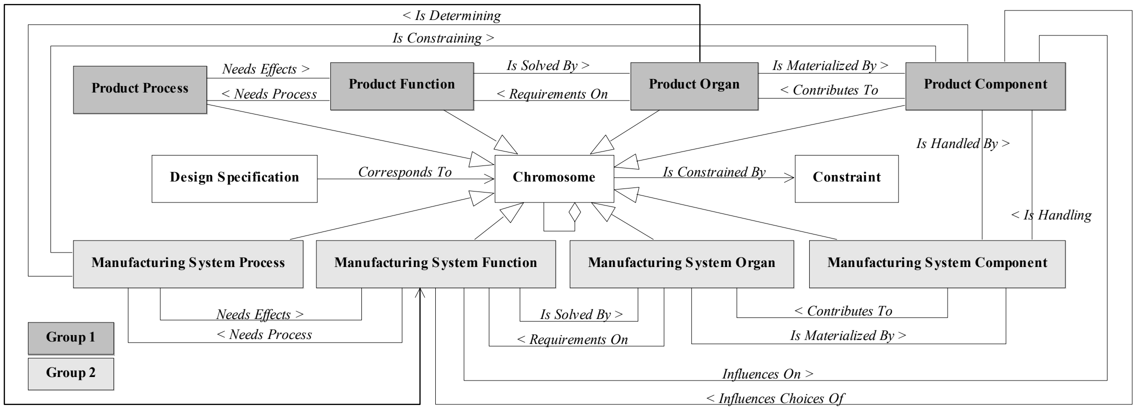


Figure 81: General Information Model for Products and Manufacturing Systems

7.2.2.5 Harmonization of the General Information Model with STEP[4]

In this section, the AP214 standard is analysed and mapped to the General UML model with the purpose to present the relationship between the Theory of Domains (ToD) and AP214. By doing this, it will be possible to understand what parts of AP214 that will be populated when zigzagging through the domains of the ToD. It is important to remark that the model in Figure 82 is simplified and some entities of AP214 and all attributes have been left out.

Product function, -organ, and –component structures are built up according to the same principles as corresponding manufacturing system structures. In the text below, only the manufacturing system structure will be discussed but all the entities that describe the manufacturing system (beside these that describe the manufacturing process structure) apply to the product descriptions as well.

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[4] The main part of the harmonization work presented in this section was conducted by Johan Nielsen at KTH Production Engineering, who participated as a co-researcher in the case study.

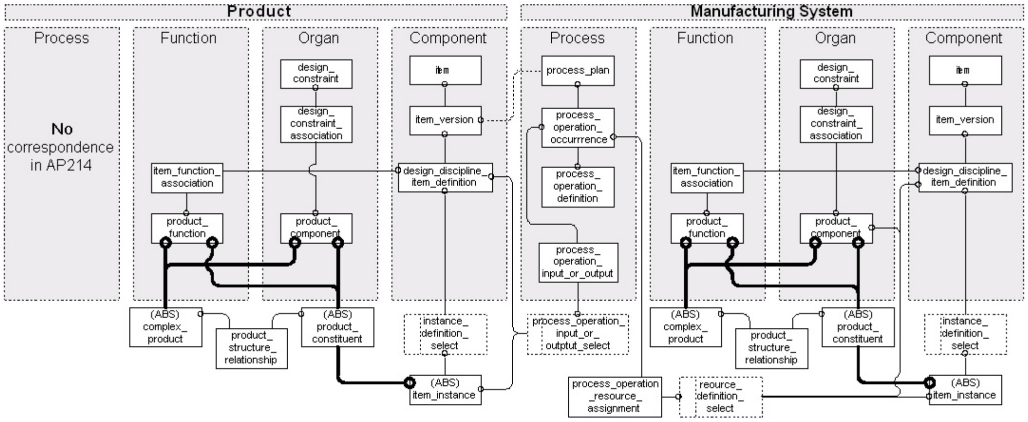


Figure 82: Simplified AP214 model mapped to the domains of the ToD-based General Information Model.

A manufacturing component is represented by the *item* entity, which always has a version, the *item_version*. The *design _discipline_item_definition* entity represents a view on the manufacturing component, such as a mechanical view or an electrical view. An *item* can occur in several different structures and is then represented by an *item_instance* for each occurrence. The *item_instance* is a specialization of *product_constituent* and therefore a connection point between the component domain and the organ domain.

The *product_component* entity is along with *design_constraint* a main entity in the organ domain. It inherits from both *complex_product* and *product_constituent*, and therefore the organ structures are constructed by using the *product_structure_relationship*. This relationship entity also connects the manufacturing organ domain with the manufacturing function domain

The manufacturing function domain consists of the *product_function*. Since the *product_function* entity has the same inheritance as the *product_component*, the function structures are constructed in analogy with organ structures.

The process plan mechanism that shapes the manufacturing process domain provides the means to describe how a product should be manufactured in terms of process steps. The process steps are represented by the entities *process_operation_occurrence* and *process_operation_ definition*. *process_operation_resource_ assignment* couples a process step, i.e. *process_operation_occurrence* with the manufacturing component, i.e. *item_instance*, that is going to execute it.

The relationship between products and manufacturing systems is in AP214 represented by the relationship between product components and manufacturing processes. The relationship is represented by *produced_output,* (the dotted line between *process_plan* and *item_version*) on the *process*_plan level and *process_operation_input_or_output* on the *process_operation_ occurrence* level.

Although similarities exist, some major differences between the Generic Information Model based on the ToD and AP214 can be recognized:

- There is no product process domain representation in AP214.
- Input constraints are only related to the product- and manufacturing organ structures.
- There is no direct connection between the process domain and the function domain of the manufacturing system in AP214. This relation is realized indirectly via the organ domain of AP214.
- There is no direct connection between an organ and a component in AP214. This connection is, instead, realized by the *product_structure_relationship*, which is a relationship between a *product_component* and an *item_instance*. The *item_instance* is then related to the component structure, to finally end in the *item*.
- There is no possibility to represent design specification, i.e. stakeholder requirements, in AP214. A design specification can, however, be represented as a document in AP214 and then be related to the main AP214 entities in the different domains.

7.2.2.6 Remarks

This case contributes to the increased understanding of the relationship between products and manufacturing systems in context of the ToD. Earlier contributions have been focused on the area of product development (Andreasen (1992), Hubka and Eder (1988)). The area of manufacturing systems development is considered to be an important *victim* area that, because of being out of focus, is regarded as a black box.

One limitation with this work is that it is based on a single case study. In order to gain better understanding of the problem domain and increase validity of the results further case studies should be performed.
It is important to mention that the ToD has been subjected to some modifications. A *new* approach, where the function domain has vanished as a structure of its own and the function has come to be seen as a behavior of its organ (function-carrier) has emerged (Andersson (2001), Andreasen (1998). In this case study, the mapping from process domain into organ domain has been carried out through function domain. It is a natural way of working since functions are carrying out processes and thus are appropriate *interface* between processes and organs. Since functions and organs have one-to-one relationship it is possible to assume that the function structure in this paper is just a perspective on the organ structure and thus in conformance with the *new* view on the ToD.

The exclusion of supply chain design (e.g. make/buy decisions) is an important delimitation. Another delimitations are, for example, the exclusion of details regarding verification of product functionality, the exclusion of internal manufacturing system logistics design, and the exclusion of fixture design.

Furthermore, the fact that the existing product has been used as case, all the conclusions about the design process could not be drawn. For example, already when defining the desired functionality of the product and its realization in the product organ, one could start considering the possible manufacturing process concepts. In addition, the telecommunications product functionality is always tested after the final assembly which leads to the conclusion that already when product organs are determined, the test strategy in form of the desired testing procedures and test instruments can be conceptualized. Since lead-time for delivering test instruments is long the test strategy must be considered as early as possible. Having this in mind one understands that some kind of associations may exist between, on one side *Product Function* and *Product Organ* and on the other side *Manufacturing Process*, *Manufacturing. Func-*

tion and *Manufacturing Organ* as well as probably *Manufacturing Component*. These associations could not be identified in this study since an excising product has been emphasized.

The presentation of findings through an UML-model is supporting the implementation of a PDM-system for dynamic extended enterprises that is based on engineering design theory. By using the ToD as a foundation for design process control it is possible to assure that the relevant aspects and decisions about the product and the manufacturing system design are captured and at all times can be traced. Some product-focused steps in this direction were also made in earlier work (Andersson (2001), Malmqvist and Schachinger (1997), Sivard (2001)).

7.2.2.7 Conclusions

The following conclusions are made:

- The ToD provides comprehensive modeling framework for product and assembly system design.
- The relationship between a product and a manufacturing system can be expressed as:
    - determinative/constraining relationship on the system level between product and manufacturing processes
    - determinative/constraining relationship on the detail level between product components and manufacturing functions
    - spatial determinative/constraining relationship between product components and manufacturing resources
    - dependency relationship between product organs and manufacturing function
- Although it is a complex and relatively complete standard, STEP AP214 is, currently, not able to represent all the relationships between, and within, product and manufacturing system representations in the context of the ToD.

7.3 Case Study 3: Development of a Manufacturing System for Attana 100

7.3.1 Case Study Data

This case study of a student project is performed in collaboration between students of KTH's Department of Production Engineering and engineering staff of Attana AB during the period between January and May 2003. In this context, the student teams have been regarded as project groups within an engineering consulting company specialized on manufacturing system development.

7.3.1.1 Question

How can various manufacturing system development tools be utilized throughout different development process stages for generating a manufacturing system concept for an already introduced product, i.e. a biotech-instrument?

7.3.1.2 Proposition

- ToD, as proposed in 6.2, can be utilized as a master structural model during the development of the manufacturing system.
- The structural model can be continuously fed with the data created due to the development decisions made through utilization of appropriate manufacturing system development tools.
- A stage-gate manufacturing system development model can be used to coordinate utilization of different development tools depending on the level of completeness in the design object.
- A PDM-system can be utilized for development information management where the structural model is used as a blueprint for the PDM item structure.
- Activity modeling as to IDEF0 can be used in transferring processes (MP) into uncoupled functions (MF) and corresponding organ (MO) structures.
- Process flow chart can be used for aiding the decisions on e.g. location of buffers and quality controls, transportation routes and for understanding the relationship between value-adding proc-

esses and other, more or less necessary, manufacturing system functions. A process flow chart thus supports IDEF0-modeling activity.

- Manufacturing system layout where overall structure and spatial relationship between physical components (MC) that embody organs are specified can be developed using layout tools such as trip matrix, REL-chart or precedence diagram.
- Job design tools, e.g. MTM, can be used together with process flow charts and activity models in definition of manual processes (MP and MF) and resources (MC). Thus, the human system is treated as an integral part of overall manufacturing system.
- SDP-tools such as DES and CAD/CAM can be used for validation and improvement of developed system concepts as well as for generation of corresponding control programs and 3D manufacturing resource models.

7.3.1.3 Sources of Evidence

- Documentation:
    - Product documentation (3D model and drawings)
    - Manufacturing system documentation (3D models, drawings, simulation models)
    - Project documentation
- Open-ended interviews:
    - 2 Project Managers
    - 2 System Designers
    - 2 Manufacturability Analysts
    - 2 Assembly System Designers
    - 2 Discrete Manufacturing System Designers
    - Product Designer
- Participant-observation
    - Case study researcher has defined the assignment and

working methods used in the project. Case study researcher has also participated in the development project as advisor and chairman of the project steering group.

7.3.2 Case Study Report

7.3.2.1 Manufacturing System Development Process Model

The development process in the Attana-project is executed according to the stage-gate model in Figure 84. The complete model was accessible on the Internet, i.e. sub-processes in Figure 84 were linked to detailed descriptions of activities, including their inputs and outputs as well as documentation templates and links to the PDM- and SDP-clients.

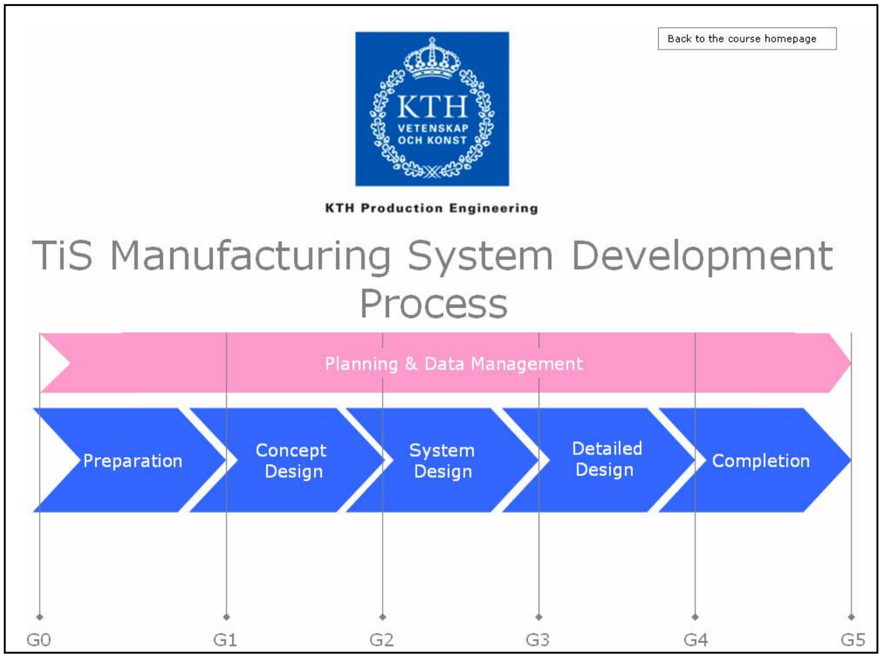


Figure 84: Manufacturing System Development Model @ www.iip.kth.se/~dag/teaching/tis0203/kthipm/

Every stage was executed after a gate-decision made by the steering group based on the progress report presented by each of the two project groups. Both project groups were consisted of a project manager, a system designer, a manufacturability analyst, an assembly system designer, and a discrete manufacturing system designer.

7.3.2.2 The Product: Attana 100

A manufacturing system concept has been developed for a product realized by a Stockholm based biotechnology start-up, Attana AB. Attana's product, Attana 100, is used for chemical analysis in for example development of pharmaceuticals. The product applies Quartz Crystal Microbalance (QCM) technique and is built up of several mechanical subsystems. Some subsystems are developed by Attana while others are standard components acquired from external suppliers. The project was focused on the two product subsystems developed by Attana, namely the analysis unit and the exchangeable chip containing the quartz crystal (cf. Figure 85 for analysis unit).

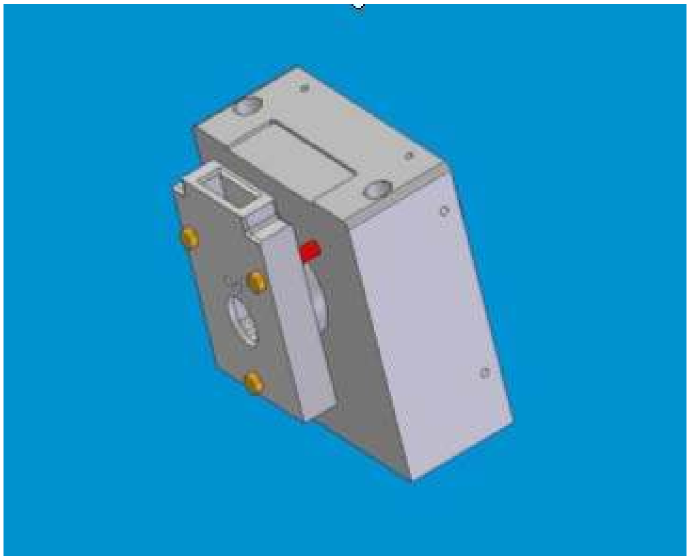


Figure 85: Analysis unit in Attana 100

When the preparation phase started, each group got, besides an assignment specification, a 3D product model and a set of drawings representing each component in the existing product. In order to be able to assess manufacturability and propose product design improvements, project members of each group performed a functional analysis, which resulted in a FR-DP-tree depicted in Figure 86. The functional analysis gives a better understanding of the product components' raison d'être. Thereafter, an initial manufacturability analysis (DFMA), was performed. The manufacturability analysis resulted in a set of product design improvements, of which some were accepted and some were rejected by the Product Designer. A manufacturability analysis was performed for every new product design proposal.

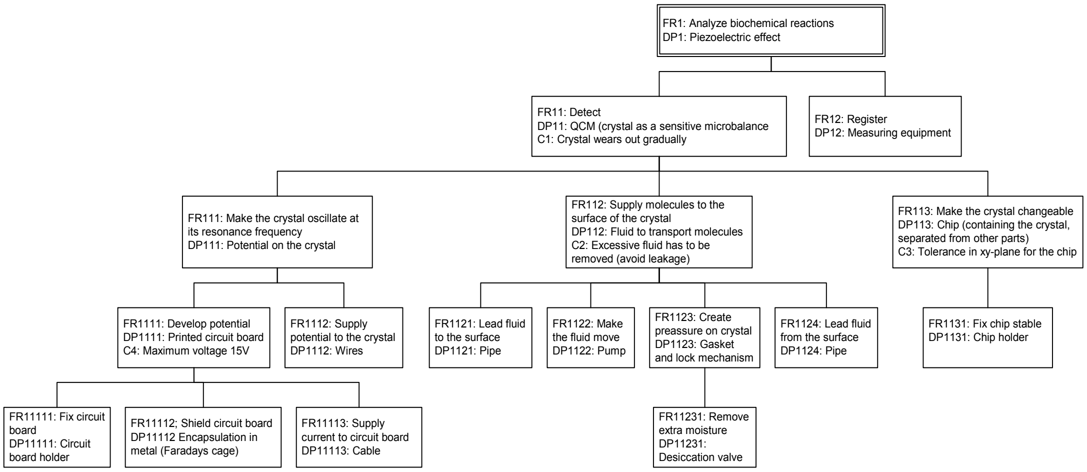


Figure 86: A high-level FR-DP-tree for Attana 100

7.3.2.3 The Manufacturing System

At this point, when the structure of product components (PC/PO) and corresponding functions (PF) is agreed upon, the structure of the manufacturing system must be developed.

In the Concept Design phase the activity modeling method, corresponding to the standard IDEF0-method, has been utilized to create structures for manufacturing functions (MF). First, an overall manufacturing process (MP) structure was proposed. MPs express the value-adding operations that transform input material into components with desired features, as specified in the PC-structure. The MP-structure is product centric and it does not say anything about which manufacturing processes (e.g. turning, milling) are going to be used in order to create a desired product features. These processes are expressed in the MF-structure created using the IDEF0-method (cf. Figure 89).

In the activity model, the value-adding functions of the manufacturing system, e.g. turning and milling, along with the other functions, e.g. transportation and quality controls, were specified and their mutual relationship was examined. This relationship is expressed in material and information flows between the functions. IDEF0 was used concurrently with a process flow chart in order to support the decisions on establishment and elimination of various manufacturing functions, as well as to enhance the understanding of distribution between value-adding and other functions in the manufacturing system.

Besides supporting the establishment of MF-structures, IDEF0 also aids establishing the conceptual structures of the resources (MO) that are going to realize the specified functions. Mechanisms that execute IDEF0-functions correspond to manufacturing resources, e.g. a turning machine or a human operator. Here, layout development tools might be used as an aid for determining a manufacturing system's physical characteristics. MOs are in the System Design phase embodied into specific manufacturing resources (MC), which are structured according to a basic layout type. MCs were selected based on performance requirements due to the product's physical characteristics (MPs and MFs) and on Attana's business data, i.e. input for return on investment calculations. Since a process layout was chosen, a REL-chart was used as a decision support tool.

After an initial layout had been created the manufacturing system was optimized and validated using a DES-tool. Operations times for different MCs were in this stage theoretical, i.e. estimated using formulas for e.g. milling. Figure 87 shows a snapshot of a simulation model created with Extend and the corresponding workshop layout. The structures of the MP, MF, MO, and MC are established concurrently; therefore a change introduced due to a DES-optimization can cause certain changes in a REL-chart and/or IDEF0-activity model.

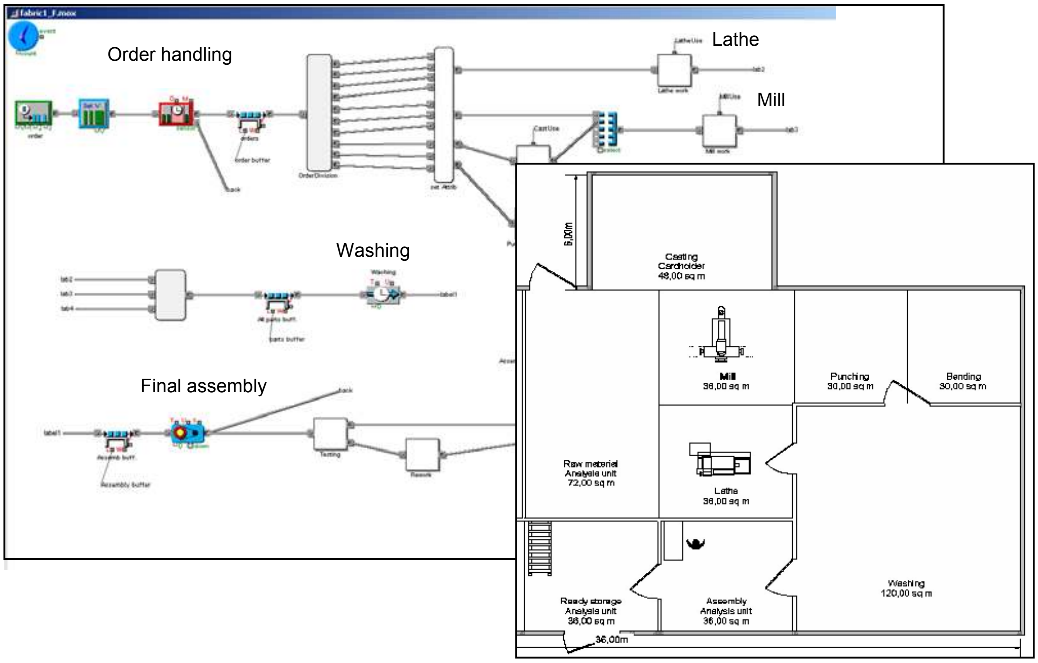
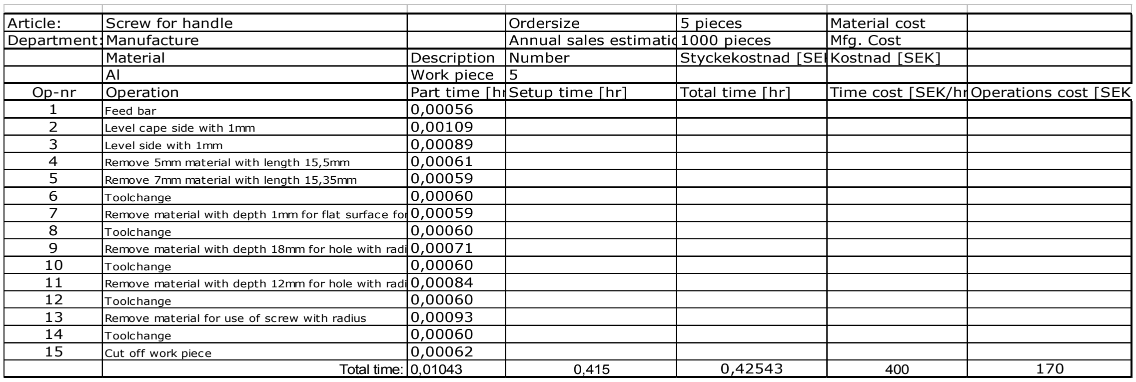


Figure 87: A snapshot of the DES-model for manufacturing of Attana 100's analysis units, and the corresponding layout of the workshop.

When a high-level structure has been established, the detailed resource-level structure must be created. In the Detailed Design phase, MP- and MF-structures were first developed by breaking down the IDEF0-activity models. On these levels, internal manufacturing resource operations, e.g. fixturing of the work piece and material removal, are specified. Operation lists, including operation- and setup-times and -costs are generated together with IDEF0-models (cf. Figure 88).

IDEF0 also helps in generating MO-structures, e.g. fixture- and tool types. MOs are thereafter embodied into specific MCs. Realization of resource-level MPs/MFs into MOs/MCs is supported by SDP-tools. Fixtures for Attana 100 components were modeled using a 3DCAD-tool. Material removal operations, specified in the IDEF0-model, were modeled and simulated using a CAM-tool. Operations times from CAM-simulations were also used for updating the DES-model. Finally, CAM



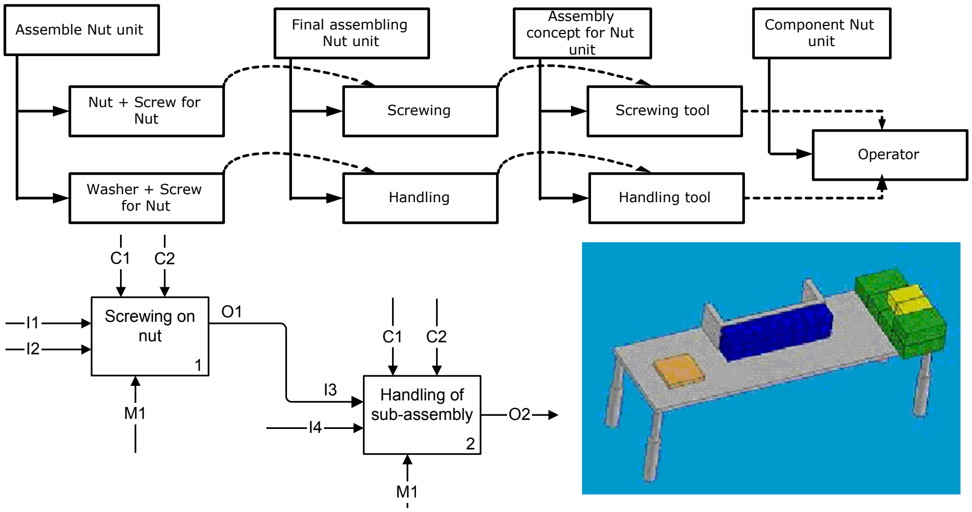
Article:	Screw for handle		Ordersize	5 pieces	Material cost	
Department:	Manufacture		Annual sales estimatio	1000 pieces	Mfg. Cost	
	Material	Description	Number	Styckekostnad [SEI	Kostnad [SEK]	
	Al	Work piece	5			
Op-nr	Operation	Part time [hı	Setup time [hr]	Total time [hr]	Time cost [SEK/hı	Operations cost [SEK
1	Feed bar	0,00056				
2	Level cape side with 1mm	0,00109				
3	Level side with 1mm	0,00089				
4	Remove 5mm material with length 15,5mm	0,00061				
5	Remove 7mm material with length 15,35mm	0,00059				
6	Toolchange	0,00060				
7	Remove material with depth 1mm for flat surface fo	0,00059				
8	Toolchange	0,00060				
9	Remove material with depth 18mm for hole with radi	0,00071				
10	Toolchange	0,00060				
11	Remove material with depth 12mm for hole with radi	0,00084				
12	Toolchange	0,00060				
13	Remove material for use of screw with radius	0,00093				
14	Toolchange	0,00060				
15	Cut off work piece	0,00062				
	Total time:	0,01043	0,415	0,42543	400	170

Figure 88: Operations list for subpart of Attana 100.

aided in generating the control code for NC-machines that shall manufacture the Attana 100 components.

All manufacturing functions are not realized by machines. Operations, such as manual assembly, executed by human resources must also be modeled. In cases where a manual MF is selected, job design tools can be utilized along with IDEF0 to define details of lower-level MP-, MF-, MO-, and MC-structures. MTM was used as a modeling tool for development of Attana 100 assembly work-cells. Figure 89 shows a MTM-table with corresponding physical model, structural model, and IDEF0-model for an Attana 100 component assembly cell.

A manufacturing system development project involves several engineers that produce a great number of documents using many different computer tools. Information management in the Attana-project was carried out using a PDM-system whose metadatabase is based on STEP AP214. PC- and MC-structures were used as items to which documents containing various manufacturing system models (e.g. IDEF0, CAM, DES) were associated.



Left Hand	Time (s)	Symbols	Symbols	Time (s)	Right Hand	Repetition	Time units for left hand		Time units for right hand	
Get nut from #2	1,1916	RB G1C2	RB G1C2	1,0872	Get screw for the nut from #14		24,4	8,7	21,5	8,7
Place screw to the nut	1,6272	MA P2SSE	MA P2NSE	1,5624	Place screw to the nut		25,5	19,7	22,4	21
Hold			TS9.4	3,384	Screw nut with its screw	10			94	
Hold			RD G1C2	1,026	Get washer from #23				19,8	8,7
Hold			MC P1SSE	1,1232	Place washer to the top of the screw				22,1	9,1
Push washer to its place	0,1944	AP	AP	0,1944	Push washer around the screw			5,4	5,4	
Release nut unit to the side of the table	0,6408	MB RL	MB RL	0,6408	Release nut unit		15,8	2	15,8	2
Total time for the left hand	3,654			9,018	Total time for the right hand					

Figure 89: A MTM-table with corresponding physical model, structural model and IDEF0-model.

7.3.2.4 Reflections on the Design Methodology

This case study shows how various development tools can be applied in a manufacturing system development project. As it will be presented in this section, the study also points out a set of inadequacies that must be eliminated in order to be able to present an efficient manufacturing system development methodology.

It is important to acknowledge that the treatment of concurrent engineering issues was highly limited in this case study, since the final design of the product was more or less assumed prior to the start of the manufacturing system development work. Despite that, the project groups still had the possibility to make some impact on product design as a result of manufacturing system development decisions. However, the primal strength of this case study was that the complex discipline of manufacturing system development and application of various development methods to cover different manufacturing system aspects could be studied.

Some inadequacies were however found. First, the members of the project groups found it difficult to keep track of all the data that is created when using a certain method, especially when that data is to be utilized in a future decision making situation and when another method is used. This gives following implications on methodology integration:

a. A software tool or a set of software tools that implement the complete methodology capability (ToD, IDEF0, REL, MTM …) and that operate on the same set of data should be sufficient in order to be able to use all the strengths that a multifaceted methodology provides.
b. Regardless of availability of a software tool, it is crucial to use a consistent terminology between different methods. For instance, a function in the MF-structure of ToD and a corresponding function in the activity diagram of IDEF0's should have the same name in order to enhance understanding of how different methods treat the same conceptual entity.

Second, the members of the project groups experienced difficulties in finding couplings between the different functions, i.e. functional independence could not be assessed using neither IDEF0-diagrams nor ToD-structure trees. The reason for this inadequacy is that manufacturing operations, e.g. milling and assembly, are in the ToD-structure treated as MFs by Andreasen and Ahm (1988). MFs should be regarded as capabilities of a manufacturing system to execute certain transformation processes. Thus, a capability, i.e. a MF, to create a certain surface, i.e. perform a transformation on an object, is carried by the milling device (MO), which is embodied in a milling machine (MC). Here, instead of being regarded as a capability, manufacturing operation of milling is regarded as a technical solution (MO) that provides certain capability (MF). This capability, in its turn, when applied on an object during a period of time can effect a transformation of that object's physical shape. There is a reason to believe that treatment of different manufacturing operation-types as MOs can lead to methodological ability to easier assess functional independence of that system.

Third, during the Attana-project the transition between PC- and MP-structures was carried out ad-hoc. Modeling of MP-structures could be aided by IDEF3-method. IDEF3 is a standardized method that belongs to the same methodological framework as IDEF0, and it may facilitate the data transition between the models.

Finally, robustness of the manufacturing system was not evaluated within the project. It might be possible to manage robustness of the manufacturing system if the Robust Design method is applied. Quantitative parameters that characterize MOs/MCs could be identified using Design of Experiments method and might be regarded as system inputs that together with noise factors impact on system output, i.e. quantitative parameters that characterize POs/PCs.

3.4.4 Case Study Conclusions

- ToD can be utilized as a master structural model during the development of the manufacturing system. In order to capture different system views as proposed in original TTS/ToD and to facilitate functional independence analyses, manufacturing operations, e.g. milling and assembly, should be regarded as technical solutions (MOs) rather than manufacturing system capabilities (MFs).
- The structural model of a manufacturing system can, coordinated using a stage-gate manufacturing system development model, continuously be fed with the data created by appropriate manufacturing system development tools.
- A PDM-system can be utilized for development information management where the PC- and MC-structures were used as a blueprint for the PDM item structure.
- IDEF0 and IDEF3 can be used for modeling of MF- and MP-structures, respectively. IDEF0 gives also a first hint about the MO-structure. Modeling in IDEF0 can be supported with process flow charts during the development of overall manufacturing sys-

tem concept. Operations lists and MTM support IDEF0 in development of manufacturing cells.

- Manufacturing system layout where overall structure and spatial relationship between MCs that embody MOs are specified can be developed using layout tools such as REL-chart.
- Quantitative parameters that characterize MOs/MCs, i.e. PVs, and quantitative parameters that characterize POs/PCs, i.e. DPs, might be found through the application of DoE and utilized to enhance robustness of the manufacturing system.
- DES and CAD/CAM can be used for validation and improvement of developed system concepts as well as for generation of corresponding control programs and 3D manufacturing resource models.
- In order to enhance methodology efficiency and effectiveness when applied, the methods should be integrated. This integration can be supported through implementation of methodology as a software toolbox and through use of consistent terminology between different methods.

7.4 Case Study 4: Information Management in Manufacturing System Development Operations at Ericsson

7.4.1 Case Study Data

This case study is performed at industrial engineering department of Ericsson's Stockholm-Kista manufacturing plant during the period between February and December 2001.

7.4.1.1 Question

- How are product and manufacturing system development activities supported by the information system at a telecommunication systems development company?
- How are data that describe products and manufacturing systems created, used and related to each other?

7.4.1.2 Proposition

- The various manufacturing system development activities are supported by a dispersed set of interconnected information systems, i.e. separate activities are supported by a separate application within the information system.

- The data that describe the developed products and corresponding manufacturing system are created in different applications but are all interrelated in an enterprise-wide product data management system.
- The product data management system contains different versions of structures that describe functions and technical solutions for developed products and manufacturing systems. The various structures are strictly interrelated.

7.4.1.3 Sources of Evidence

- Documentation
  - Ericsson Corporate IT/IS-strategy
  - Ericsson Corporate PDM-strategy
  - Reports from PDM-implementations at Ericsson
  - IS-datasheets
  - White papers from IS-vendors
  - Research papers on PPRDM and digital manufacturing
  - Reports from PDM market research companies
- Focused interviews
  - Project Manager
  - Mechanics Designer
  - RF-Designer
  - Industrial Engineer – Mechanics
  - Industrial Engineer – Printed Circuit Boards
  - Industrial Engineer – Test
  - Test Designer
- Open-ended interviews

    - PDM System Manager
    - Technology Development Manager
    - Operational Development Manager
- Participant-observation:
    - Case study researcher has participated in the PPRDM-pre-implementation project as project manager. The project contained the mapping of requirements on information management systems for manufacturing system design as well as evaluation of such PPRDM-systems and –vendors
- Physical artifact:
    - Legacy PDM-system: PRIM/GASK2
    - PPRDM-systems by three vendors
    - Digital manufacturing applications by 11 vendors

7.4.2 Case Study Report

By the time the case study was performed, Ericsson Corporation was executing a change process, with a main goal to provide better information management support to Ericsson's core business processes. Redesign and integration of information system architecture for product and manufacturing system development was considered as a hot issue. Therefore, this case study report presents a picture of current information system architecture for product and manufacturing system development and a picture of the future architecture that the enterprise aim to implement.

7.4.2.1 Current Situation

The development of the manufacturing systems and processes at Ericsson is carried out according to the unit-specific application of the Corporate NPI (New Product Introduction) process model. This model is, intentionally, generic in its nature and it is up to the project manager to, within some specified directives, determine how the model will be applied to a specific project. There are no templates that can support this decision.

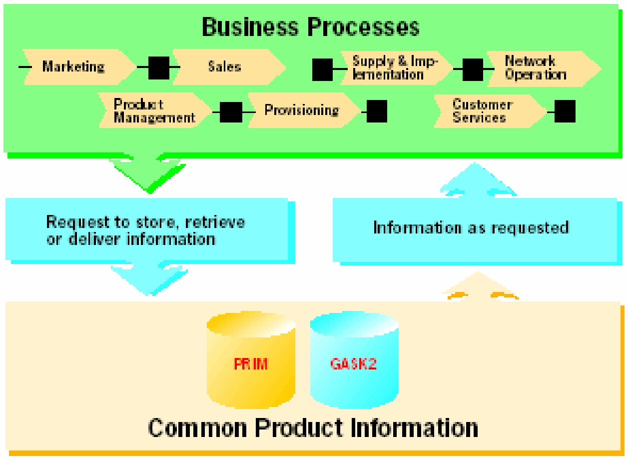
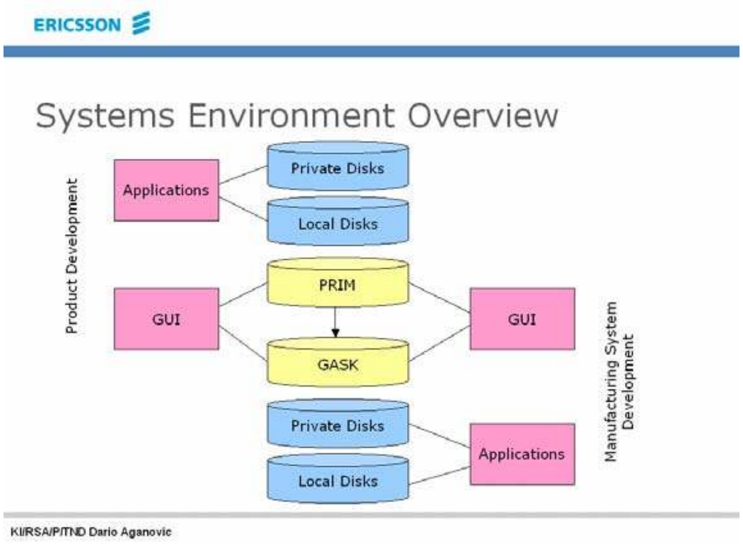


Figure 90: PRIM handles product structures and GASK2 contains documents managed throughout the execution of Ericsson's business processes. Product structures and documents that describe them are interrelated with pointers from PRIM to GASK2.

Although it is a very competent industrialization process description, the NPI model does not specify the coupling between human resources and project activities at all levels.

The documentation that is required for the milestone evaluation as well as for the tollgate decisions is seldom available in its entirety, which causes decision-making on assumptions rather than facts.

Information exchange between the projects, between the organizational units and inside of the organizational units is poorly coordinated. The information is available in PRIM and GASK2 (cf. Figure 90) but without target-user notification upon the creation/change of the relevant information (no workflow capability). PRIM/GASK2 information is only released information - there is no access to draft information, which in turn causes waiting and thus increases time-to-market. Furthermore, GASK2-documents are linked to PRIM-structures on a high level only. The lack of possibility for the development work based on the open (draft) PPR-models is in fact directly disabling execution of the NPI-process according to the concurrent engineering principle.



ERICSSON

Systems Environment Overview

Product Development

Applications

Private Disks

Local Disks

GUI

PRIM

GASK

GUI

Manufacturing System Development

Private Disks

Local Disks

Applications

KI/RSA/P/TND Dario Aganovic

Figure 91: Most of the information is managed locally. Only product structures are managed while process and resource documents are coupled to the product structure without having a structure of their own.

PRIM is handling only product structures without coupling to any process and resource structures. It is therefore hard to relate manufacturing process information to products, which causes difficulties in quality assurance work and can create bad reputation among the customers. It is also impossible to relate the manufacturing system modules to the product modules. Therefore, there is a reason to believe that the utilization of existing manufacturing resources is not optimal.

Usage of the Digital Factory applications is marginal and not integrated with the unit-specific NPI-model. There is also low, if any, utilization of existing PPR-models (e.g. 3DCAD, simulation models, etc) due to the lack of model libraries and small application user group. That causes longer task execution times and re-creation of the information. Ericssons's personnel have just started to use 3D product models for manufacturability studies but there is no utilization of virtual product models for creation of virtual process and resource models. Furthermore, there is no support for manufacturing system requirements management, i.e. management of relationship between manufacturing system's features and its functional requirements based on e.g. product characteristics and business conditions.

Production transfer project execution is associated with costs that are related to the PPR-information transfer from master to clone factory. Long project lead times due to the information seeking, structuring and translating as well as manufacturing system conformance checking cause significant productivity losses. PRIM and GASK are used for information handling.

7.4.2.2 Wanted Position

The development of the manufacturing systems and processes at Ericsson is carried out according to the unit-specific application of the Corporate NPI process model. This model is implemented in the workflow mechanism of the PPRDM-system. The project manager can choose between several predefined alternatives.

The human resources are through the workflow mechanism coupled to the project activities at all levels. This feature enables event notification and improves project monitoring and control.

All the documentation that is required for the milestone evaluation as well as for the tollgate decisions is available for the right users at the right time, which is a fundamental prerequisite for decision-making based on actual facts.

Information exchange between the projects, between the organizational units and inside of the organizational units is well coordinated. The information is available in file servers and all data management activities such as structuring, version handling, permission, check in/out and notification are carried out through Metaphase PDM and eFactory PRDM (PDM + PRDM = PPRDM). All authorized users have always access to needed draft information so that they are at all times able to work with the absolutely latest set of data. This in order to achieve true concurrency among the activities in the integrated product development process.

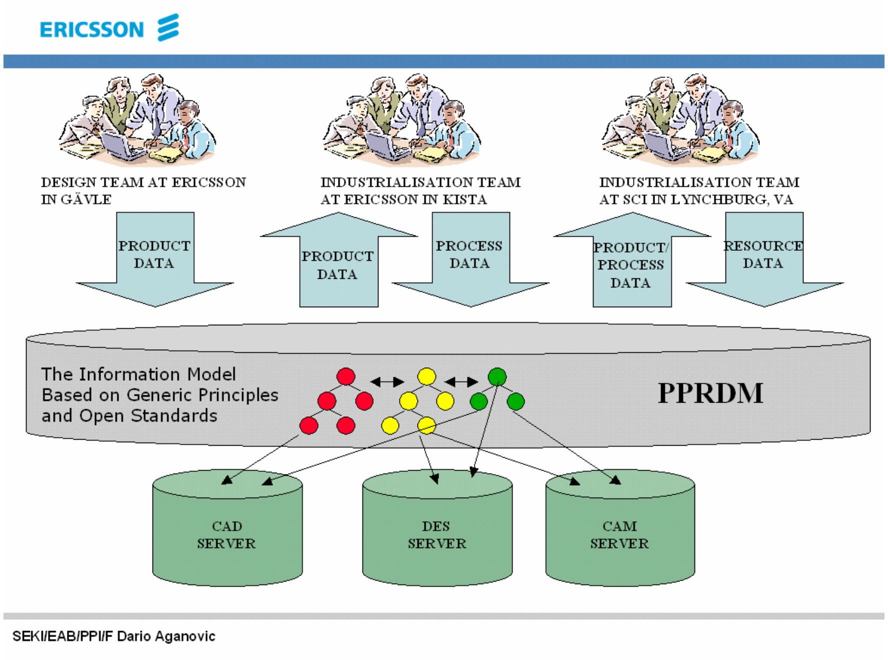


Figure 92: PPRDM-strategy

Relating design structures in all domains of the design (PPR), and handling of those structures via a PPRDM-meta-database, enables concurrent decomposition of the products, manufacturing processes and manufacturing resources. A PPRDM-system with capability to capture and relate structures of products, manufacturing processes, and manufacturing resources improves the decision traceability and thus helps in the business process quality excellence strivings. In a PPRDM-system any product or manufacturing system design feature can be linked to the requirement satisfied by that feature. It is also possible to relate the manufacturing system modules to the product modules and by that always have capability to consider using the different configurations of the same manufacturing system. The resource library of the PPRDM-system is here used for administration of the company-wide manufacturing system platform (today known as a HW- and SW-platform).

The Digital Factory applications are integrated with the data management platform. The applications are utilizing and creating the PPR-information managed by the PPRDM-system. Task execution time and waiting time are significantly reduced due to the usage of the applications (task (semi-) automation) and the integration with the PPRDM-system (task coordination).

Production transfer project execution is carried out by the PPRDM-system control of the PPR-information transfer from master to clone factory, i.e. from the factory where the product is industrialized into a factory where the high-volume production will be carried out. The structure of the transferred product is coupled with the appropriate process and resource structure. Those structures are associated with all the documents that need to be transferred between the sites. Alternative processes can be compared on the functional level so that the corresponding manufacturing system (with same capability) and not the exactly same manufacturing system can be implemented at the clone site. The effectiveness and the lead-time of the production transfer projects is significantly improved.

7.4.3 How to make the transition?

In order to be able to make the transition Ericsson has identified a couple of critical prerequisites that must be in place prior to implementation of the PPRDM-system:

- A common detailed representation of the NPI-process, as well as production transfer process, allover the engineering organization. This includes description of process activities (including recommended methods and tools) and rigorous specification of activities' inputs and outputs, i.e. project documents and design object structures.
- A common conceptual representation of products and their manufacturing systems in several interrelated design object structures, e.g. requirement structure, function structure, design structure, supply embodiment structure for both system types. These structures are developed gradually in NPI-process' various activities.
- A common formal representation of all the data that describe the design object structures managed in Ericsson's information sys-

tem. This data model should be harmonized with accepted international data management standards in order to be able to seamlessly communicate the development information with external partners within a dynamic extended enterprise.

7.4.4 Case Study Conclusions

- The various manufacturing system development activities are supported by a dispersed set of unrelated applications within the information system.
- At Ericsson, there is no common product data management system that carries and interrelates the information about structures that describe functions and technical solutions for developed products and manufacturing systems.
- Within the enterprise, there is a deep understanding of problems related to the two above bulleted statements. There is also a strategy for creation of new information management architecture suited for product and manufacturing system development and operation within extended enterprises. This will be enabled through application of the enterprise's specialist knowledge within development processes, systems engineering, and information management.

7.5 Case Study 5: A Concurrent Engineering Information Model Based on Theory of Domains, STEP AP-233, and RDFS

7.5.1 Case Study Data

This case study is performed at industrial engineering department of Ericsson's Stockholm-Kista manufacturing plant during the period between May and June 2001.

7.5.1.1 Question

- Does the information management standard STEP AP233 have all the necessary mechanisms to represent a telecommunication product (Bias-T by Ericsson) and its assembly system structured according to the framework provided by the Theory of Domains?

- How can the information model based on the Theory of Domains and STEP AP233 be used as a blueprint for a web-service infrastructure implemented with Semantic Web technologies?

7.5.1.2 Proposition

- STEP AP233 can represent all the domain structures for both products and their manufacturing systems by applying its mechanisms for functional and physical architectures to represent function, organ, and component structures for products and their manufacturing systems. Product process structure is represented by functional behavior mechanism, i.e. a subset of the mechanism for management of functional architectures. The engineering process management mechanism is used for representation of the manufacturing processes.
- The subset of STEP AP233 based on the Theory of Domains can, when implemented as RDF-schema, be used for instantiating RDF-statements, which in their turn are regarded as fundamental building blocks for web-services based on Semantic Web technology.

7.5.1.3 Sources of Evidence

- Documentation:
    - Bill of material
    - Drawings
    - Assembly and test instructions
    - Generic Information Model based on the Theory of Domains
- Open-ended interviews:
    - STEP AP233 Specialist

7.5.2 Case Study Report

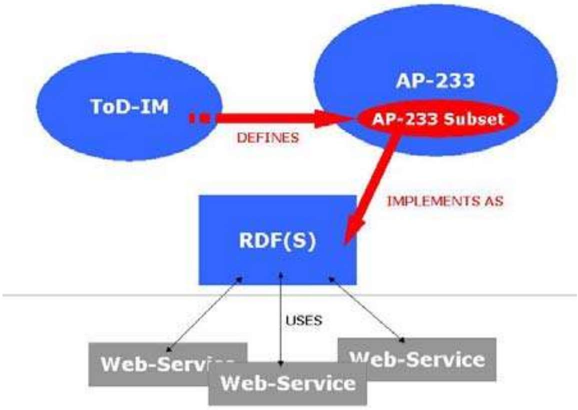


Figure 93: The approach of this case study

This case study will contribute to increased understanding of how STEP AP-233 corresponds to the requirements, which are set by the ToD. This is achieved through using the information model in Figure 81 in Section 7.2.2.4 as a definition base for an AP-233 subset (here called ToD-IM). The entities of this subset correspond to the information requirements set by the ToD.

Furthermore, this case study will show how an AP-233-ToD information model (ontology) can be implemented as a RDF-schema so that various web-services can use this ontology as a common communication platform.

7.5.2.1 ToD-IM expressed as a AP-233-subset

The AP-233-subset (AP-233-ToD) defined according to the ToD-IM is presented in Figure 94. The AP-233-ToD is composed of AP-233 entities as specified in ISO 10303-PAS 20542. The model can be divided in four conceptual sections:

- Product Process Domain
- Product and Manufacturing System Function Domain
- Product and Manufacturing System Organ Domain and Component Domain

- Manufacturing Process Domain

The four conceptual sections originate from the separation of the technical system views (domains) of the ToD.

Product Process Domain:

This section is representing the Product Process Domain with entities from the *Functional Behaviour – causal chain Unit of Functionality (UoF)* of AP-233. Here, the product process is regarded as an ordered set of events (*cb_functional_place* and *cb_functional_transition*) that can be expressed in a causality graph. These events are functional behaviors implied by a product's functions. The coupling between a function and its functional behavior *functional_behaviour_model _assignment*.

Product and Manufacturing System Domain

The functional structure of a design artifact is represented with entities from the *Functional Hierarchy UoF* and *Explicit Functional Reference UoF*. A product and its manufacturing system are two separate technical systems that can be represented by using the same function structuring principles. A function is represented as *function_instance,* which is defined in *general_function_definition*, which must be specialized either as *composite_function_definition* or *leaf_function_definition*. A function that is described by *composite_function_definition* consists of at least one *function_instance*. Functions of a technical system are carried out by its organs that are related to functions through *functionality_allocation_relationship* between *functionality_instance_reference* and *physical_instance_reference*. The relationship between several entities of type *functionality_instance_reference* is carried out through *functionality_reference_composition_relationship* entities, which is analogous to the relationship between referenced functions, *functional_decomposition_relationship*.

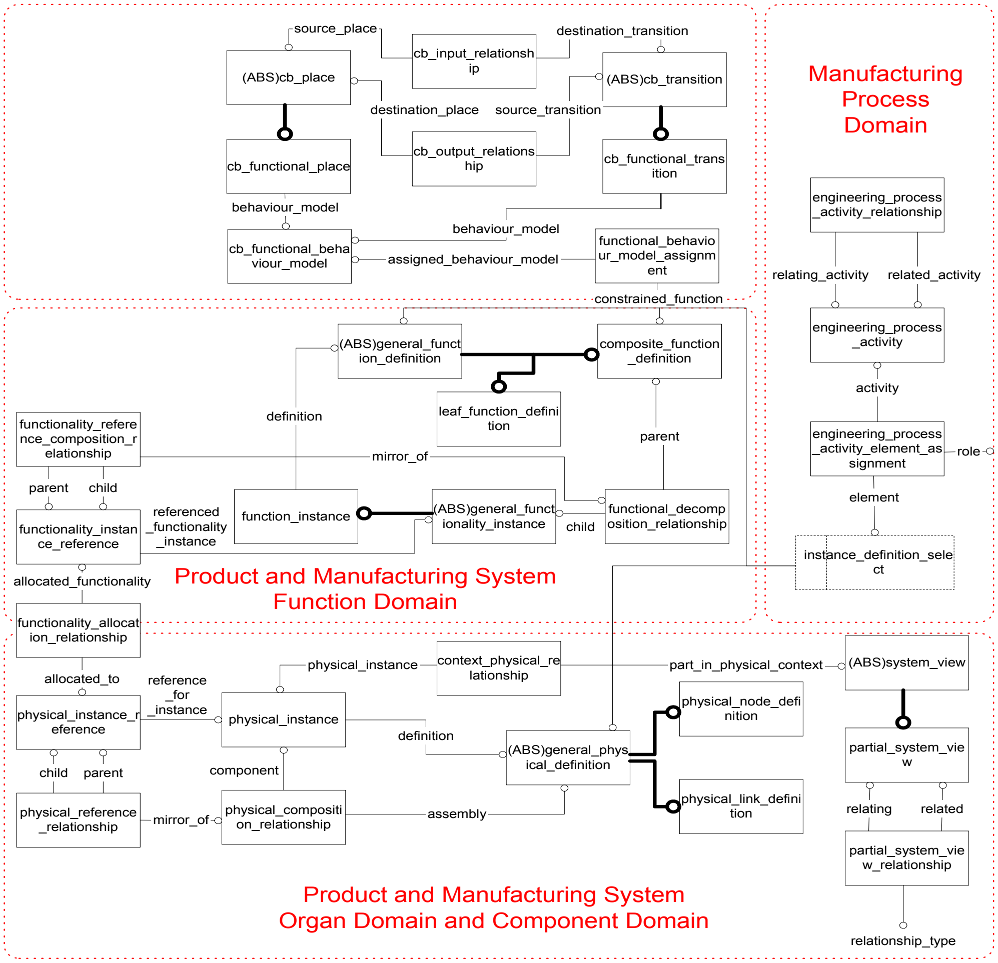


Figure 94: AP233-subset for ToD-IM

Product and Manufacturing System Organ Domain and Component Domain

Functions expressed in the function domain are allocated to an organ structure. Organs are embodied in components. Under the assumption that they represent two perspectives (two different abstraction levels) on the physical architecture of a mechanical system, organs and components can be structured by using the same principle. Therefore, the same set of entities from the *Physical Architecture UoF*, *Explicit Physical Reference UoF*, and *System Architecture UoF* of AP-233 can be used to represent both organs and components of a technical system.

A product and its manufacturing system are two separate technical systems that also can be represented by using same structuring principles. Functions are allocated to organs through *functionality_allocation_relationship*. Here, the similar referencing mechanism (*physical_instance_reference*) as in the function domain is used. *functionality_allocation_relationship* is utilized for linking functions and organs only, which implies that linking functions and components is not intended. Organs and components are represented by the entity *physical_instance* entity defined by a *general_physical_definition*, which must be specialized either as *physical_node_definition* or *physical_link_definition*.

Organ structure and component structure are regarded as two partial system views (*partial_system*_view), where organs and components are linked through a *partial_system_view_relationship*. An organ or a component is associated to a partial system view through *context_physical_relationship*.

Manufacturing Process Domain

The product process can be expressed as a causal chain. Since a manufacturing system is analogous to the product that it is going to produce (both are technical systems) it is possible to represent manufacturing processes as causal chains. However, AP-233 provides also support for representing engineering processes, where structures (i.e. functional and/or physical structure) representing the engineered technical system are managed as operands. Here, it is not hard to perceive the analogy between an engineering process for a product and the same product's manufacturing process.

In both processes, the product is used as an operand and its structural growth is maintained. So, conceptually, AP-233–entities that represent engineering processes can beused to represent manufacturing processes as well.

Hence, manufacturing processes are represented with entities from the *Work Management UoF*. The fundamental building block is *engineer-*

ing_process_activity. This entity is through *engineering_process_activity_element_assignment* related to either a physical structure of a product or a function structure of its manufacturing system. The selection is carried out through *Instance_definition_select*. An *engineering_process_activity_relationship* is used to manage the relationship between different operations in a manufacturing process (i.e. sequential relationship).

7.5.3 Instantiation of AP-233-ToD

An example instantiation of the information model presented in 6.1 is shown in Figure 96. The instantiated model is based on a case study, which is presented in Section 7.2. In Section 7.2, a telecommunication product, Bias-T, and its assembly system are decomposed according to the ToD. Only a small part of that decomposition is used in Figure 6 to illustrate how AP-233-ToD can be applied. The instantiation of the Product Process Domain is excluded since only one product function (one process operation) is exemplified. The *functional_behaviour_model_assignment* is instantiated as an interface to the possible product process structure.

A Bias-T function *"insert RF"* is related to the Bias-T organ *"RF-interface"*, which, in turn, is related to its embodiment in a component *"N-coax"* (a cable contactor). This component is assembled in a manufacturing process *"connector assembly"*, which is carried out due to an assembly system function *"complex assembling"*. An assembly system organ, *"6DOF robot"*, which carries this function, is embodied in a component *"IRB140"* (an industrial robot).

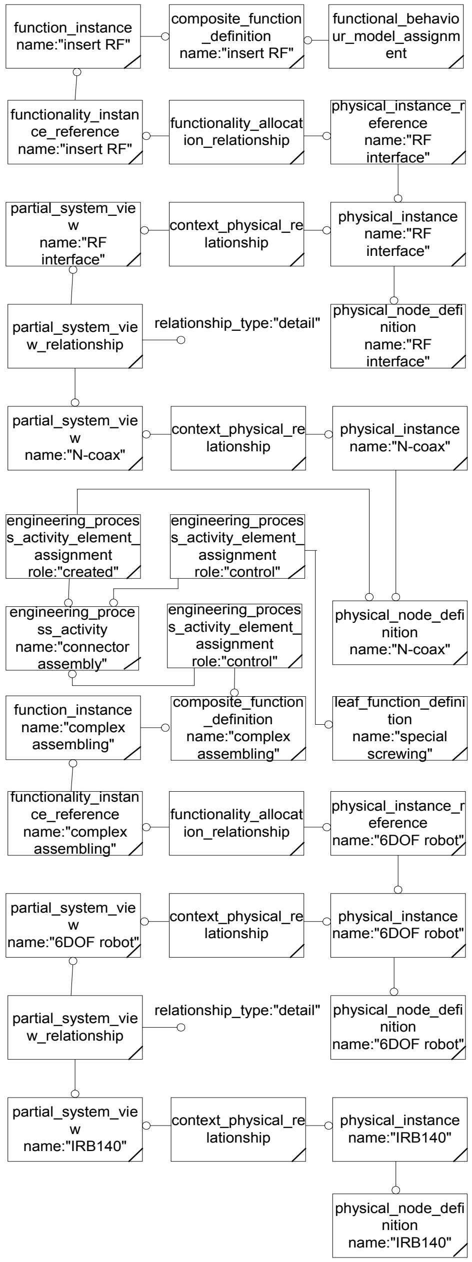
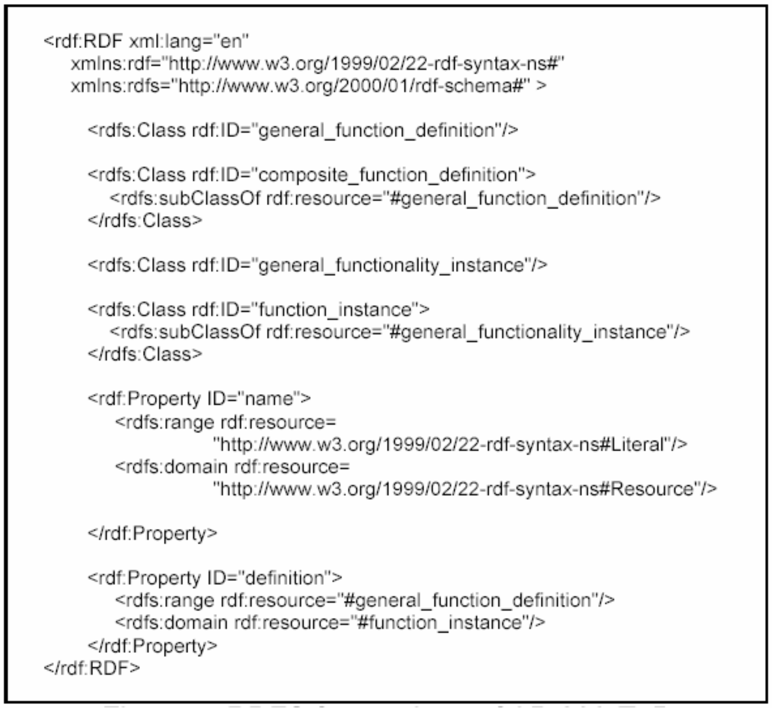


Figure 96: AP-233-ToD instantiation example case: Bias-T

7.5.4 AP-233 implemented as a RDF-schema

The ontology presented in Figure 95 can be implemented as RDF-schema in order to enable its usage as a foundation for web-service-based innovation process for extended manufacturing enterprises. A principle for such an implementation is shown in Figure 97. Here, only a very limited subset (part of the function domain) of the ontology in Figure 95 is covered.

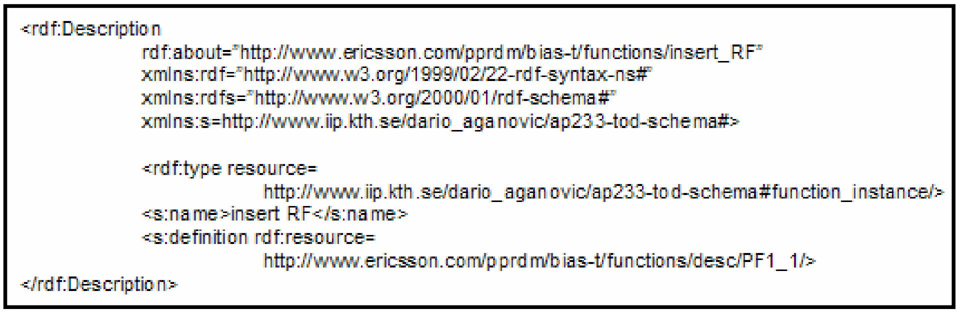
First, two namespaces, RDF-specification *xmlns:rdf* and RDF-schema specification *xmlns:rdfs*, are included. Thereafter the classes *general_function_definition* and *general_functionality_instance*, as well as their subclasses *composite_function_definition* and *function_instance*, respectively, are defined. The property *name*, with range (value) *Literal* (any string) and domain *Resource* (any class or property) as well as the property *definition* with range *general_function_definition* and domain *function_instance* are also defined.



```
<rdf:RDF xml:lang="en"
    xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
    xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#" >

      <rdfs:Class rdf:ID="general_function_definition"/>

      <rdfs:Class rdf:ID="composite_function_definition">
         <rdfs:subClassOf rdf:resource="#general_function_definition"/>
      </rdfs:Class>

      <rdfs:Class rdf:ID="general_functionality_instance"/>

      <rdfs:Class rdf:ID="function_instance">
         <rdfs:subClassOf rdf:resource="#general_functionality_instance"/>
      </rdfs:Class>

      <rdf:Property ID="name">
          <rdfs:range rdf:resource=
                     "http://www.w3.org/1999/02/22-rdf-syntax-ns#Literal"/>
          <rdfs:domain rdf:resource=
                     "http://www.w3.org/1999/02/22-rdf-syntax-ns#Resource"/>

      </rdf:Property>

      <rdf:Property ID="definition">
          <rdfs:range rdf:resource="#general_function_definition"/>
          <rdfs:domain rdf:resource="#function_instance"/>
      </rdf:Property>
</rdf:RDF>
```

Figure 97: RDFS for a subset of AP-233-ToD

The RDF-schema of Figure 97 is instantiated in the RDF-statement, which is presented in Figure 98. This RDF-statement says that the fictive resource *http://www.ericsson.com/pprdm/bias-t/functions/insert_RF* is typed as *function_instance* with properties *name = "insert RF"* (literal string) and *definition = http://www.ericsson.com/prdm/bias-t/functions/desc/ PF1_1* (fictive resource). The statement is made according to the RDFS in Figure 97 that in this example is assumed to have following URI: *http://www.iip.kth.se/dario_aganovic/ap-233-tod-schema#.*



```
<rdf:Description
            rdf:about="http://www.ericsson.com/pprdm/bias-t/functions/insert_RF"
            xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
            xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
            xmlns:s=http://www.iip.kth.se/dario_aganovic/ap233-tod-schema#>

            <rdf:type resource=
                        http://www.iip.kth.se/dario_aganovic/ap233-tod-schema#function_instance/>
            <s:name>insert RF</s:name>
            <s:definition rdf:resource=
                        http://www.ericsson.com/pprdm/bias-t/functions/desc/PF1_1/>
</rdf:Description>
```

Figure 98: An RDF-statement according to the RDF-schema in Figure 97.

7.5.4.1 Case Study Conclusions

- STEP AP233 is capable of representing process-, function-, organ-, and component structures for products and their manufacturing systems in accordance with the Theory of Domains. However, in future work, some additional attention should be directed towards links between the domains that represent products and the domains that represent their manufacturing systems.
- A RDF-schema based on STEP AP223 can be created and published on Internet in order to introduce standards-based web-service framework for product and manufacturing systems development.

8 MANUFACTURING SYSTEM DEVELOPMENT THEORY

8.1 Universal Statements: the hard core

As stated in 2.2.4.2, when a concept of research programs is adapted, it is possible to commit to and develop a useful complex theoretical system, which rests on well-defined hard core of universal statements, where every falsification is extremely carefully examined before acceptance. When a researcher further develops a theoretical system, he/she accepts this hard core. The hard core of universal statements of the theory presented in this thesis consists of definitions, axioms, theorems and corollaries presented by Suh (1990) and Suh (2001) and axioms and laws presented by WDK-theorists Andreasen (1980) and Hubka and Eder (1988). Appendix 1 presents the universal statements that comprise this hard core.

8.2 Universal Statements: new hypotheses and definitions

In this section, new hypotheses are going to be presented. These hypotheses contain new terms that are defined by a set of formal definitions. A set of auxiliary hypotheses is used to support the defined hypotheses. The hypotheses are tested in Section 8.3. Figure 99 depicts the structure of the hypotheses system.

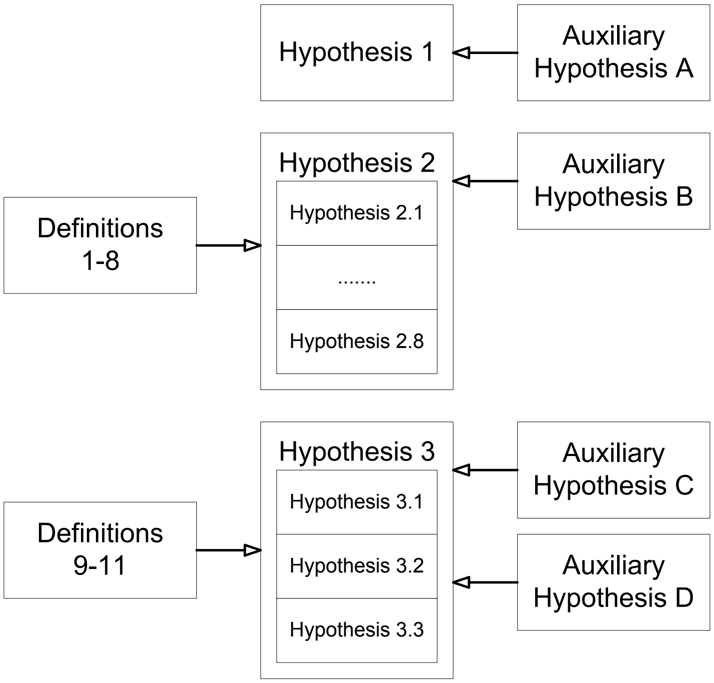


Figure 99: Hypotheses and definitions

8.2.1 Homogeneity of Manufacturing Systems

Theory of Technical Systems introduces four design perspectives on a technical system and isolates technical from human, information, and management systems. This segregation of the transformation system into subsystems is, as we saw in Sections 4.2. and 4.3, also significant for several contributions to Theory of Domains and Axiomatic Design. Since manufacturing systems incorporate resources that belong to all of these systems, there is a need to regard manufacturing system as *one, and only one* system, which exist in order to produce products. This single transformation system carries functions and is constrained by constraints that are set by the stakeholders of the manufacturing system, i.e. customers (whose requirements are partly embodied in product models), employees, and capital owners as well as the society. Therefore, a manufacturing system should even during its synthesis be regarded as a single integrated system. If that is the case, the developer is for example free to satisfy a functional need with a machine- or a human resource. This resource becomes thereafter a part of a total manufacturing system structure. The choice of a machine or a human being as a manufacturing resource implies the need for control information which can be provided through a NC-system or management system respectively. Also, detail manufacturing, assembly and transportation are regarded as parts of a single system. For example, a decision to manufacture a product component in a manufacturing process sequence executed in two different machines implies the need for transportation. This need is expressed on the next level of the function tree and is satisfied with a technical solution embodied in a transportation resource, e.g. a conveyor.

Main Hypothesis 1: *Every resource in every manufacturing system structure (for electromechanical products) satisfies a functional need imposed by at least one of the following drivers: (i) physical characteristics of the product that the manufacturing system is going to manufacture, (ii) development decisions made on the higher level of the manufacturing system structure, or (iii) the business (e.g. capacity, delivery speed) and/or moral (e.g. outer environment, workplace ergonomics) constraints set by the stakeholders of the manufacturing system.*

Auxiliary hypothesis A: *Every manufacturing system structure can be viewed as an assembly of machines and/or humans (including their respective control systems) that perform manufacturing operations such as assembly, detail manufacturing, handling, transportation, and quality control.*

8.2.2 Inter-domain Relationship between Products and Manufacturing Systems

An important aspect to be considered when applying the theories of the WDK-school on manufacturing system design is that of transformation processes. A manufacturing process could be regarded as a transformation process, which is executed by a transformation system – a manufacturing system. In such a process an operand, e.g. a product, is transformed from an initial state, i.e. material, into a desired state, i.e. finished product – product component system.

Product components embody organs that, in their turn, realize functions, which carry the process that transform customer's operands. Product components' physical properties are determined in the manufacturing process executed by the manufacturing resources (manufacturing components). Manufacturing components embody the manufacturing organs, which realize manufacturing functions that carry out the manufacturing process. Therefore, it can be proposed that there exist a relationship between products and their manufacturing systems established during the execution of the development process and expressed in the causality links between the product system domains and manufacturing system domains.

It is important to realize that, as already stated in section 1.6, the research presented in this thesis is delimited to considering only the physical relationship between products and their manufacturing systems. In other words, the main focus is on specifying this relationship based on physical shapes and technical principles for a product and its manufacturing system, rather than specifying the relationship based on other factors, e.g. the product demand profile.

Main Hypothesis 2: *Every manufacturing process is executed by a manufacturing system that can be described in terms of four domain system models (manufacturing process, -function, -organ, and –component), which are directly related to the corresponding four domain system models of the manufactured product (product process, -function, -organ, and -component).*

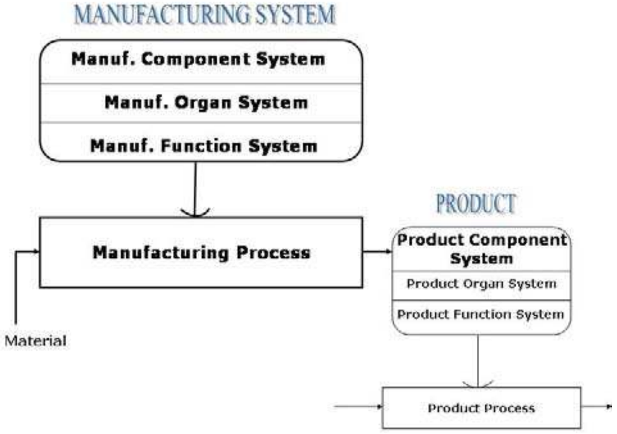


Figure 100: Manufacturing process executed by a manufacturing system

(transform material into a finished product)

Now, in order to be able to properly test the hypothesis, its key terms must be unambiguously defined.

Definition 1: *A product process is a sequence of events undertaken by a product in order to, according to product's customers' requirements, in space and time transform an operand (material, information, and/or energy) from an initial into a new state.*

Example 1: A stepper motor is a product that transforms electrical energy into mechanical energy manifested as controlled rotational motion. One of the product processes can be denominated as *Rotation*.

Definition 2: *A product function is the capability of a product to deliver the effects needed to, directly or indirectly, support carrying out the transformation of an operand, i.e. the execution of the product process.*

Example 2: In order to be able to execute the product process in Example 1 the product must have the capability generating rotation. The capability, i.e. product function, can be formulated as *Generate Rotation.*

Definition 3: *A product organ is a specific mean, a conceptual technical solution, employed to realize a function in a product.*

Example 3: The product function in Example 2 is realized by the product organ *Rotating Shaft with Permanent Magnet*. The product organ is represented in a conceptual model, e.g. a sketch showing the working principle.

Definition 4: *A product component is a concrete hard- or software entity that embody an organ, or a set of organs, and that is characterized by detailed description in terms of e.g. quantitative properties.*

Example 4: The product organ in Example 3 is embodied into the product component *Rotor, Product No. AB12*. The product component is represented in a detailed product model that shows e.g. dimensions, tolerances, material properties. Deeper in the product component structure a component *Cylinder X* with surface roughness $R_a=0.6\mu m$.

Definition 5: *A manufacturing process is a sequence of operations undertaken by a manufacturing system in order to in space and time transform material, or a product component in an initial state, into a product component in the new state.*

Example 5: The product component in Example 4 is generated in a manufacturing process *Rotor Manufacturing*, where one of sub-processes may be denominated as

Generation of Cylinder X.

Definition 6: *A manufacturing function is the capability of a manufacturing system to deliver the effects needed to, directly or indirectly, support carrying out the transformation of a product component, i.e. the execution of the manufacturing process.*

Example 6: The manufacturing process in Example 5 is carried out due to the manufacturing system's capability to provide the manufacturing function *Generate Cylinder* with surface roughness $R_a=0.6\mu m$.

Definition 7: *A manufacturing organ is a specific mean, a manufacturing method, employed to realize a function in a manufacturing system.*

Example 7: The manufacturing function in Example 6 is realized by applying the manufacturing method, i.e. manufacturing organ, of *External Turning*.

Definition 8: *A manufacturing component is a concrete hard- or software entity, e.g. machine, operator, or tool, that embody an organ, or a set of organs, and that is characterized by detailed description in terms of e.g. quantitative properties.*

Example 8: The manufacturing organ in Example 7 is embodied in the manufacturing component *Turning Tool T-MAX U, serial no. 654321.* with insert radius $r_\varepsilon=0.4$ *mm* that when feeding speed of $f_n=0.07$ *mm/r* is applied, have the capability of achieving surface roughness $R_a=0.6\mu m$.

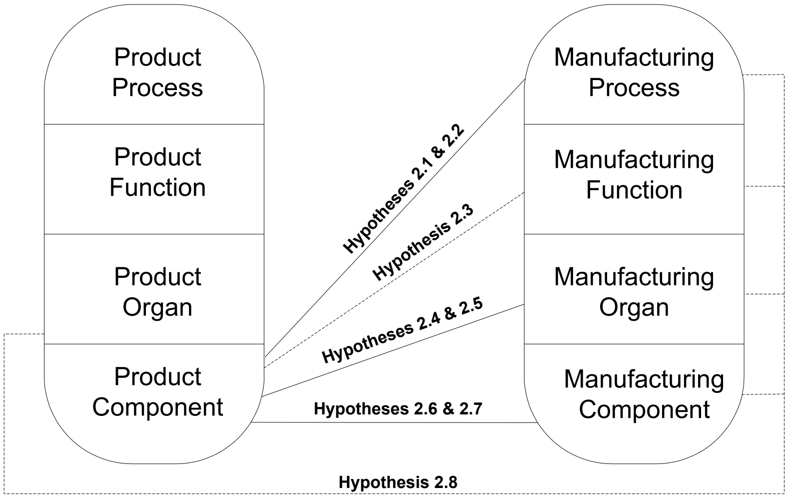


Figure 101: The relationship between product and manufacturing system

domain system models

Furthermore, since Main Hypothesis 2 assumes certain relationships between the defined terms, Auxiliary Hypothesis B, based on the existing hard core of universal statements (cf. Section 8.1) and a set of sub-hypotheses (2.1-2.8) based on the hard core and case studies in Section 7, must be formulated (cf. Figure 101.).

8.2.2.1 Building on the Existing Body of Knowledge

First, the theory formulated in this thesis is a part of the theory system consisted of two theory sub-systems, the WDK-theories and Axiomatic Design. Therefore, it do not intends to falsify the already existing universal statements, expressed as axioms, theorems and corollaries in original Axiomatic Design and axioms and laws in original WDK-theories. This theory attempts to integrate two theory sub-systems and it also adds new hypotheses in the areas that were either not covered by original theories or that were insufficiently treated in other contributions.

Auxiliary Hypothesis B: *The relationship between four domain system models of every electromechanical product and the relationship between four domain system models of its corresponding manufacturing system always follows the set of axioms, theorems, corollaries and laws defined in Axiomatic Design and the WDK-theories.*

8.2.2.2 Product Components and Manufacturing Processes

Next two sub-hypotheses attempt to describe the relationship between a product and the manufacturing process in which the product is going to be generated. Manufacturing processes are representations of a sequence of events that material or product components in an intermediary state of completion are subjected to. The nature of this sequence depends on the product component structure[5]. Naturally, a decision to, for example, optimize the manufacturing system performance by adjusting manufacturing process sequence may have an impact on the corresponding product

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[5] The items in a product component structure are not only the discrete parts but even various geometric features, e.g. plane surface, hole, cylinder, that constitute a discrete part.

component structure.

Example 9: By embodying a product in several modules that can be assembled independently, a parallel assembly process can be implemented instead of a serial one.

Hypothesis 2.1: *Every electromechanical product determines, through the structure of its product components, the possible sequences and the outcome of the corresponding manufacturing processes.*

Hypothesis 2.2: *Every manufacturing process sequence constrains the structure of corresponding electromechanical product components.*

8.2.2.3 Product Components and Manufacturing Functions

In order to be able to execute a manufacturing process, the corresponding manufacturing system must possess a set of capabilities. When considering a design relationship between a product and its manufacturing system, these capabilities depend on the nature of product component structures. The main characteristics of the product component structure are mapped into a manufacturing process sequence. This structure is, through the specification and sequence of manufacturing processes, propagated into the structure of manufacturing functions.

It might be argued that these manufacturing functions are also directly, i.e. not through the manufacturing process structure, impacted by the product components. This impact should occur due to the fact that a product component may possess a set of quantitative properties that should be rephrased as target values to be achieved by the manufacturing system. This particular relationship between product components and manufacturing functions expressed in quantitative capability targets (design parameters) is, along with the corresponding quantitative manufacturing system characteristics (process variables), described and handled in a quantitative relationship structure as presented in Section 8.2.3.

Hypothesis 2.3: *Every electromechanical product determines indirectly, through a manufacturing process sequence based on the corresponding product component structure, a set of capabilities, i.e. manufacturing functions that the corresponding manufacturing system must have.*

8.2.2.4 Product Components and Manufacturing Organs

The capability of a manufacturing system to achieve certain target value also depends on the choice of manufacturing organs and -components. Thus, the relationship between a capability, i.e. a manufacturing function, and its corresponding product components is indirectly managed through corresponding manufacturing organs and manufacturing components that embody these organs.

As remarked in Section 5.2.2 the new approach to the Theory of Domains, where the function domain has vanished as a structure of its own and a function has come to be seen as a behavior of its organ, leads to the conclusion that functions should be regarded as interfaces between processes and organs. Therefore, there is no direct relationship between manufacturing function and product component; the relationship between a product and its manufacturing system is instead managed through dependencies between product components and manufacturing processes and –organs.

It should also be illuminated that all manufacturing functions are not directly derived from the product components and the corresponding manufacturing process. There are functions that deliver a direct effect, which leads to the accomplishment of product component transformation and that occur due to the choice of certain manufacturing organ or –component, e.g. two manufacturing functions realized in manufacturing two organs in two separate components instead in one.

Example 10: Manufacturing function *Transport the Semiproduct* accomplishes a transformation in space, i.e. moving a product component from location A to location B. This function is needed since manufacturing functions *Generate Curved Surface X* and *Generate Curved Surface Y*, realized by manufacturing organs *Turning* and *Milling,* are allocated to two physically separated manufacturing components *Lathe A* and *Mill B* instead of to a single integrated manufacturing component, e.g. *Lathe C*.

Some manufacturing functions do not deliver the direct effect that leads to the accomplishment of product component transformation. These functions support the functions that deliver the effect directly used for accomplishment of that transformation.

Example 11: Manufacturing function *Control the Lambda Wave Temperature*, introduced due to the choice of the manufacturing organ *Wave Soldering*, is realized by a manufacturing organ *PID-controller*.

As already stated in this section, manufacturing functions do not have direct relationship with product component structure. Manufacturing functions are impacted by product components through manufacturing processes. This indirect relationship is actually twofold; manufacturing functions impact product components through the choice of means, i.e. manufacturing organs, employed to realize functions. When selecting an organ, the manufacturing system developer is constrained by the product component structure. The selected organ, in its turn, impacts the product component structure by e.g. adding the features that enhance the manufacturing system's capability to perform its tasks.

Example 12: Manufacturing function *Generate Pocket X* is realized by the manufacturing organ *Edge Milling*. This implicates that the product component structure will be modified by addition of e.g. clamping surfaces and runouts.

Example 13: Manufacturing function *Join PC1 and PC2* is realized by the manufacturing organ *Robotic Screwing*. This implicates that the product component structure will be modified by addition of a set of screws and corresponding holes.

Hypothesis 2.4: *Every electromechanical product constrains, through the structure and other properties of its product components, the selection of manufacturing methods, i.e. manufacturing organs.*

Hypothesis 2.5: *Every manufacturing organ constrains, through its ability to provide the desired capability to the manufacturing system, the structure and the property goal values for electromechanical product components.*

8.2.2.5 Product Components and Manufacturing Components

When manufacturing organs are embodied into a manufacturing component, a set of specific physical properties gets manifested. These properties characterize the selected manufacturing resource and they enhance the developer's knowledge about the impact of certain manufacturing component on certain product component. A manufacturing component is a concretization of manufacturing organs and is to be regarded as a carrier of manufacturing system's capability.

Example 14: Manufacturing function *Generate Thread X M16, D=16 mm (major diameter), d=13.55 mm (minor diameter), P=2 mm (pitch)* is realized by the manufacturing organ *Thread Rolling*. The manufacturing organ is embodied into the manufacturing component *Cylindrical Dies (double), serial no. Y.* This component with physical properties P_d*=8 mm (pitch),* D_d*=53 mm (major diameter)* can provide the capability of creating the desired product component property.

Hypothesis 2.6: *Every electromechanical product constrains, through the structure and the property goal values of its product components, the structure and property values for manufacturing components.*

Hypothesis 2.7: *Every manufacturing component constrains, through its structure and property values, the structure and the property goal values for electromechanical product components.*

8.2.2.6 Product Organs and Manufacturing Processes, -Functions, -Organs, and -Components

As discussed in Section 8.2.2.5, already when electromechanical product functions are mapped into product organs, it is possible to draw important conclusions on how the desired functionality will be verified during manufacturing. Therefore, the work on specification of the in-manufacturing test process and the corresponding functions, organs, and components can be started even before the final embodiment of product organs is determined. Also, the possibility that, in certain other applications, the relationship between product organs and manufacturing system domain models is established before product components are determined, can not be eliminated.

Example 15: During the development of a mobile system it is established that the product function *Amplify Signal* will be realized with a *Multi Carrier Power Amplifier (MCPA)*. Experts on radio technology know that usage of MCPA as technical solution implies the possibility that in-manufacturing tests include spectrum measurements. Therefore it is possible to, at least preliminarily, assume existence of the manufacturing process *Spectrum Measurement* and a corresponding manufacturing function *Measure Spectrum,* realized by the organ *ACLR* and embodied into the manufacturing component *Agilent GS9200, Serial No. 123456*. The test developers can now start programming test methods and experiment with approximate product component parameters. When product component is selected the selected manufacturing component will be tuned and its capability to perform the required task will be assessed. A possible change of manufacturing component will most certainly result in minor program corrections such as driver routine adjustments.

Hypothesis 2.8: *Every electromechanical product organ that needs to be verified during manufacturing directly impact, and is impacted by, the structures of manufacturing processes, -functions, -organs, and -components regardless of whether corresponding product component structure has been determined or not.*

8.2.3 Quantitative Parameters in a Single Logical System

Integrating the Axiomatic Design into the WDK-framework may further facilitate management of coupling between the product and manufacturing system design. Axiomatic Design also adopts the concept of domains, even if these domains are not the same as in the Theory of Domains. Axiomatic Design has, due to its mathematical base, the capability to support structuring and analyzing of key quantitative properties of technical systems. These properties can be regarded as the essence of the design solution developed and structured using the WDK-theories. For instance, a DP can represent the critical solution parameters expressed in the design structure in the organ domain of the Theory of Domains as well as the critical geometrical parameters embedded in the design structure in the component domain. In this way, quantitative properties of the design as well as the couplings between them can be analyzed and controlled for both product and its manufacturing system. While Axiomatic Design provides the critical parameter management capabilities to the Theory of Domains, the Theory of Domains provides a comprehensive system-modeling framework to Axiomatic Design.

A strength of Axiomatic Design is its decision support system that contains two axioms and a set of corollaries and theorems, which are based on these axioms. When quantitative parameters (FR, DP, PV) are set it is possible to perform analysis of e.g. robustness in a design proposal using principles embodied in Axiomatic Design's axioms 1 and 2.

Main Hypothesis 3: *For every electromechanical product and its corresponding manufacturing system, it is possible to extract a set of quantitative parameters that characterize the designed artifacts and their representations in domain system models and that can be used to assess, manage, and improve their robustness.*

Now, in order to support Main Hypothesis 3, a set of auxiliary- and sub-hypotheses must be defined. Sub-hypotheses 3.1-3.3 make statements about the relationship between domain system models and quantitative parameters that characterize them. This relationship is also illustrated in Figure 102. Auxiliary hypotheses 3 and 4 make explicit statements about the existing body of theory that is assumed to be true.

8.2.3.1 The Relationship between Qualitative Domain Structures and Quantitative Parameters that characterize them

In Figure 102, a product and its manufacturing system that are subjected to design activities are each represented by a ToD-chromosome. Unstructured qualitative CNs are formalized as product processes that are carried out by product functions. Product functions are solved by product organs and embodied in product components. A manufacturing process transforms product components from an original state into a new state. A product is therefore regarded as operand in the manufacturing system. Manufacturing processes are carried out by manufacturing functions that are solved by manufacturing organs and embodied into manufacturing components.

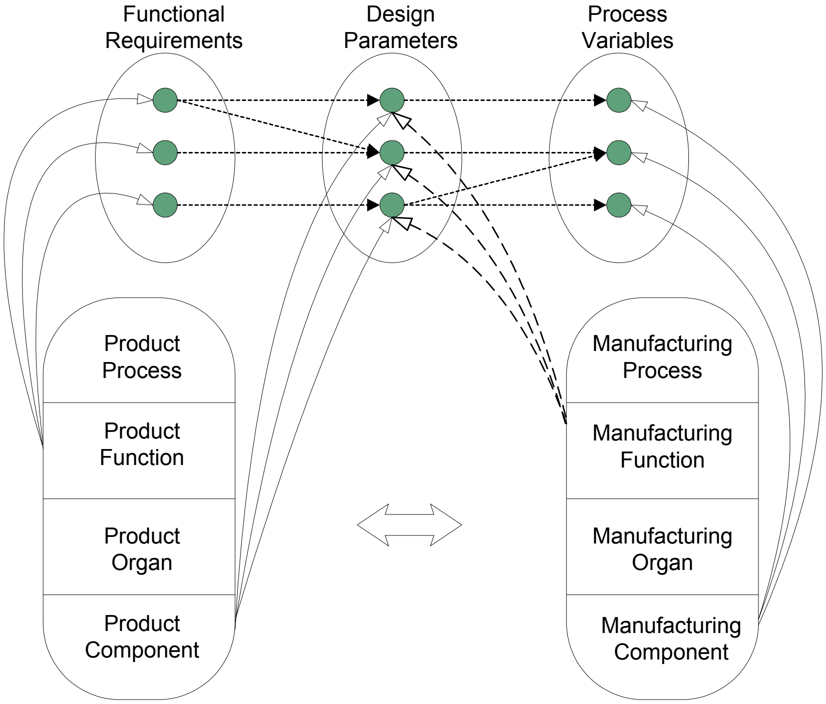


Figure 102: The relationship between domain system models and quantitative parameters that characterize them

Product and manufacturing system structures created in the ToD-framework are characterized by certain quantitative parameters whose values (and tolerances) must be set and be properly managed. This is facilitated by extracting quantitative parameters into the Axiomatic Design framework. Product process and -function are characterized by FRs while product organ and -component are characterized by DPs. Manufacturing process, -functions, -organs, and -components are characterized by PVs.

In order to be able to fit in the allover theory framework the FR-, DP-, and PV-definitions have to undergo some minor modifications.

Definition 9: *Functional Requirements (FRs) are a minimum set of quantitative independent requirements that completely characterize the functional needs of the product design solution in the functional domain.*

Definition 10: *Design Parameters (DPs) are the quantitative properties of the product design solution in the physical domain that are chosen to satisfy the specified FRs.*

Definition 11: *Process Variables (PVs) are the quantitative properties in the process domain that characterize the manufacturing system, which produces the specified DPs.*

Figure 102 also displays a dotted line between manufacturing functions and DPs. This line primarily represents the fact that DPs as product organ and -component key characteristics set requirements on the manufacturing system performance, i.e. a DP is also an expression of (desired) manufacturing system capability. However, DPs are entirely product-centric and therefore the relationship between DPs and manufacturing functions is dotted, i.e. it symbolizes an indirect relationship.

Hypothesis 3.1: *For every electromechanical product, it is possible to extract a set of quantitative FRs that characterize the required product functions.*

Example 16: Although the FRs are not always easy to quantify, a quantitative FR such as *Generate torque of 0.5 Nm (+/- 0.01Nm)* or *Generate rotational velocity of 25000 rev/s* is easier to understand and realize than a subjective qualitative product function such as *Provide rotation*. A qualitative product function can be characterized by several quantitative FRs.

Hypothesis 3.2: *For every electromechanical product, it is possible to extract a set of quantitative DPs that characterize the selected product organs and their corresponding product components.*

Example 17: A quantitative DP such as *Cylinder with surface roughness Ra=0.2µm* represents a qualitative product component such as *Shaft*. A qualitative product organ or component can be characterized by several quantitative DPs.

Hypothesis 3.3: *For every electromechanical product, it is possible to extract a set of quantitative PVs that characterize the selected manufacturing organs and their corresponding manufacturing components.*

Example 18: A quantitative PV such as insert radius $r_\varepsilon=0.4$ *mm* or feeding speed $f_n=0.07$ *mm/r* represents a qualitative manufacturing organ/component such as *Turning Tool*. A qualitative manufacturing organ or component can be characterized by several quantitative PVs.

8.2.3.2 Maintaining the Robustness of the Developed Systems

The relationship between FRs and DPs of a product highlights robustness of the product solution, while the relationship between DPs and PVs highlights robustness of the manufacturing process solution. The nature of this relationship, on which the auxiliary hypotheses presented in this section are based, is previously discussed by Suh (1990) and Engelhardt (2001).

A change of DP-value impacts the corresponding FR-value. By structuring the quantitative FRs and DPs, a possible malfunction can be identified, measured, and attributed to an appropriate DP. It is also possible to directly estimate the impact that a change in the customer needs, represented in changed FRs, will have on the design object and its DPs. Figure 103 shows an example of the relationship between FRs and DPs. The diagram shows the relationship between FR3 and DP3 for two different DP3-solutions. Alternative 1 is considered to be better since its stiffness is lower, i.e. the DP-value can fluctuate significantly before affecting the corresponding FR-value so that it falls outside of specified boundaries.

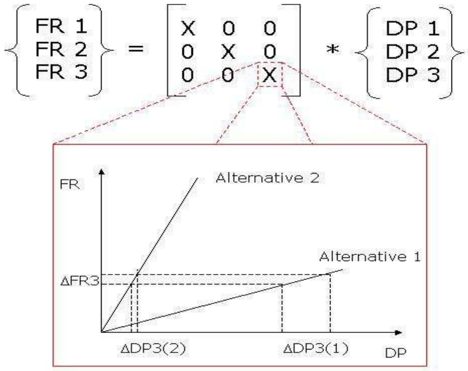


Figure 103: The relationship between FRs and DPs. Relationship between DPs and PVs follows a similar pattern

Analogously, a change of PV-value impacts the corresponding DP-value, and thus sometimes also the corresponding FR-value. By structuring the quantitative PVs and DPs, an insufficient manufacturing system output can be identified, measured, and attributed to an appropriate PV. Naturally, it is also possible to directly estimate the impact that a change in the manufacturing resource capability, represented in changed PVs, will have on the design object and its DPs.

Figure 104 shows a simple example of the relationship between DPs and PVs for a solution where relationship between PV3 and DP3 is spatial. A change in e.g. screw scull diameter can cause a malfunction during the assembly process execution if an existing feeder tube is not replaced by the one with more suitable diameter.

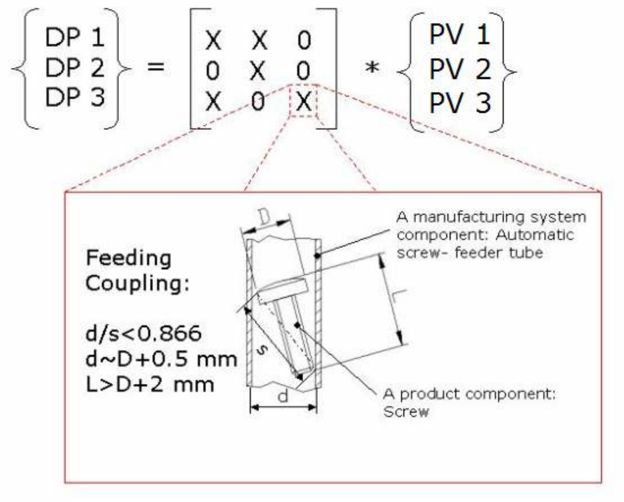


Figure 104: The relationship between DPs and PVs for a screwing application.

Auxiliary Hypothesis C: *The relationship between quantitative parameters that characterize domain system models for any electromechanical product and the corresponding manufacturing system can be used as a basis for understanding of how changes in manufacturing system parameter values (PV) impact product parameter values (DP and FR) and vice versa.*

As already stated in the Auxiliary Hypothesis B, the theory resulted from the research presented in this thesis rests on a hard core of universal statements formulated in WDK-theories and Axiomatic Design.

During the case studies it has been observed that it is possible to assume that the relationship between product- and manufacturing functions and product- and manufacturing organs and -components follows the same principle like the relationship between FRs and DPs with regard to the axiom 1 of Axiomatic Design. Consequently, elements of these qualitative domain system models (functions and organs/components) could, like quantitative parameters FR, DP, and PV, be mapped to each others and design matrices ([A] and [B]) that capture their relationship could be created.

In other words, the functional independence should be maintained and can be analyzed already when mapping between different domain system models, i.e. coupled and uncoupled designs may be identified even before the quantitative parameters are determined. This analysis can aid the developer in identifying the critical quantitative parameters and, naturally, the identification of FRs and DPs can facilitate the analysis. It is possible to draw the conclusion that Axiomatic Design is in this context utilized as analysis framework while ToD is used as synthesis framework. Synthesis and analysis are regarded as inseparable activities that must be executed when designing a technical system.

Auxiliary Hypothesis D: *For every electromechanical product and its corresponding manufacturing system, functional dependence can be assessed, and if needed resolved, by creating and manipulating design matrices that capture the relationship between product functions and product organs/components as well as between manufacturing functions and manufacturing organs/components.*

When creating the domain model structures axiom 1 as well as axiom 2 could be used as decision-making support. Robust design principles could also be used in order to support uncoupling of matrices, e.g. by decreasing the coupling between DPs and PVs ($dPV_j/dDP_i \Rightarrow 0$).

8.3 Manufacturing System Development Process and its Supporting Tools and Methods

8.3.1 The Toolbox

Structuring of a manufacturing process is carried out according to manufacturing system design principles about e.g. manufacturing process and workshop layout, batching and manufacturing resource resetting, manufacturing process control or inventory management. Manufacturing functions, -organs and –components are determined while considering various manufacturability principles, economic constraints, and existing resource infrastructure at the manufacturing company.

Domain system models of the ToD are not entirely sufficient for efficient decision-making during the execution of product and manufacturing system development process. Here, the domain system models must be coupled to conceptual (e.g. IDEFØ), geometric (e.g. 3DCAD) and behavioral (e.g. discrete event simulation) models. In fact, tools for creation of these conceptual, geometric, and behavioral models help in creation of domain system models by supporting the decision-making and feeding the domain system model structures with appropriate information, e.g.:

- IDEF3 can be used for creation of product- and manufacturing process structures,
- IDEFØ can be used for creation of corresponding functions and organs and for analysis of functional couplings,
- Process Flow Charts (PFC) can be used for capture and analysis of the relationship between value-adding and other manufacturing processes,
- REL- and precedence diagrams (PD) can be used for determination of high-level, primary spatial, manufacturing organ and -component structures,
- DES can be used for creation and analysis of high-level manufacturing organ and -component structures,
- MTM can be used for determination of cell-level manual manufacturing organs and –functions, i.e. spatial relationships and work procedures,
- MBS and CAM can be used for creation and analysis of spatial and behavioral properties of numerically controlled manufacturing organs and –components on the cell-level,
- CAD can be used for modeling the geometric shape of product- and manufacturing components.
- Design of Experiments (DoE) can be used for determination of sets of key DPs and their relationship with corresponding FRs, as well as for determination of sets of key PVs and their relationship with corresponding DPs. This relationship is then managed by applying axioms of Axiomatic Design as well as Robust Design principles.
- DFMA can be used either proactively during product develop-

ment in order to implement product components that allow creation of optimal manufacturing process and –component structure or reactively to evaluate product components' manufacturability from the perspective of available manufacturing processes, -organs, and –components.

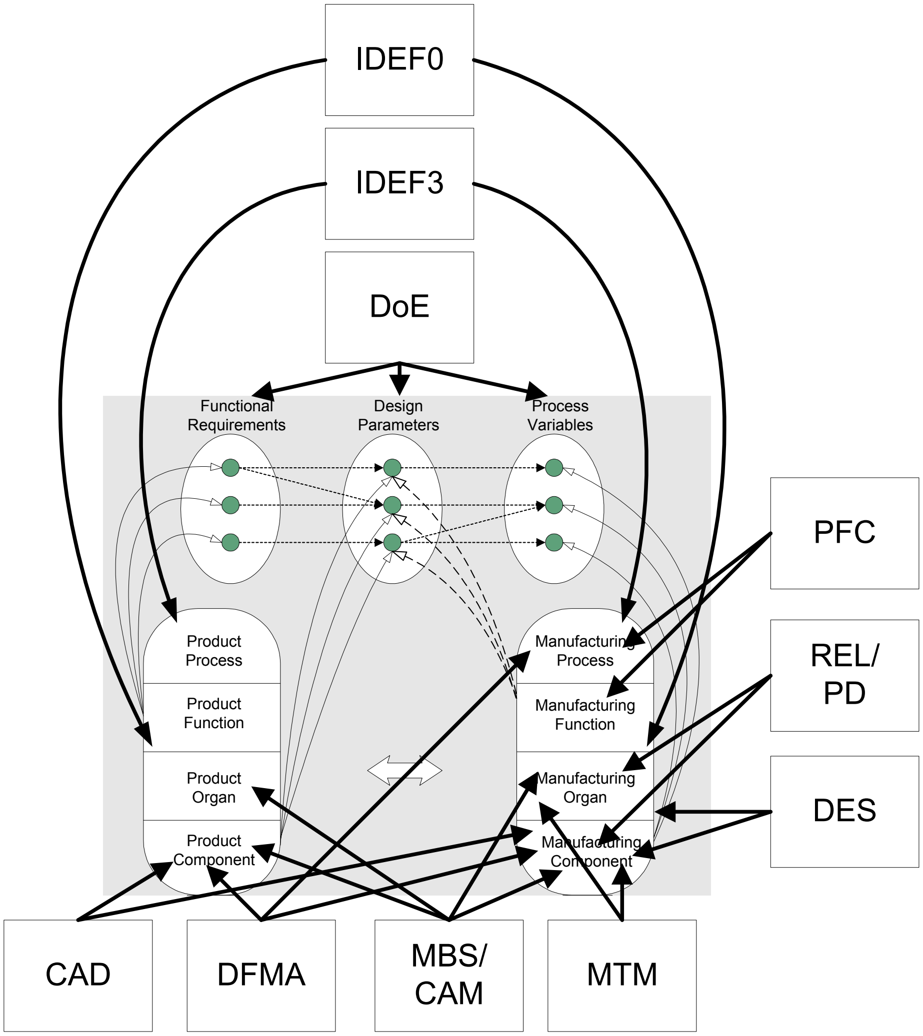


Figure 105: Various tools and methods support the creation of core product and manufacturing system structures.

As shown in Figure 105, various tools and methods can be applied in order to be able to create structures in domain system models and their corresponding quantitative parameter structures. Methods and tools support also each others by sharing or exchanging model data.

Here it is important to stress that, as pointed out in findings from case study 3 (cf. Section 7.3.2.4), when using a compiled methodology, the data portability between different methods must be facilitated. This is achieved through usage of consistent terminology between different methods, i.e. an information entity is either termed identically in every method or conversion between its different representations is performed unambiguously. For example, a function must be formulated identically in an IDEFØ-model as well as in the domain system model that represents manufacturing functions.

8.3.2 The Process: Development Project Control Model

It is easily understood that this great number of different methods and tools that manage substantial amount of information needs to be coordinated. In other words, in order to be able to effectively and efficiently use the methodology it must be made sure that right method is used for a right purpose in the right moment.

When utilizing the above mentioned methods and corresponding tools, the engineers continuously shift their perspective on the manufacturing system and thereby bring the design problem to a final solution. Since a manufacturing system development project involve several individuals and organizations that utilize different work methods during different time intervals, a project control model that systematizes the interaction between different design methods is needed. This project control model can be implemented as an internet application. Such an implementation has already been done by the author and it is the principles of that implementation that are to be briefly explained here. Appendix 2 contains a detailed description of the project control model.

The manufacturing system development process is an aggregation of five sub-processes:

i. preparation,
ii. concept design,
iii. system design,

iv. detailed design, and
v. completion.

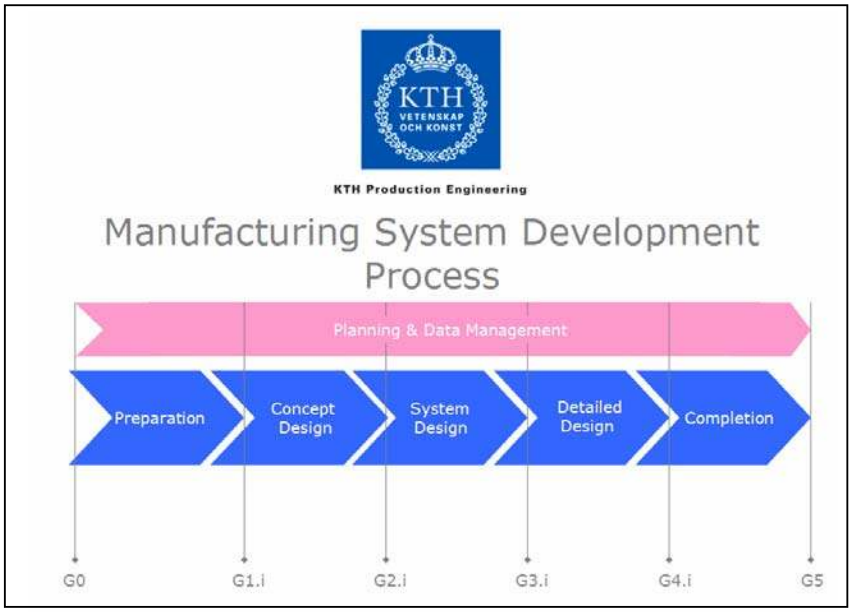


Figure 106: Generic process and project control model for manufacturing system development

Each of the sub-processes is then described in terms of its inputs, its outputs, and the activities that need to be executed in order to transform inputs into outputs. The activities are executed using the above mentioned methods and tools. During the course of work, the engineers will generate a set of manufacturing system models and project documents. The format of the manufacturing system models is controlled by the used methods, and project document format is controlled by pre-defined templates that can be downloaded from the Internet. By clicking on the arrow that symbolizes a sub-process, an engineer arrives at a page where inputs, outputs, and activities for that sub-process are described. From the sub-process page, project document templates are downloaded.

8.3.2.1 Project Assignment and Project's Internal Organization

The main input that triggers a project is an assignment specification prepared by the project sponsor. In the assignment specification different roles within the project are defined and assigned to the project members. The defined project roles are: project manager, system designer, manufacturability analyst, assembly engineer, and discrete manufacturing engineer.

8.3.2.2 Steering Group and Project Gates

The project is monitored by a steering group consisting of the project sponsor representatives. Prior to the initiation of each sub-process a gate-meeting is held between the project group and the steering group. At gate meetings the project assessment is performed, i.e. fulfilment of project goals is evaluated, and one of three outcomes is generated; *go*, *no* and *redirect*.

Go means that the objectives of the previous phase are fulfilled and the next phase can be initiated, *no* means that the process is terminated and will not be continued and *redirect* means that the objectives of the previous phase are not fulfilled and, consequently, some rework has to be done. There are at least six gate meetings, one meeting prior to each phase and a project completion meeting.

8.3.2.3 Project Stages (Sub-processes)

In this section, a short description of sub-processes within the manufacturing system development process will be presented. A more detailed process description and corresponding documentation templates are included in Appendix 2.

During the execution of the sub-process *preparation*, the engineers need to understand the operations strategy of the company, its existing processes and resources, as well as product design rationale. In this stage the project specification is generated.

Concept design is the first manufacturing system design sub-process. Here, a high-level manufacturing process, -function, and -organ structure is established. Methods like IDEFØ, IDEF3, and PFC are used.

Naturally, DFMA and CAD are also used during the course of the whole project for manufacturability assessment and generation of product design change proposals. Preliminary supplier lists and an investment plan are generated.

In *system design* phase the decomposition of structural models (manufacturing processes, -functions, -organs, and -components) is continued until the manufacturing station level. A special attention is directed towards selecting appropriate manufacturing components and the corresponding workshop layout (using relationship and/or precedence diagrams) as well as manufacturing system operation principles. Based on the manufacturing system business requirements and the proposed manufacturing system design, a simulation experiment plan is created and a DES-tool is used to build the system model, and through experiments find and/or verify an optimal manufacturing system configuration.

The next phase is *detailed design*, where manufacturing stations are designed. Here, structural models are further decomposed (manufacturing processes, -functions, -organs, and –components on a detailed level)and methods/tools like IDEFØ, MTM and CAM are used for design of manual and automatic manufacturing station components. When station design is proposed the all over manufacturing system concept, i.e. stations arranged according to the workshop layout and controlled according to the proposed operation principles, are analyzed through conducting the simulation experiments using a DES-tool.

The project is terminated in the sub-process *completion*, where necessary design adjustments are made and a final project report is compiled from the generated project documents.

8.3.2.4 Information Management

During the course of the project, several methods and computerized tools are used and a great amount of information is created. In order to be able to manage the information flow, engineers are using a PDM-system for handling product and manufacturing system structures and the associated documentation. Also project documents are handled within the PDM-system. Furthermore, the PDM-system facilitates communication between the project group members, between the project group and its partners, and between the project group and the members of the steering group.

8.4 Validation of the Theory

The new hypotheses specified in Section 8.2 can now be tested. The test will be performed as analysis of an existing product and manufacturing system design. Here, the hypotheses test in a design synthesis situation should be regarded as more preferable, but due to the economical and time constraints such a test could not be performed.

8.4.1 Case: Manufacturing of a piezoceramic micro-actuator

The analyzed product is a piezoceramic micro-actuator. This micro-actuator, as presented by Bexell (1998), is developed and manufactured in an academic research environment. In order to be able to extrapolate the manufacturing system structure suited for the realities of the market, discussions with senior management for Piezomotor AB have been conducted. Piezomotor AB is a commercial spin-off from the micromechanics research group at Uppsala University; a part of their research is presented by Bexell (1998). Piezomotor AB develops and manufactures a piezoelectric micro-actuator that is a commercial variant of the research prototype. Due to the competitive reasons the details about this new micro-actuator and its manufacturing system cannot be disclosed.

The manufacturing system must be suited to the demands set by the market, where main customer group is here assumed to be manufacturers of biotech instruments. The fictive potential of the company's market and thus the required manufacturing system capacity is:

- Year 1: 500 actuators
- Year 2: 1.000 actuators
- Year 3: 8.000 actuators
- Year 4: 10.000 actuators

8.4.2 Hypotheses Testing: Expected Empirical Consequences

8.4.2.1 Hypothesis 1

Hypothesis 1 is stated as:

Every resource in every manufacturing system structure (for electromechanical products) satisfies a functional need imposed by at least one of the following drivers:

- *physical characteristics of the product that the manufacturing system is going to manufacture.*
- *development decisions made on the higher level of the manufacturing system structure.*
- *the business (e.g. capacity, delivery speed) and/or moral (e.g. outer environment, workplace ergonomics) constraints set by the stakeholders of the manufacturing system.*

Its auxiliary hypothesis yields:

Every manufacturing system structure can be viewed as an assembly of machines and/or humans (including their respective control systems) that perform manufacturing operations such as assembly, detail manufacturing, handling, transportation, and quality control.

Accordingly, the expected empirical consequence is:

The existence of every resource in the observed manufacturing system for piezoceramic actuators is motivated by either the physical characteristics of the piezoceramic actuator, development decisions made on the higher hierarchy level of the developed manufacturing system, or business/moral constraints set by the market, the share holders, or the authorities.

8.4.2.2 Hypothesis 2

Hypothesis 2 is stated as:

Every manufacturing process is executed by a manufacturing system that can be described in terms of four domain system models (manufacturing process, -function, -organ, and -component), which are directly related to the corresponding four domain system models of the manufactured product (product process, -function, -organ, and -component).

Eight separately testable sub-hypotheses that entirely cover the main hypothesis are derived:

1. *Every electromechanical product determines, through the structure of its product components, the possible sequences and the outcome of the corresponding manufacturing processes.*
2. *Every manufacturing process sequence constrains the structure of corresponding electromechanical product components.*
3. *Every electromechanical product determines indirectly, through a manufacturing process sequence based on the corresponding product component structure, a set of capabilities, i.e. manufacturing functions that the corresponding manufacturing system must have.*
4. *Every electromechanical product constrains, through the structure and other properties of its product components, the selection of manufacturing methods, i.e. manufacturing organs.*
5. *Every manufacturing organ constrains, through its ability to provide the desired capability to the manufacturing system, the structure and the property goal values for electromechanical product components.*
6. *Every electromechanical product constrains, through the structure and the property goal values of its product components, the structure and property values for manufacturing components.*
7. *Every manufacturing component constrains, through its structure and property values, the structure and the property goal values for electromechanical product components.*
8. *Every electromechanical product organ that needs to be verified during manufacturing directly impact, and is impacted by, the structures of manufacturing processes, -functions, -organs, and -components regardless of whether corresponding product component structure has been determined or not.*

Accordingly, the expected empirical consequences are:

The manufacturing process for piezoceramic actuators is executed by a manufacturing system that can be represented by four system domain *models, which are directly related to the corresponding four domain system models of the piezoceramic actuator. This relationship has following characteristics:*

1. *The structure of piezoceramic actuator's components determines the sequence and the outcome of the corresponding manufacturing processes.*
2. *The manufacturing process sequence for piezoceramic actuators determines the structure of corresponding actuator components.*
3. *The design of the piezoceramic actuator determines indirectly, through the manufacturing process sequence based on the corresponding actuator component structure, a set of capabilities, i.e. manufacturing functions that the manufacturing system for piezoceramic actuators must have.*
4. *The design of the piezoceramic actuator constrains, through the structure and other properties of its product components, the selection of appropriate methods for actuator manufacturing, i.e. manufacturing organs.*
5. *Manufacturing organs in the manufacturing system for piezoceramic actuators constrain, through their ability to provide the desired capability to the manufacturing system, the structure and the property goal values for actuator components.*
6. *The design of the piezoceramic actuator constrains, through the structure and the property goal values of its product components, the structure and property values for manufacturing components in the manufacturing system for piezoceramic actuators.*
7. *Manufacturing components in the manufacturing system for piezoceramic actuators constrain, through their structure and property values, the structure and the property goal values for actuator components.*
8. *Piezoceramic actuator organs that need to be verified during manufacturing directly impact, and are impacted by, the structures of actuator manufacturing processes, -functions, -organs, and -components regardless of whether corresponding actuator component structure has been determined or not.*

8.4.2.3 Hypothesis 3

Hypothesis 3 is stated as:

For every electromechanical product and its corresponding manufacturing system, it is possible to extract a set of quantitative parameters that characterize the designed artifacts and their representations in domain system models and that can be used to assess, manage, and improve their robustness.

In addition, three separately testable sub-hypoteses that partially cover the main hypothesis have been formulated:

1. *For every electromechanical product, it is possible to extract a set of quantitative FRs that characterize the required product functions.*
2. *For every electromechanical product, it is possible to extract a set of quantitative DPs that characterize the selected product organs and their corresponding product components.*
3. *For every electromechanical product, it is possible to extract a set of quantitative PVs that characterize the selected manufacturing organs and their corresponding manufacturing components.*

Two auxiliary hypotheses support the testing procedure:

- *The relationship between quantitative parameters that characterize domain system models for any electromechanical product and the corresponding manufacturing system can be used as a basis for understanding of how changes in manufacturing system parameter values (PV) impact product parameter values (DP and FR) and vice versa.*
- *For every electromechanical product and its corresponding manufacturing system, functional dependence can be assessed, and if needed resolved, by creating and manipulating design matrices that capture the relationship between product functions and product organs/components as well as between manufacturing functions and manufacturing organs/components.*

Accordingly, the expected empirical consequences are:

A set of quantitative parameters that characterize the piezoceramic ac-

tuator and its manufacturing system can be defined. These parameters can be used to assess, manage, and improve the robustness of the piezoceramic actuator as well as its manufacturing system. Following quantitative parameters can be defined:

1. *FRs that characterize the required actuator functions.*
2. *DPs that characterize the selected product organs and their corresponding components for the piezoceramic actuator.*
3. *PVs that characterize the selected manufacturing organs and their corresponding manufacturing components in the manufacturing system for piezoceramic actuators.*

8.4.3 Product Decomposition: Level 1 and 2

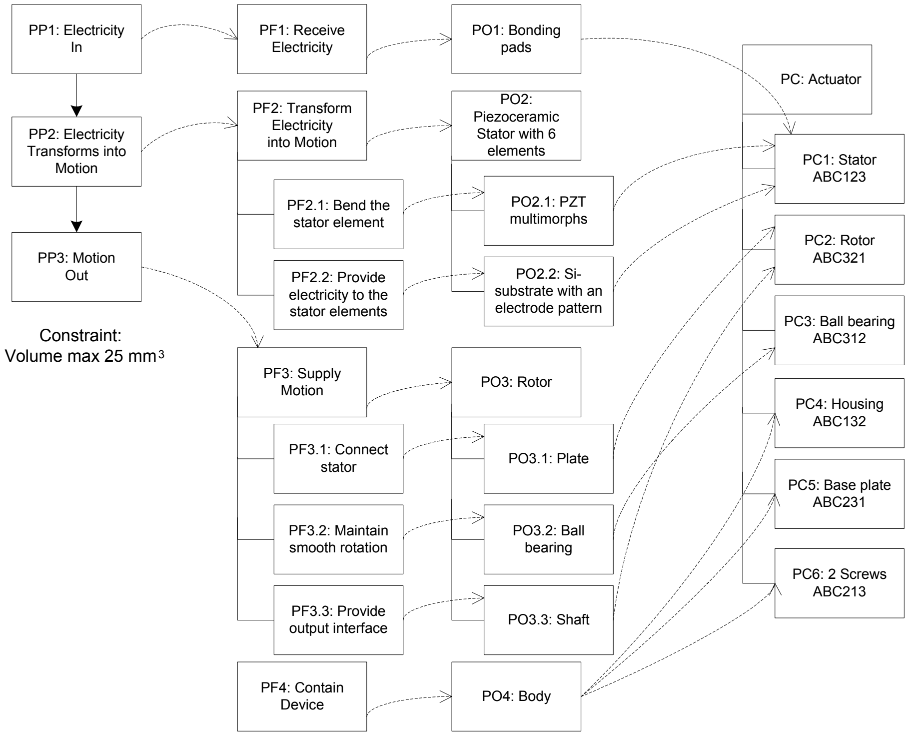
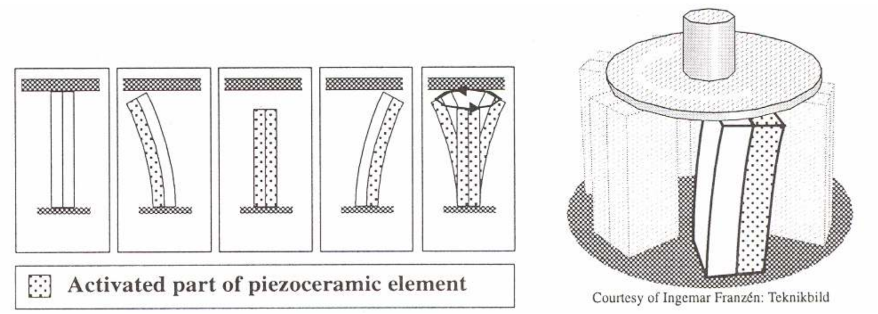


Figure 107: Process-, function-, organ-, and component structure for the piezoelectric micro-actuator

Figure 107 shows a domain model structure for the product: a piezoelectric micro-actuator. Product's process is divided into three sub-processes (PP1-PP3) that input electricity, transform it into motion, and output the motion to the external environment. The product's volume must not exceed 25 mm^3. These processes are translated into the product functions (PF1-PF4). In order to be able to satisfy the volume constraint, the piezoelectricity has been chosen as a basis for the technical solution. The technical solution, as described in Figure 107, assumes a piezoceramic stator and a rotor. These two features together with an electricity input device (bonding pads) and a body constitute an allover organ structure (PO1-PO4).



Courtesy of Ingemar Franzén: Teknikbild

Figure 108: The principal solution for a piezoceramic actuator, Bexell (1998)

The selection of the stator and the rotor reinforce the function brakedown into PF2.1-PF2.2 and PF3.1-PF3.3, respectively. These functions are then satisfied by organs PO2.1-PO2.2 and PO3.1-PO3.3, respectively.

Now, the defined set of organs can be embodied into a physical component structure (PC1-PC6). These components are depicted in Figure 109.

Since product organs PO2.1 and PO2.2 are defined, it is possible to go on with specification of their embodiment. PO2.1 can be embodied in physical stator elements with determined dimensions and PO2.2 can be embodied in a printed circuit board (PCB). This decomposition of PC1 is depicted in Figure 110.

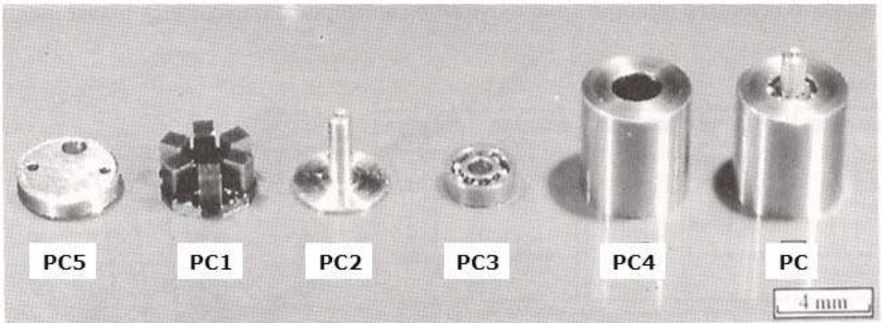


Figure 109: Actuator's components, adapted from Bexell (1998)

In this hypotheses validation, we are going to focus on developing a manufacturing system for actuator's stator. Therefore, the product will now be decomposed only with respect to PF2: *Transform Electricity into Motion*. Hypothesis validation will be performed only with respect to decomposition of PF 2, i.e. PF2, PF2.X, and PF2.X.Y.

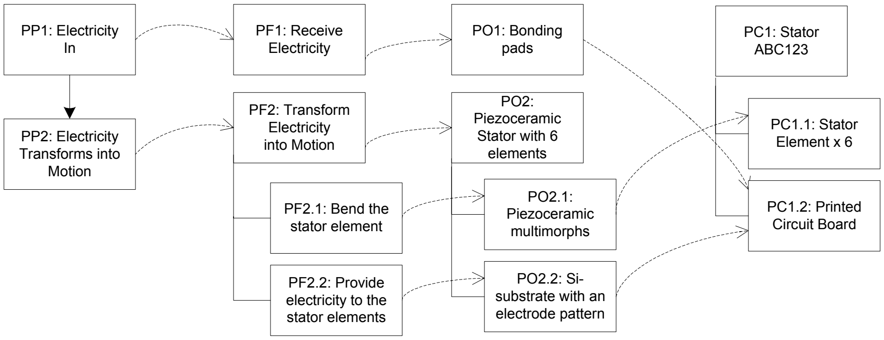


Figure 110: PC1 decomposes in PC1.1 and PC1.2

8.4.4 Manufacturing System Decomposition: Level 2

Figure 111 shows an IDEF3-model of the stator manufacturing process. The model focuses on transformation of the operand from an initial state, i.e. material, through intermediate states, i.e. a set of unconnected stator elements and PCB, to the final state, i.e. a stator embodied in a single component. Before stator unification in a single component all stator elements and PCB must be available. The IDEF3-model links therefore product components with manufacturing processes.

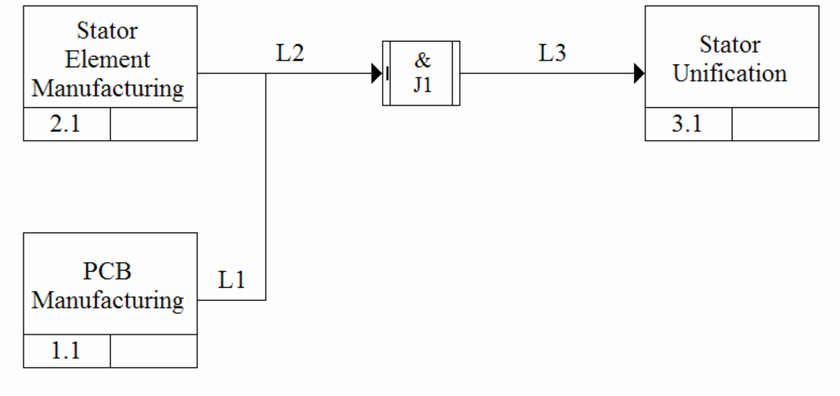


Figure 111: Stator manufacturing process

The manufacturing processes require a set of capabilities that the manufacturing system must possess. These capabilities, i.e. manufacturing functions, can be modeled using the IDEFØ-method. Figure 112 shows a manufacturing function model for stator manufacturing. Besides functions directly related to transformation of physical operands a planning and control function (A4) is defined. The IDEFØ-model also indicates the manufacturing organs, i.e. IDEFØ-mechanisms, selected in order to carry the required functions.

The fictive company sees its competitive advantage within stator elements manufacturing and assembly. PCB-manufacturing with lithographic techniques is a mature line of business for a vast number of contract manufacturers. Because of need for substantial investments in lithography equipment if PCBs are manufactured in-house and a wide range of capable external suppliers, manufacturing of PCBs will be outsourced. This decision impacts function A2-A4; Functions A2 and A3 will be controlled by a Kanban-order generated by A4 and A1 will be controlled by a forecast batch order generated by A4.

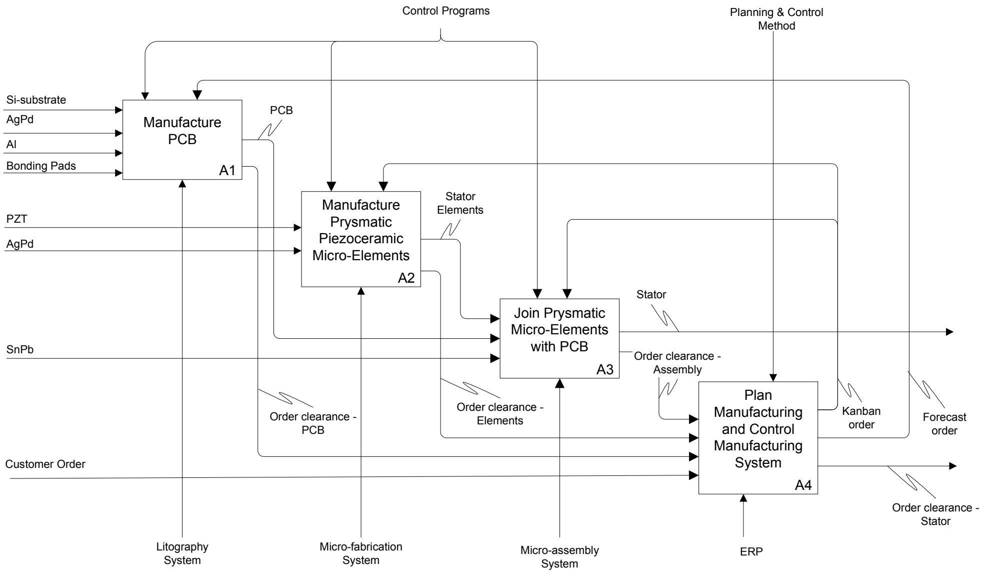


Figure 112: Function structure for the stator manufacturing system

Figure 113 depicts the domain structures for stator manufacturing system based on development decisions made using IDEF3- and IDEFØ-methods.

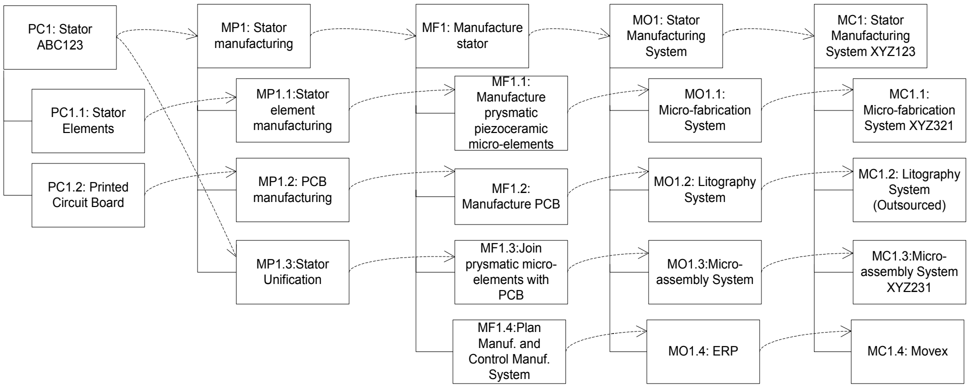


Figure 113: Top-level domain structure for the stator manufacturing system

8.4.5 Product Decomposition: Level 3

Figure 114 shows further product decomposition including functional and organ structure for stator elements (PC 1.1) and the printed circuit board (PC 1.2) that connects them. Stator elements are embodiments of Piezoceramic multimorphs, which are layered rectangular pieces of a piezoceramic material.

Now, the decomposition of PF2.1 and PF2.2 can be performed, which is also showed in Figure 114. Functions that enable insertion of electricity and its transformation into mechanical load are realized by piezoceramic multimorphs' AgPd-electrode layers and PZT[6]-layers, respectively. Naturally, the dimensions of these layers determine the dimensions of corresponding stator element as well as its performance capability.

The thickness of electrode lines is not specified by Bexell (1998), but it is evident that electrode pattern and stator element layers must align in order to be able to make contact. Therefore, it is suitable to approximate the thickness of PCB electrode lines to be only slightly thicker than electrode layers in the stator elements. Here, clear product design specifications and the capability of PCB-supplier's lithography system are of great importance.

Furthermore, Bexell (1998) stresses that, because of the alignment requirement, the manufacturing equipment must be capable to join the stator elements and the PCB with high precision, i.e. ±1 µm.

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[6] PZT is a piezoceramic material, a solid solution of $PbZrO_3$ and $PbTiO_3$

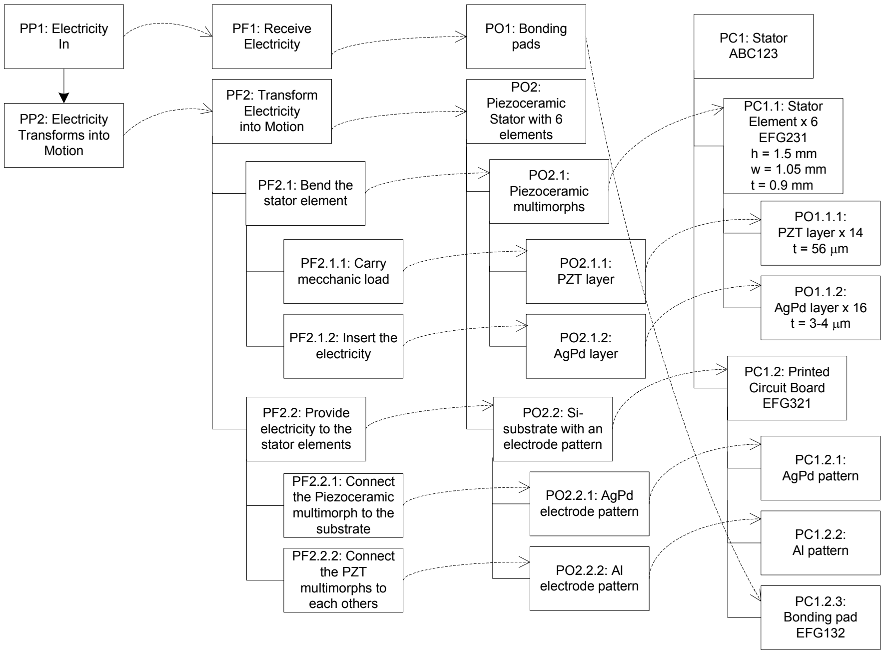

Figure 114: PF2, PF2.1, and PF2.2 decomposed

8.4.6 Manufacturing System Decomposition: Level 3 and 4

Now, when the manufacturing system structure on the top level is proposed and the product is further decomposed it is possible to continue the decomposition of the manufacturing system. A manufacturing subprocess that will be decomposed is *Stator Unification*.

8.4.6.1 Stator Unification

Figure 115 shows the decomposition of the stator unification process. The first level of this decomposition is a direct consequence of the decision to allocate organs that carry functions A1, A2, and A3 into three different physical embodiments. This allocation in different physical embodiments implies the need for transportation- and receive/storage processes.

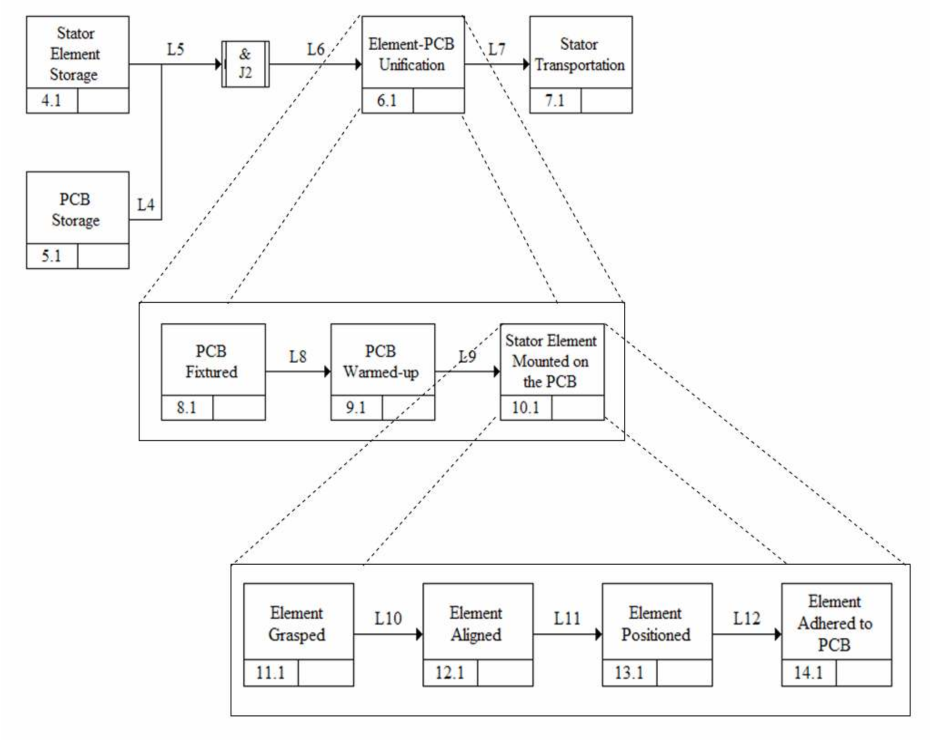

Figure 115: Stator Unification Process

This first process-decomposition level is mapped into a function structure, i.e. decomposition of function A3. Figure 116 depicts this functional decomposition and reveals the capabilities required by the manufacturing system in order to be able to perform the unification operation. The selected mechanisms and the relationship between functions imply the functional coupling in the manufacturing system due to the choice of technical solutions and their embodiments. The manufacturing function MF1.3 (A3) covers the responsibility of the manufacturing component MC1.3 to receive and store stator elements and PCBs, join them together, and transport the subassembly to the actuator assembly station.

The domain model structure is depicted in Figure 117. The system is decoupled due to the sequential dependency between functions. Embodiment of functions MF1.2.1 and MF1.2.2 in two separate components MC1.2.1 and MC1.2.2 uncouples the relationship between them.

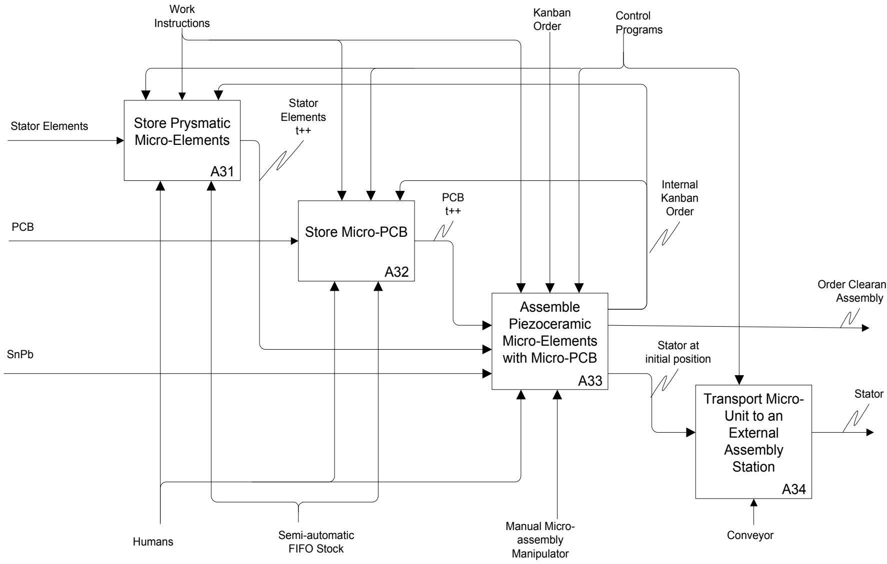

Figure 116: Decomposition of manufacturing function MF1.3 (A3)

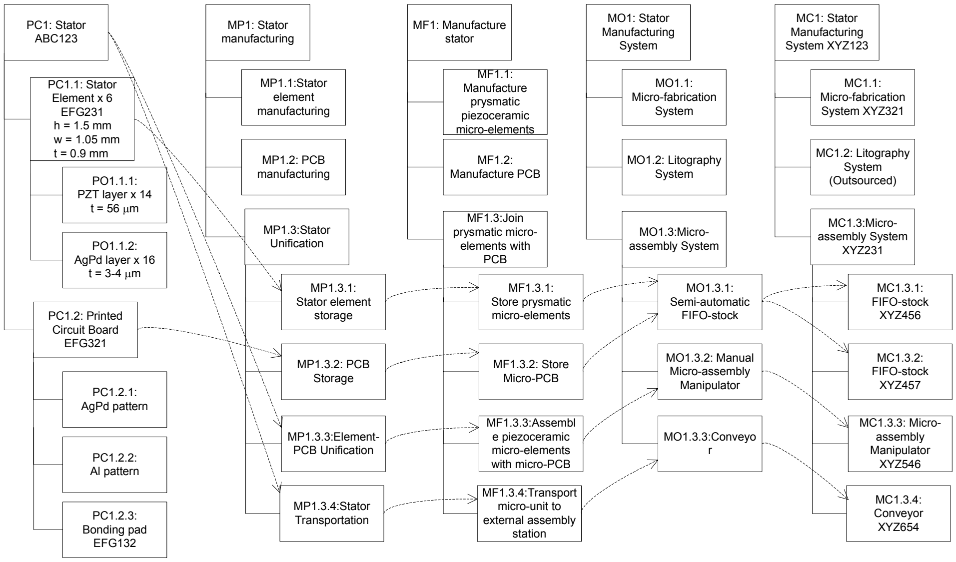

Figure 117: Stator assembly system decomposed

Now it is possible to continue braking down the structure into the higher level of detail. Naturally, in order to be able to examine all couplings between functions due to the choice of technical solutions and their embodiments, and thus evaluate the robustness of the system as a whole, all branches of the system hierarchy should be decomposed. However, since the hypotheses validation may not require this extensive enterprise, only one branch will be further decomposed, namely function MF1.3.3 (A33). Figure 118 shows the structure of the function A33.

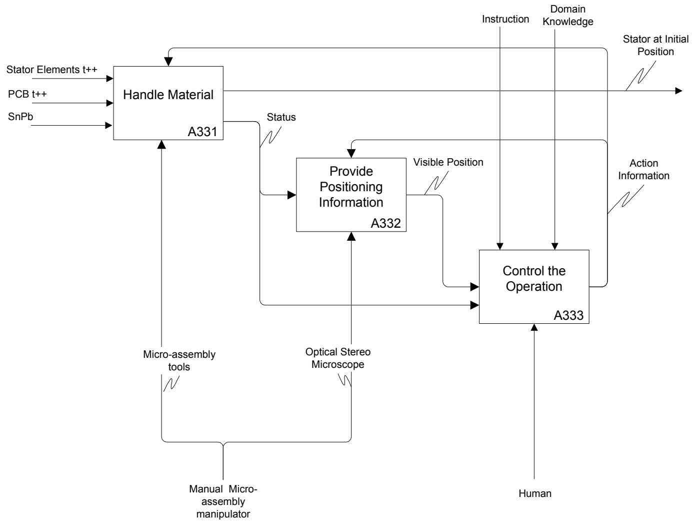

Figure 118: Decomposition of the function MF1.3.3 (A33)

Function A33 is decomposed into three sub-functions. Function MF1.3.3.1 (A331) is the actual working function that takes care of material manipulation. This function is executed by the manufacturing organ MO1.3.2.1: Micro-assembly tools. The assembly operation is manual and is executed and controlled (manufacturing function MF1.3.3.3, i.e. A333) by a human operator (manufacturing organ MO1.3.2.3), who due to the miniature size of the assembled components need a tool that enables him/her to continuously view the progress of the assembly work in order to be able to make appropriate decisions. This progress information is provided by the manufacturing function MF1.3.3.2: Provide Positioning Information who is carried out by the manufacturing organ

MO1.3.2.2: Optical Stereo Microscope.

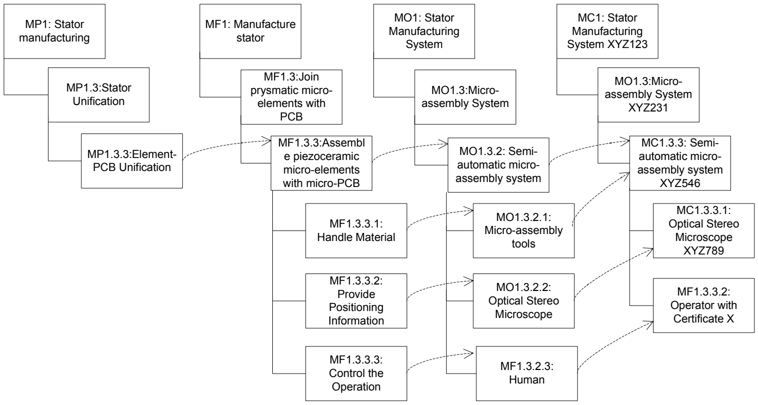

Figure 119: Semi-automatic micro-assembly system decomposed

The function MF1.3.3.1 is then decomposed into its sub-functions as depicted in Figure 120. The decomposition of the function MF1.3.3.1 also shows the technical solutions, i.e. the organs, which are going to be applied in order to carry out the function. Figure 121 shows the MF/MO/MC decomposition for the micro assembly manipulator and its tools.

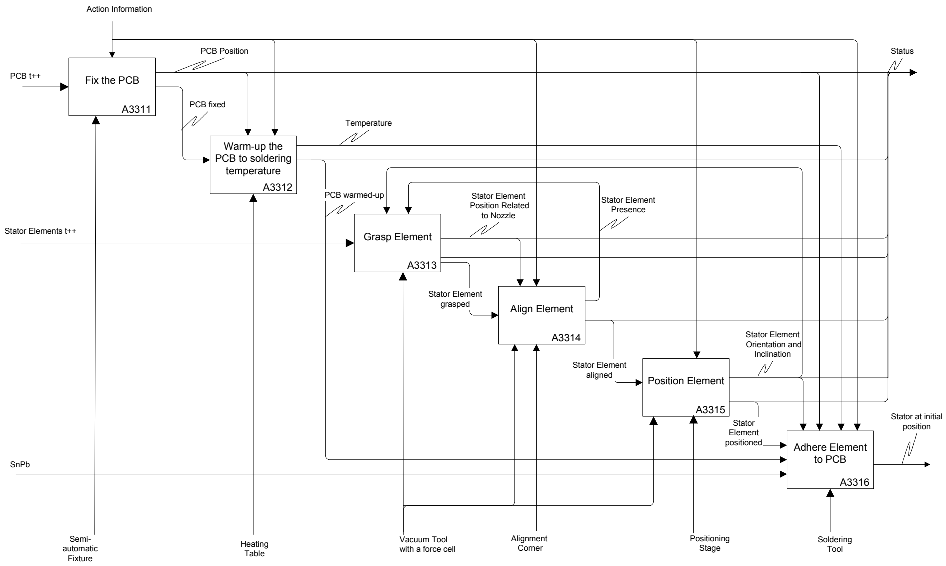

Figure 120: Decomposition of the function MF1.3.3.1 (A331)

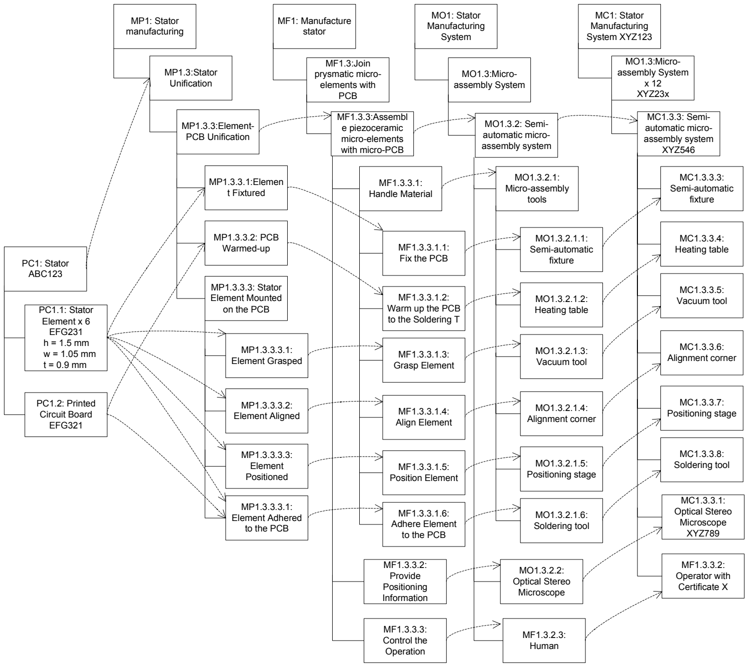

Figure 121: Decomposition of the micro-assembly manipulator

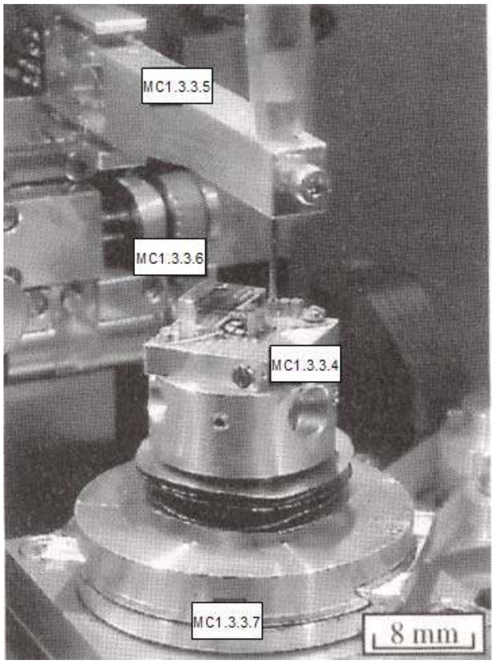

Figure 122: A part of the micro-assembly manipulator, adapted from Bexell (1998)

8.4.6.2 Number of stator assembly stations

As stated in Section 8.4.1 the manufacturing capacity need is assumed as following:

- Year 1: 500 actuators
- Year 2: 1.000 actuators
- Year 3: 8.000 actuators
- Year 4: 10.000 actuators

Tests performed by Mats Bexell at Uppsala University have shown that the stator assembly time, when using the proposed micro-assembly system, can be approximated to 2.5 hours. Moreover, tests have also shown that the assembled stators need to be polished before final actuator assembly. This polishing operation takes approximately 8 hours and is the main bottleneck of the whole actuator manufacturing process. However, even if the necessity for this polishing operation may be dictated by the performance of the stator assembly process, the polishing operation will in this case not be regarded as a part of the stator assembly process.

So, under the assumption that there are 2000 hours/year available for production (50 weeks * 40 hours), there is the need for:

- Year 1: 1 assembly station (overcapacity)
- Year 2: 2 assembly stations (overcapacity)
- Year 3: 10 assembly stations
- Year 4: 12 assembly stations (undercapacity)

8.4.6.3 Quantitative parameters and design robustness analysis

At this decomposition level the micro-assembly system's capability to achieve its tasks could be evaluated. The micro-assembly system is modeled so that a miniature stator could be assembled. One of the PFs for stator, PF2.1: Bend the stator element, is characterized by several quantitative parameters. The first one FR2.1a is concerned with the requirement to during the operation extend or contract the element. FR2.1a is labeled extension, e [µm]. The second FR, FR2.1b, which aims to capture the requirement to deflect the element, is labeled as deflection w [µm]. Third FR, FR2.1c captures the requirement on bending strength that the element must be able to exert and is labeled as output force F [mN].

PF2.1 is solved by PO2.1, which after embodiment in PC1.1 is determined to be characterized by several DPs. DP2.1a, element's length L [mm] solves the extension/contraction requirement. Maximum extension/contraction depends, besides on material properties, mainly on the length of the piezoceramic element. The number of existing PZT-layers, i.e. thickness, determines possible deflection. Therefore, the deflection requirement, FR2.1b, is solved by element thickness t [mm], i.e. DP2.1b. Off-course deflection depends also on the element length and the material properties. Design parameter DP2.1b depends on DPs that characterize PO2.1.1/PC1.1.1 and PO2.1.2/PC1.1.2, i.e. PZT-layer thickness and AgPd-layer thickness, respectively.

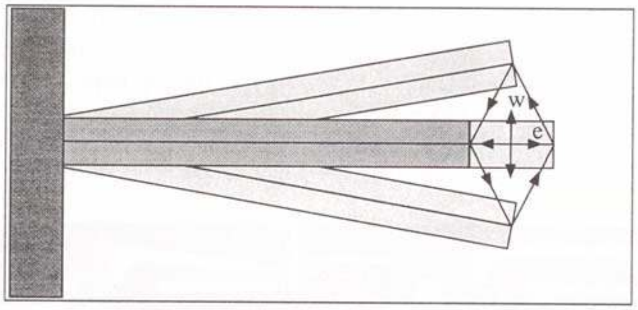

Figure 123: Extension, e and deflection, w, Bexell (1998)

Finally, the output or holding force mainly depends on material properties, such as the piezoelectric coefficient, Young's modulus and elastic deflection. These material properties are labeled as X_m. Naturally, the element dimensions, like thickness, width, and length, also have some impact on the output force. Width, however, do not impact on e and w, has negligible impact on F compared to t, is not changeable during the stator operation, and is generated with same tool and in same process as L. Therefore, width is not regarded as a key-DP that needs to be considered separately. The relationship between FRs and DPs can be represented in the following design equation:

$$\begin{Bmatrix} e \\ w \\ F \end{Bmatrix} = \begin{pmatrix} X & 0 & X \\ X & X & X \\ X & X & X \end{pmatrix} \begin{Bmatrix} L \\ t \\ X_m \end{Bmatrix}$$

The design equation implies that the stator element design is coupled.

The other stator-PF, PF2.2: Provide electricity to the stator elements, is solved by PO2.2, which after embodiment in PC1.2 cannot be characterized by a quantitative parameter but need to be decomposed further. PF2.2.1 is not easy to quantify with a continuous variable but is regarded to be characterized by a discrete variable "connect", c [true/false] (FR2.2.1). PO2.2.1/PC1.2.1, is characterized by quantitative parameters width (DP2.2.1a) of, and spacing (DP2.2.1b) within, the AgPd-pattern. These parameters mirror the stator element design, i.e. the number and thickness of PZT and electrode layers. This implies the coupling between PF2.1 and PF2.2. Since FR2.2.1 is solved with two DPs the design is over-determined and therefore coupled.

Now, which PVs characterize the manufacturing system solution and how are they related to the control of the DP-values and thus the satisfaction of specified FRs? It should be understood that the above discussed DP-values are primarily controlled by the PVs within MC1.1 and MC1.2. MC1.1 and MC1.2 are not formally decomposed in this thesis but after analyzing the manufacturing system solution by Bexell (1998) it is possible to infer that DP2.1a, i.e. L, is controlled by PVs within the dicing process, DP2.1b, i.e. t, is controlled by PVs within the wet-building process, and DP2.1c, i.e. X_m, is controlled by the PVs within the PZT-manufacturing process.

However, since PO2.1 and PO2.2 are embodied into two different components an assembly process must be modeled. The assembly process has also been proposed by Bexell (1998) and presented in previous sections. The assembly process is realized by MC1.3. Since the correct assembly of stator components is probably crucial for allover performance of the stator as a whole, the relationship between assembly system's PVs and product's DPs and FRs need to be analysed.

In order to be able to determine relevant PVs, an experiment using either virtual or physical assembly system model should be performed. Experimentation performed by Bexell (1998) shows that there are two PVs in the assembly system that exert control on the discussed DPs and thus impact the corresponding FRs.

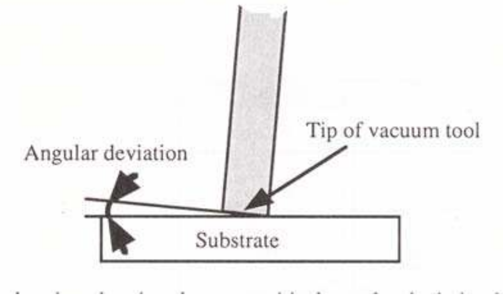

Figure 124: Angular deviation the vacuum tool's tip and the PCB-substrate, Bexell (1998)

The first PV is angular deviation, α [mrad], between the vacuum tool's tip and the AgPd-pattern on the PCB (cf. Figure 124). This PV, denominated PV2.1, impacts on the alignment of stator elements with the PCB's pattern and, accordingly, it might be a reason why all the mating points between the stator element and the PCB are not established. In other words, a certain angular deviation results in the fact that a number of AgPd-lines on the PCB do not make a contact with a number of corresponding AgPd-layers on a stator element. This, in its turn leads to malfunction related to PF2.2, i.e. c = false, as well as malfunction related to PF2.1, i.e. insufficient value for variables w and F due to the lower number of active PZT-layers (lower stator element thickness, t) in the PC1.1. Experiments have shown that angular deviation must be lower than 6 mrad in order to be able to make contact between all the PZT-layers and all AgPd-lines on the PCB.

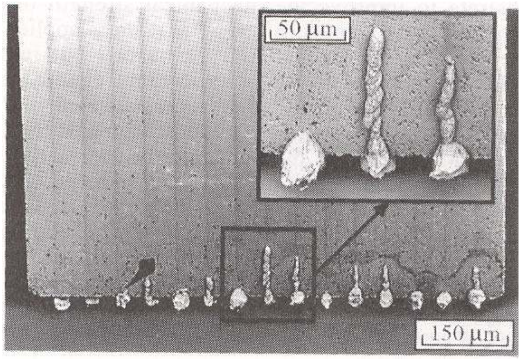

Figure 125: A stator element joined with the PCB, Bexell (1998)

One solution to this problem could be introduction of adaptive control by installing a force sensor on a vacuum tool that will measure the force between a stator element and the PCB during fitting. Experiments conducted by Bexell (1998) have shown a direct correlation between contact failures and the applied fitting force. In order to avoid contact failures and short circuits the fitting force should lie in the interval 6 mN > F_f > 100 mN.

The second PV, PV2.2, is xy-deviation. It represents the assembly system's ability to align a stator element with the corresponding PCB-pattern (DP2.2.1a, DP2.2.1b). PV2.2 is expressed as allowed deviation or positioning accuracy with maximum value ±1 µm. This tight tolerance is needed since the system must be able to align AgPd-layers in the stator element (thickness 3-4 µm) with AgPd-layers in the PCB. Tolerances of this magnitude set tremendously high requirements on assembly system's positioning accuracy. The inability to achieve the specified positioning accuracy results in the contact failure, i.e. c = false (FR2.2.1), and therefore insufficient or null values on e, w, and F (FR2.1a-c).

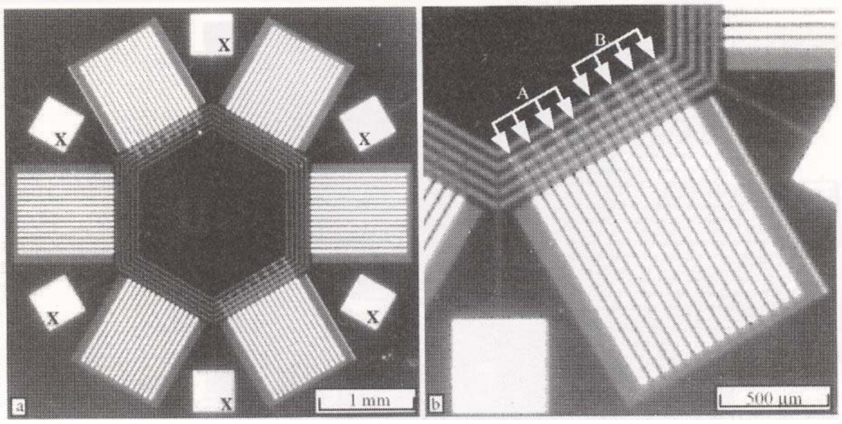

Figure 126: PCB electrode pattern, Bexell (1998)

In order to be able to bring positioning accuracy requirements to a reasonable level, a redesign of the stator has been proposed by Bexell (1998). In this new design, stator elements will be consisted of parallel instead of vertical PZT- and electrode layers (43 active layers). Every stator element will in this new design be divided into two electrically separated electrode areas in order to behave like a piezoelectric bimorph. Connection of internal electrode layers is made through application of silver metal paste at the sides of the elements. The electrical contact between stator elements and the PCB is maintained through a new component, a flexible PCB-cable. This new design adds an extra assembly operation, i.e. assembly of the flexible PCB-cable, but it also changes the requirement on positioning accuracy from maximum value ±1 µm to maximum value ±50 µm. The increased positioning tolerance has the potential to significantly decrease the manufacturing cost associated with e.g. assembly cycle time, assembly equipment costs, and assembly failure rate.

8.4.7 Falsification and/or Corroboration

8.4.7.1 Hypothesis 1

The expected empirical consequence of the Hypothesis 1 (cf. Section 8.4.2.1) has been found in the case study presented in Section 8.4.3. All the resources in the manufacturing system for piezoceramic actuators originate from the decision sources predicted by the Hypothesis 1. For example:

- The existence of MC1.3.3.2: Optical Stereo Microscope XYZ798 is motivated by the physical characteristics of the stator and its components, i.e. the product component size.
- The existence of MC1.3.1: FIFO-stock XYZ456 as well as transportation means for transferring the PCBs and the stator elements to the assembly station is motivated by the decision to embody MO1.1: Micro-fabrication System and MO1.3: Micro-assembly System into two different machines, i.e. two spatially separated manufacturing components.
- The existence of 12 instances of MC1.3: Micro-assembly System XYZ231 – XYZ2312 (cf. Section 8.4.6.2) is motivated by the manufacturing volume demand from the market and senior management's decision to deliver, i.e. business constraints, combined with the micro-assembly cycle time primarily based on the physical characteristics of the product.

The conclusion from this case study is that the Hypothesis 1 is corroborated.

8.4.7.2 Hypothesis 2

The empirical consequences of the Hypothesis 2 (cf. Section 8.4.2.2) have been assessed in the case study. The following has been found:

<u>Hypothesis 2.1:</u> The structure of piezoceramic actuator determines the structure of manufacturing processes executed by its manufacturing system. For example: PC1.1: Stator Element and PC1.2: Printed Circuit Board must both be manufactured in MP1.1 and MP1.2, respectively, before PC1: Stator ABC123 can be assembled in MP1.3.

<u>Hypothesis 2.2:</u> In the available information sources it was difficult to

find direct evidence on alternative process sequences and their impact on product design. However, it is possible to suppose that e.g. re-sequencing of the assembly process from serial into parallel can lead to significant time-cuts in the order-to-delivery process. This in its turn may require certain product design changes. For instance, a sub-assembly consisted of PC2, PC3, and PC4 (cf. Figure 109) could be introduced. Normally, the stator (PC1) is first assembled and then is together with PC2, PC3, PC4, and PC5 assembled into an actuator. The sub-assembly PC2, PC3, and PC4 could be assembled in parallel with PC1. In order to be able to carry out the final assembly operation the new sub-assembly must be stable, i.e. the constituent components must be prevented from moving in relation to each others during the final assembly. These requirements may lead to the introduction of product design changes. Furthermore, when having these two parallel sub-assemblies that easily can be joined into a final product, the existence of the base-plate (PC5) can be questioned. Maybe there is the possibility to integrate the base-plate and the PCB (PC2.2) so that the assembly process can be simplified. In that case the final assembly could be executed by only snapping the stator on the sub-assembly consisting of a homogenous package of rotor, ball-bearing and housing.

Hypothesis 2.3: Manufacturing process sequence for (based on) the piezoceramic actuator determines the set of capabilities that the corresponding manufacturing system must have. For example: A specific MP1.3.1: Stator Element Storage requires the generic capability MF1.3.1: Store Prismatic Micro-elements.

Hypothesis 2.4: The actuator component PC1: Stator ABC123 requires through its structure (i.e. several prismatic parts and a PCB) and the size of that structure's constituent parts (a couple of mm^3), usage of the manufacturing method Micro-assembly represented by the organ MO1.3: Micro-assembly system.

Hypothesis 2.5: The manufacturing method micro-assembly represented by the manufacturing organ MO1.3: Micro-assembly system has the capability to assemble small (a couple of mm^3) product components with the accuracy of approximately 10 µm. Although the size of stator elements lies within the manageable area for micro-assembly technology, there is the reason to reconsider the requirements on positioning accuracy of few µm (i.e. to consider product design changes), if the proposed assembly method is to be used successfully.

Hypothesis 2.6: The requirements set by the actuator component PC1: Stator ABC123 on the manufacturing method micro-assembly can be regarded as requirements that lead to the selection of the micro-assembly machine MC1.3: Micro-assembly system XYZ231. For example, the size of stator elements (h = 1.5 mm, w = 1.05 mm, t = 0.9 mm) determine the size of the feeding manipulator components or the gripper size, the thickness of PZT-layers (t = 56 µm) and AgPd-layers (t = 3-4 µm) determine the required positioning accuracy to 1 µm.

Hypothesis 2.7: The micro-assembly machine MC1.3: Micro-assembly system XYZ231 has certain performance characteristics, which can meet the requirement on positioning accuracy 1 µm. The problems are long assembly operation times and low yield which lead to long time-to-delivery and high manufacturing costs (e.g. investment- and WIP-cost). If the positioning accuracy requirement is much lower, e.g. 50 µm, the assembly operation could be performed much faster and with a significantly improved yield. The positioning accuracy requirement can be reduced to 50 µm by a redesign of stator components, where PZT- and AgPd-layers would be ordered in a horizontal rather than vertical manner.

Hypothesis 2.8: Since the objective of the actuator development project has been to create a miniature piezoceramic actuator it has been evident that already when organs PO2.1: Piezoceramic multimorphs and PO2.2: Si-substrate with an electrode pattern were determined, there has been introduced a need for an assembly process that has to be realized by using the micro-assembly method. Piezoceramic multimorphs and Si-substrate must obviously be manufactured in separate processes and due to their usual ways of embodiment and due to the fact that there are at least two separate material areas involved it is possible to assume that there will exist separate miniature components that must be joined together. Some implications on selection of testing equipment could not be identified due to the delimitations in the available sources of evidence.

The conclusion from this case study is that the Hypothesis 2 is neither corroborated nor falsified in its entirety. Hypotheses 2.1-2.7 are to be regarded as corroborated. Hypothesis 2.8 is not properly tested and therefore is neither to be regarded as corroborated nor falsified. However, its definition has to be to be reconsidered since the findings of the case study imply that the current definition is too narrow and of low generality. The generality and thus the scientific value of the hypothesis as well as its falsifiability could be improved if Hypothesis 2.8 is rephrased as following:

Every electromechanical product organ directly impact, and is impacted by, the structures of manufacturing processes, -functions, -organs, and -components regardless of whether corresponding product component structure has been determined or not.

There is the task for future research to attempt to falsify and/or further elaborate the proposed hypothesis.

8.4.7.3 Hypothesis 3

The empirical consequences of the Hypothesis 3 (cf. Section 8.4.2.3) have been assessed in the case study. The following has been found:

Hypothesis 3.1: Quantitative FRs that characterize the required actuator functions were identified. An example is PF2.1: Bend the stator element, characterized by FR2.1a: extension e [μm] and FR2.1b: Deflection w [μm].

Hypothesis 3.2: Quantitative DPs that characterize the selected actuator organs were identified. An example is PO2.1: PZT-multimorphs, characterized by DP2.1a: element length L [mm] and DP2.1b: element thickness t [mm].

Hypothesis 3.2: Quantitative PVs that characterize the selected actuator manufacturing organs and components were identified. An example is MC1.2.2: Micro-assembly manipulator characterized by PV2.1: Angular deviation, α [mrad], between the vacuum tool's tip and the AgPd-pattern on the PCB.

As described in Section 8.4.6.3, the system robustness can be assessed (and later even managed and improved) by analyzing the relationship between quantitative parameters. The relationship is analyzed through creation of a design matrix and application of the independence axiom (cf. statement 5 in Section 8.1). However, even if it was applicable in analyzing the product, the independence analysis framework of Axiomatic Design (i.e. design matrix and axiom 1) was insufficient for analyzing the robustness of the relationship between the product and its assembly system. When analyzing this relationship, the natural way of doing it is to relate the product components to the discrete manufacturing processes embodied into machines, i.e. manufacturing components. In the case of assembly, one could argue that an assembled product component could be related to an assembly system that generates it. In that case, the continued system decomposition results in including discrete manufacturing system as a subsystem of the decomposed assembly system. Within both the industry and the academia it is agreed that the assembly system is composed of machines and tools for assembly and not of machines for creation of discrete parts, e.g. lathes.

So, either is the relationship between DPs and PVs not so straight forward as Axiomatic Design theory presents it in its matrices or every product that contain more then one physical component yields a coupled (i.e. non-robust) manufacturing system. A feasible approach could be to regard the DP-structure as a hierarchical decomposition and the PV-structure as a corresponding process sequence in which the different manufacturing resources produce the product.

Whatever is the case, the state of facts needs to be investigated. In other words, some additional research need to be conducted in order to present the robustness management theory for assembled products and their manufacturing systems (including both assembly and discrete manufacturing) in a comprehensive and homogeneous way.

Anyhow, even if the robustness of the proposed manufacturing system is not manageable using the design matrices and axiom 1, it is possible to relate every single PV to corresponding DPs and to understand how a changed PV-value impacts on corresponding DP-values and vice versa.

The conclusion that can be made is that sub-hypotheses 3.1-3.3 have been corroborated and Hypothesis 3 as a whole has been falsified. The falsification has occurred either due to insufficient decomposition of the main hypothesis, or due to the insufficient testing procedure or due to the falsity of the Auxiliary Hypothesis D.

There is the reason to question this falsification since the design matrices and the axiom 1 are not the only robustness management tools. A straightforward application of Robust Design (RD) approach within the proposed framework is intuitively more feasible than the Axiomatic Design approach. Anyhow, the test of Hypothesis 3 is partially based on the Auxiliary Hypothesis D, whose proposed insufficiency is enough reason to declare falsification of the tested hypothesis. However, there is no reason to not repeat the test of the Hypothesis 3, either with new auxiliary hypothesis (RD) or with new testing and/or inferring paths.

9 A CONCEPTUAL INFORMATION MODEL FOR MANUFACTURING SYSTEM DEVELOPMENT

9.1 The Manufacturing System Development Information Model

Based on research findings presented in Chapter 8, a conceptual manufacturing system development model can be presented. The primary purpose of this model is to present the idea of how qualitative and quantitative structural building blocks interrelate within product and manufacturing system representations according to the presented theory (cf. Chapter 8).

Although the purpose of the conceptual information model is to outline the information requirements set by the manufacturing system development theory, i.e. which information elements that represent the design objects must be manageable within the information system, there is no intention to present a directly implementable information model. The conceptual information model will be harmonized with the implementtable AP233-proposal and a subset of AP233 will be presented. Furthermore, an example of RDF-implementation of that AP233-subset will also be given.

9.1.1 The Information Model

In Figure 127, the conceptual information model is depicted. The entities are grouped into two sections, i.e. qualitative and quantitative entities.

9.1.1.1 The qualitative entities

Most of the qualitative entities, i.e. the entities that describe product and corresponding manufacturing system structures according to the extended Theory of Domains (cf. Section 8.2.2), are specializations of the abstract entity *structural_element*. These specializations represent the building blocks for the domain system models representing a product and corresponding manufacturing system, respectively, i.e. processes, functions, organs and components. An instance representing a *struc-*

tural_element can be the instance of either of its specializations.

Every *structural_element* has a *name* and is *constrained_by* a *design_requirement_specification*. This requirements specification entity points out a compilation of various stakeholders' requirements on the design objects.

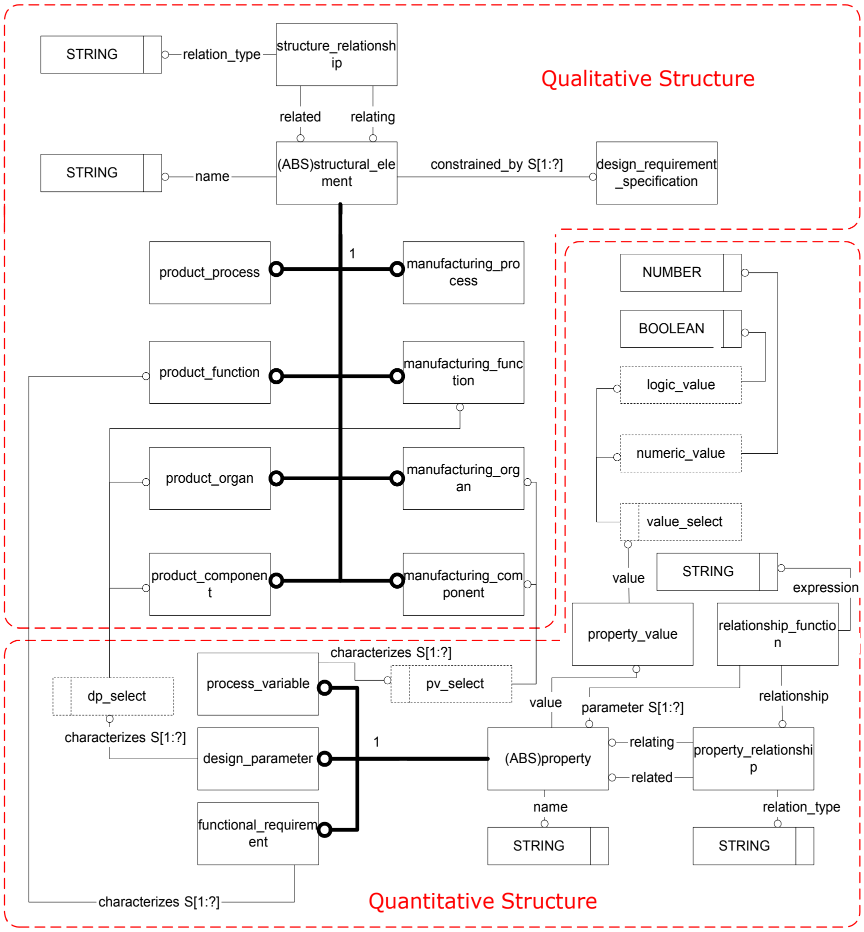

Figure 127: The conceptual information model of manufacturing system development theory

The structural elements are interrelated by the entity *structure_relationship* that has three different modes of the *relationship_type* attribute:

- *constraint*, i.e. the *relating* element constrains the *related* element.
- *decomposition*, i.e. the *relating* element is decomposed into the *related* element.
- *realization*, i.e. the *relating* element is realized by the *related* element.

9.1.1.2 The quantitative entities

Quantitative entities, adapted from the Axiomatic Design theory, characterize the qualitative entities. All qualitative entities are specializations of the abstract entity *property*. The specialization *functional_requirement* is through the attribute *characterizes* linked to the entity *product_function*, i.e. a qualitative structural representation of a product function is characterized by the quantitative entity functional requirement.

Second specialization of *property*, the *design_parameter* entity characterizes product organ and -component structures, represented by the entities *product_organ* and *product_component*. The *design_parameter* entity also characterizes the *manufacturing_function* entity since, according to the theory presented in Section 8.2.3, a product's design parameters act as a subset of functional requirements on the corresponding manufacturing system.

Third specialization of *property*, the *process_variable* entity characterizes manufacturing organ and -component structures, represented by the entities *manufacturing_organ* and *manufacturing_component*. Process variables may, in this context, be regarded as design parameters for manufacturing system as the design object, where functional requirements are set by the corresponding product's design parameters.

Every *property* has a *name* and is related to other properties by the entity *property_relationship* that has two different modes of the *relationship_type* attribute:

- *decomposition*, i.e. the *relating* element is decomposed into the *related* element.
- *realization*, i.e. the *relating* element is realized by the *related* element.

The relationship may be defined by a formal definition represented by the entity *relationship_function*. The *relationship_function* entity is expressed by a text string containing for example a mathematical formula that explains how the attributed properties relate to each others.

Every *property* has a *value* represented by the *property_value* entity. This value can be either numerical or logical, i.e. true/false.

9.1.2 Instantiation of the Information Model

In this section, the conceptual information model that represents the manufacturing system development theory presented in Section 8.2 will be instantiated. The model instance will be based on the theory validation case presented in Section 8.4. Figure 128 shows the instantiation of the conceptual information model for a subset of the piezoceramic actuator representation and its corresponding manufacturing system.

The product-section in Figure 128 contains instances that describe a part of the stator decomposition and two of its quantitative properties, namely the functional requirement "deflection" (FR2.1b) and the corresponding design parameter "element thickness" (DP2.1b). The relationship between these two quantitative properties is described by a *relationship_function*, which contains a formula based on experiments conducted by Bexell (1998). The *structure_relationship* instances that represent the realization relationship are ordered so that the direction of the realization goes from left to right (*relating* -> *related*). The direction of the decomposition relationship is top-down.

The manufacturing system-section contains instances that describe a part of the micro-assembly system decomposition and two of its quantitative properties, namely the design parameter "element thickness" (who act as a functional requirement on the manufacturing system) and the process variable "angular deviation" (PV2.1). The *structure_relationship* instances that represent the realization relationship are ordered so that the direction of the realization goes from right to left (*related* <- *relating*).

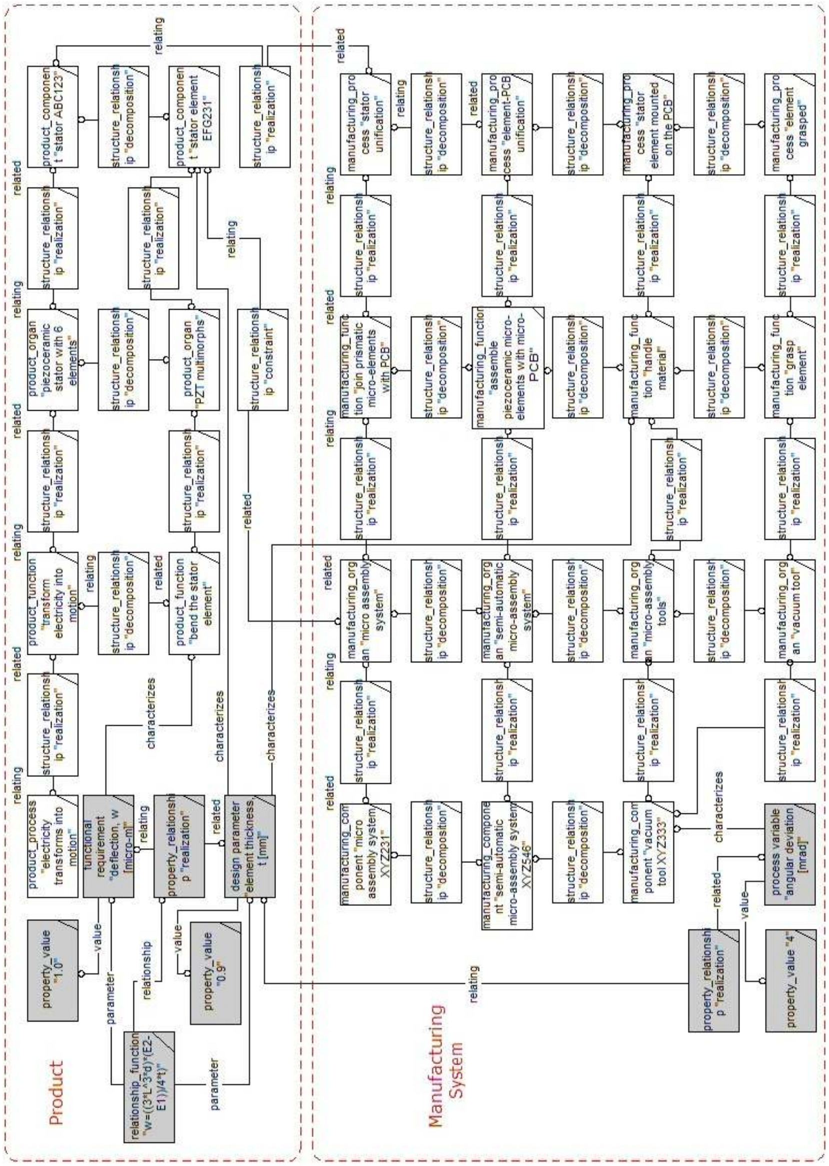

Figure 128: A conceptual information model instance for the piezoceramic actuator and its manufacturing system

The direction of the decomposition relationship is top-down. The constraint relationship is exemplified by the relation between the product component “stator element EFG231” and the manufacturing organ “micro-assembly system”. The size of the stator element, i.e. design parameter “element thickness”, implies that the manufacturing method micro-assembly must be applied. Here, Hypothesis 2.4, which describes the relationship between the product component structure and manufacturing organ structure, is utilized.

9.2 Harmonization with STEP AP233

9.2.1 The AP233-subset

Now, when a conceptual information model of the presented manufacturing system development theory is created, a harmonization attempt with STEP AP233 may be conducted. Figure 129 shows a subset of AP233 PAS 20542 capturing the information requirements by the manufacturing system development theory.

The AP233-subset is, in spite of the corrections to the represented theory, basically the same one as presented in the Case Study 5 (cf. Section 7.5). The only difference is the link to the quantitative parameters characterizing the qualitative structures. The entity *property_assignment* is now included. This entity is through the attribute *assigned_to* linked with *general_functionality_instance* that represents the product- and manufacturing function structures as well as with *general_physical_definition* that represents product- and manufacturing organ and -component structures.

Figure 130 shows a subset of AP233 that fulfills the requirements on representation of quantitative properties. The subset is through the entity *property_assignment* linked with *general_functionality_instance* and *general_physical_definition*.

STEP AP233 has, principally, the mechanisms necessary to represent the content of the conceptual information model, and thereby conform to the requirements set by the presented manufacturing system development theory. However, even at a conceptual level, some changes have to be proposed in order to be able to achieve a harmonization.

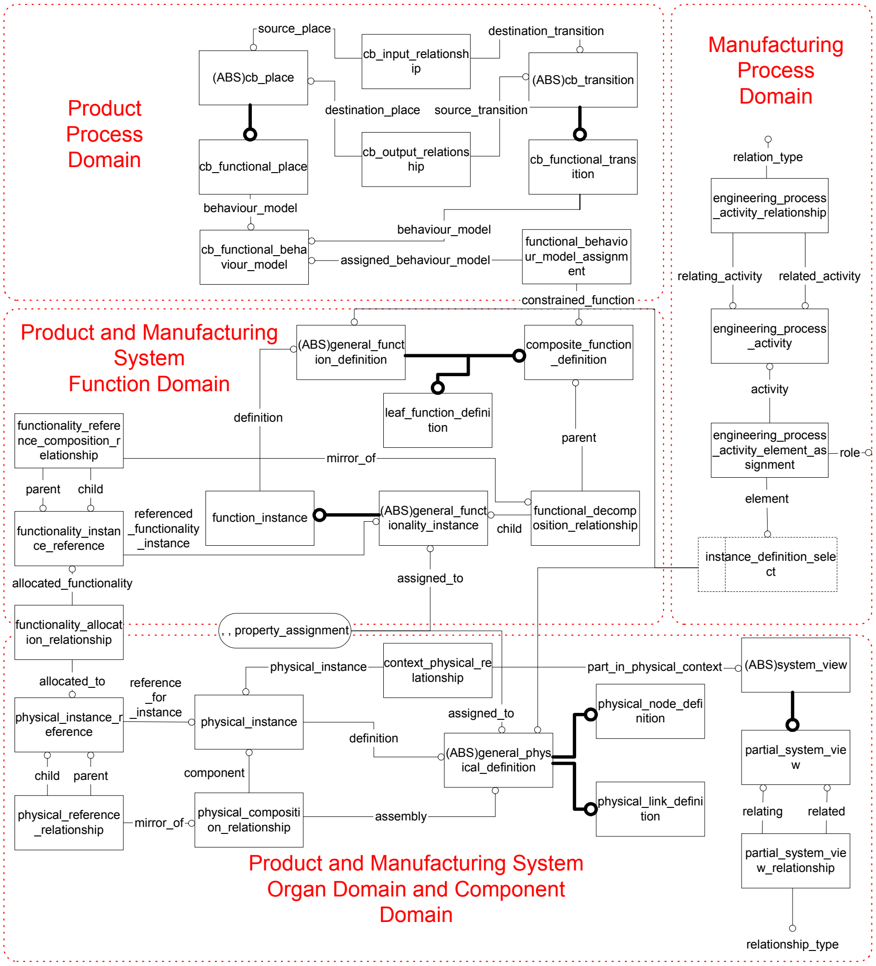

Figure 129: A subset of AP233 PAS 20542 that covers the information requirements set by the conceptual information model in Figure 126

For example, the *partial_system_view_relationship* entity that links different partial system views, which represent organ- and component domains, must be allowed to have more modes of the *relationship_type* attribute. Today, within the AP233 PAS 20542, the only allowed modes are *detail* (in the conceptual model: *decomposition*) and *precedence* (in the conceptual model: *realization*). A *constraint* mode could be introduced in order to be able to capture various links between product and manufacturing system structures. The same remark is applicable on the entity *engineering_process_activity_relationship*.

Furthermore, due to the fact that this AP233-subset is extracted from a general standard information model and since manufacturing process representation mechanism is borrowed from the *Work Management UoF*, there is the reason to either formalize this AP233-subset as a integrated product and manufacturing system development schema or create a novel *Transformation Process UoF* based on the *Work Management UoF*.

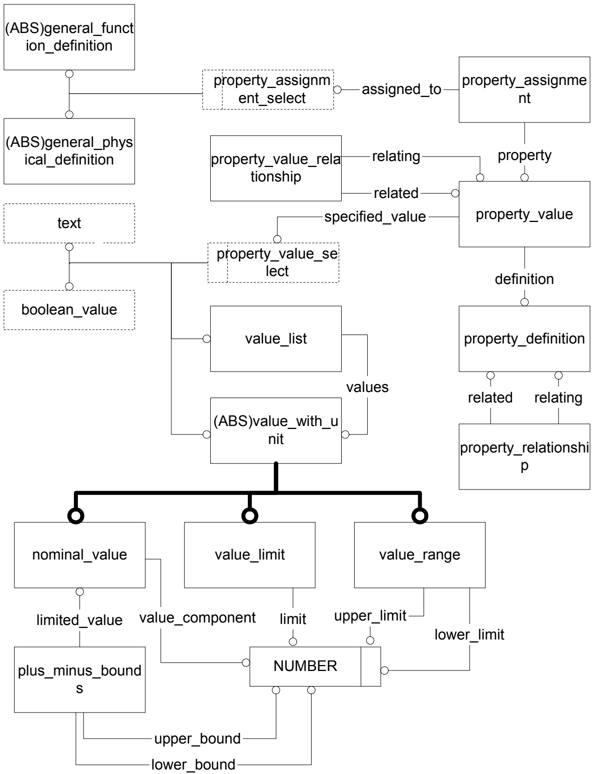

Figure 130: A subset of AP233 PAS 20542 that defines the relationship between qualitative and quantitative representations of products and corresponding manufacturing systems

9.2.2 Instantiation of the AP233 Information Model

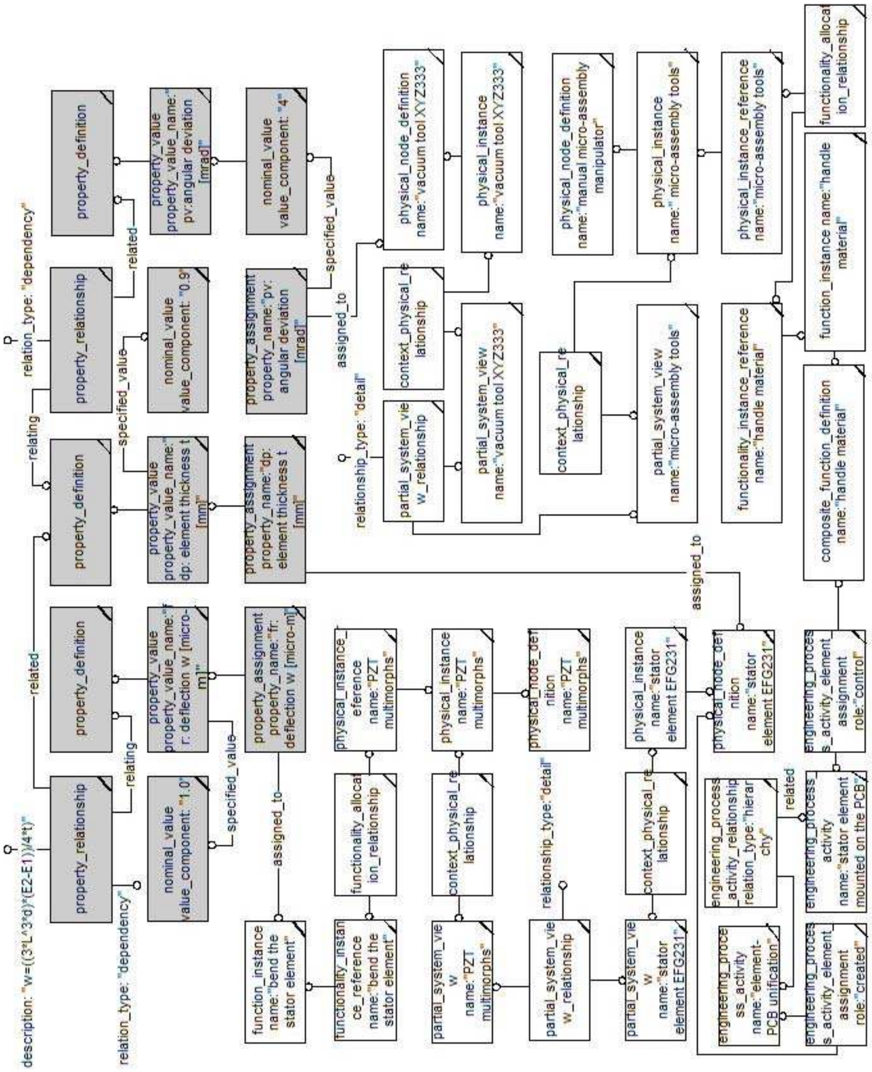

Figure 131: AP233-subset instance for the piezoceramic actuator and its manufacturing system (subset of the representation in Figure 127)

Figure 131 shows an instance of the AP233-subset representing a section of the piezoceramic actuator structure and its corresponding manufacturing system. The AP233-instance captures the relationship between the stator element (including the functional requirement and the design parameter that characterize it) and the micro-assembly system/tool (including the process variable that characterizes it) that mounts it on the PCB.

9.3 AP233-subset Implemented as a RDF-schema

Now, in order to be able to utilize the standardized information model based on the presented manufacturing theory in a web-service environment for extended enterprise, the information model could be translated into a RDF-schema. The RDF-schema can then be published on the Internet in order to be referred to by the web-services that conform to it as well as to be accessed by the web-services who want to interpret it, i.e. to "understand" the semantic context of the referring services.

Figure 132 shows an example of how a subset of the AP233-subset (cf. Figure 129 and Figure 130) could be represented as a RDF-schema.

It should be remarked that the AP233-attribute *physical_instance* must not be named *physical_instance* since there is an AP233-entity that carries the same name. It is not allowed to give the same name to two different entities in a RDF-schema. Since both classes, that map to EXPRESS-entities, and properties, that map to EXPRESS-attributes, are resources in RDF, it is easy to cause the naming conflict when interpreting between different schemas. Therefore, the attribute *physical_instance* is in the RDF-schema named *physical_instance_relationship*.

The RDF-schema in the figure 132 is a principal exhibit and since a RDF-schema requires more entities than a EXPESS-G-model to represent the same information, only a small fraction of the AP233-subset is represented.

Most of the entities in the RDF-schema have the prefix *mr3*, which is the signature of the modeling tool MR3. Since some of the entities are not defined by an external RDF-schema on the Internet, the tool automatically signs with the prefix *mr3*.

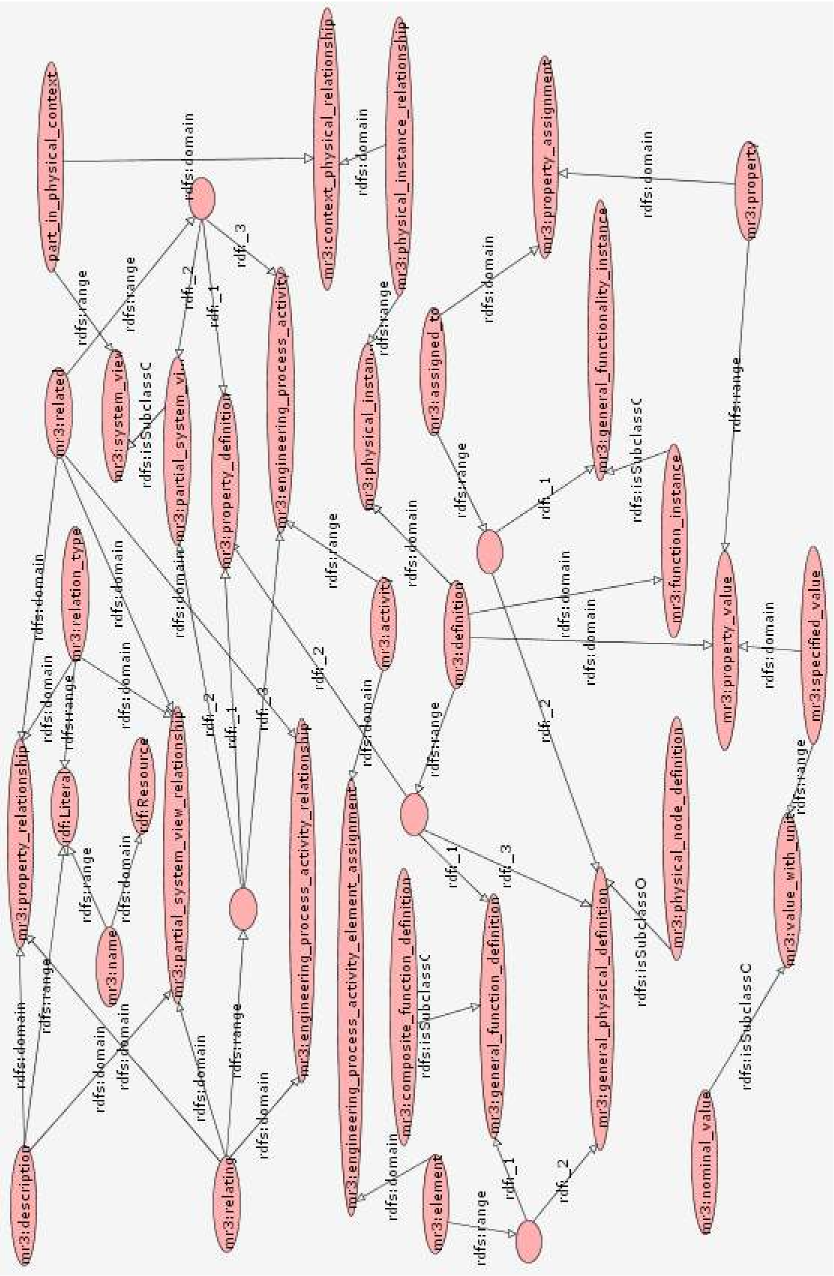

Figure 132: An example of a RDF-schema for the AP233-subset

All the entities in the RDF-schema are typed as *Class*. This typing has, due to the spatial constraints, not been showed in Figure 132. However, this typing is evident if the lexical representation of the RDF-schema is examined. The lexical representation of the RDF-schema can be viewed in the Appendix 3.

For example, the relationship between a product component and the manufacturing process that produces it can be described as following:

The product component is represented by the class *physical_instance*, which is defined by the class *general_physical_definition*. The relationship between the two classes is represented by the property *definition*, which besides to the *physical_instance* also can be attributed to *function_instance* and *property_value*. Its range is either *general_physical_definition, general_function_definition*, or *property_definition*. The range elements are constituents in a container that is typed as *Alt*, i.e. the container constituents are each others alternatives. This typing is also shown in the lexical representation of the RDF-schema. According to the RDF-schema rules, a property cannot have more than one class in its range; therefore the property points out at only one class-alternative at a time.

A manufacturing process is represented by the class *engineering_process_activity*, which is pointed out by the class *engineering_process_activity_element_assignment* through the property *activity*. The process assignment-class also points out the class *general_physical_definition* through the property *element*, which finally establishes a link between a product component, i.e. *physical_instance*, and a manufacturing process, i.e. *engineering_process_activity*. Alternatively, the process assignment-class can utilize the *element* property to point out the class *general_function_definition*, in order to be able to couple a manufacturing process with the corresponding manufacturing function.

Furthermore, the quantitative properties can be assigned to the qualitative objects that they describe through the *property_assignment* class. This class points out a quantitative *property_value* through the property *property* and links it with a qualitative object through the property *assigned_to* that points to either a *general_physical_definition* or a *general_functionality_instance* and its child *function_instance*.

10 FINAL DISCUSSION AND CONCLUSIONS

10.1 A Critical View on the Presented Research

In this thesis a manufacturing system development theory, consisted of a specification of system domain structures for products and manufacturing systems and the relationship between them, a modeling toolbox, and a development process, has been presented. This theory was then used for creation of a formal information model, its harmonization with an international information management standard, and an exemplification of an implementation of the harmonized information model using the Semantic Web technology – the foundation for the next generation internet.

Accordingly, the research presented in this thesis has helped in completing the knowledge framework composed of the already existing research results as following:

- The existing body of the engineering design theory has been completed with an elucidation of the relationship between various system domain structures that describe products and those that describe the corresponding manufacturing systems. Thereby the manufacturing system development in the context of concurrent engineering has been introduced in the classical engineering design theory.
- The existing body of modeling methods and tools has been utilized in order to create a manufacturing system modeling framework, i.e. it has been explained how existing modeling methods can be used to create the specified manufacturing system domain structures. Thereby, the traditional manufacturing system design methodology has been integrated with the engineering design theory.
- A development process that specifies a sequence of necessary development activities, in which the modeling methods and tools has been used to create the specified manufacturing system do-

main structures, has been defined. Besides putting the manufacturing system development theory in a business process context, such a definition of a development process has the potential to facilitate the practical implementation of the presented theory and the corresponding methodological framework.

- The presented description of the manufacturing system domain structures and their relationship with the structures of the products that they produce has been expressed in a formal information model, which was harmonized with an international information management standard for systems engineering, STEP AP233. This merger of the manufacturing system development theory with information management in general, and STEP AP233 in particular, is an important step towards creating a basis for successful engineering collaboration within extended manufacturing enterprises.

Naturally, the presented research results give also a reason for negative criticism. First of all, it can be discussed whether the presented manufacturing system development theory directs enough attention towards the concurrent engineering issues. The intentional delimitation of the research to primarily treat the manufacturing system development activities and their mutual relationship may have caused a shift of focus from concurrent engineering to manufacturing system development. The kernel of the theory still maintains the bi-directional coupling between products and the corresponding manufacturing systems, although on the physical manufacturability level, but the presented development process and its inherent activities (and thereby the methods) show only how the domain structures that describe the manufacturing system are created, while treating the product on the design review level. However, since the structure of the manufacturing system development process and its design objects has been underemphasized by the research community, the thesis should still be considered as a significant scientific contribution.

Another objection can be directed towards the practical applicability of the presented research results. The kernel of the theory, i.e. system domain structures and their relationships, as well as its expression in a formal information model and STEP AP233, has the potential to be practically utilized by information management system developers and implementers as well as by system architects and configuration managers. When it comes to classical manufacturing engineers, the professionals that actually develop the manufacturing systems, the learning threshold may simply be too high. The presented body of theory and the novel application of methods within the development process provide a systematic alternative to the usual ad-hocratic manufacturing system development practice. Since this ad-hocracy is very difficult to brake when already adapted and since because of the law of less resistance it is easy to adopt, a prerequisite for successful implementation of systematic manufacturing system development may be a generation shift. This, under the condition that the "new" engineers that replace the "old" ones have already adapted the systematic way of thinking. In other words, the implementation of systematic manufacturing system development starts at universities in the undergraduate engineering programs and not in a stressful and restricting industrial environment.

Furthermore, some negative criticism can also be directed towards the used research methodology. The main problem with the research methodology is the one of the ambiguity in hypotheses testing. When testing a hypothesis, a set of auxiliary hypotheses is often formulated in order to support the testing procedure. When a hypothesis turns out to be false it is not beyond all doubt that it is the hypothesis and not its auxiliary hypotheses that is untrue. An example with this methodological problem has been demonstrated in Section 8.4.7.3, where it was not completely clear whether the hypothesis or its auxiliary hypotheses did not proved their mettle.

10.2 Recommendations for Future Research

Having the presented research results in mind, which recommendations for future research could be given?

The main recommendation is to direct more attention towards the concurrent engineering issues. Decisions in product development affect different aspects of the manufacturing system, e.g. workshop and cell layout, machine and tooling design, control principles, internal and external logistics, competence requirements, product and variant flexibility, and volume flexibility. Of course, decisions during manufacturing system development affect various product characteristics. It is important to explore this *general conceptual dependency* and develop a method for proactive consideration of manufacturing system issues during product development and vice versa. The method should complement the presented manufacturing system development methodology framework and go beyond technical issues to provide the detailed understanding of how operations strategy decomposes into the requirements on the manufacturing system. Also the development process should be expanded to include even the product development activities in order to be able to strengthen the methodology's facilitation of concurrent engineering.

Furthermore, it is recognized that modular product and manufacturing system architectures are powerful means for enhancing product and variant flexibility as well as volume flexibility. *Architectural dependency* between products and their manufacturing systems could be managed through application of methods that integrate strategic modularization of products and corresponding manufacturing systems. It could be fruitful to extend Modular Function Deployment (MFD) to besides product modularization even support manufacturing system modularization. This could be done through discovery of strategic manufacturing system module drivers. The "new" MFD could be integrated with the presented manufacturing system development methodology framework.

In this setting, robust integrated product and manufacturing system design could be facilitated by finding an efficient and effective way of applying techniques for Design of Experiments and Robust Design. By applying these techniques within the manufacturing system development methodology framework, the *parametric dependency* between products and their manufacturing systems could be managed.

IT-solutions for development information management and tools for simulation and digital prototyping are regarded as important enablers of proactive decision making for development of robust systems. Moreover, in order to be able to generally manage the relationship between design objects (i.e. products and manufacturing systems), the coupling between requirements and design objects must be managed. Based on fundamental integrated development principles and corresponding methods, the management of this coupling, as well as provision of decision support tools, might be facilitated by modern off-the-shelf information systems. More efficient and effective ways of utilizing the existing software need to be considered. These *application guidelin*es *for PLM-systems* should be based on the manufacturing system development methodology framework.

Finally, information systems could, in combination with emerging web-service technologies like Semantic Web, be applied as important enablers of inter- and intra-organizational collaboration in development projects. *Application guidelines for distributed development* based on research findings coupled in the development methodology sphere as well as existing software systems and emerging web-service technologies should be developed.

10.3 Conclusions

The research results presented in this thesis can be concluded by providing the simplified answers to the stated research questions:

1. Which are the main characteristics of the relationship between a product and its manufacturing system in the context of manufacturing system development based on concurrent engineering philosophy?

- The main characteristics of the relationship between a product and its manufacturing system can be explained in qualitative and quantitative terms. The qualitative relationship is the relationship between the domain structures that describe a product and the domain structures that describe its manufacturing system. This relationship is specified in a number of universal statements. The quantitative relationship is the relationship between quantitative parameters that characterize the required functions, the selected product solution, and the selected manufacturing solution and dependency between them.

2. How can the development tasks, where various methods and tools are utilized for gradual creation of detailed manufacturing system structure models, be coordinated during the manufacturing system development process?

- The manufacturing system development tasks can be coordinated by using a stage-gate process model, where the different activities are executed by using various manufacturing system development methods to gradually populate the domain structures that define the developed manufacturing system.

3. How can the methodological framework for manufacturing system development be utilized in creation of systems for development information management in extended enterprises?

- The methodological framework for manufacturing system development can be regarded as a set of information requirements covered by a formal information model that can be used as a guideline in development, implementation, and/or configuration of information management systems. This information model can be harmonized with an international information management standard for systems engineering in order to be able to facilitate the implementation of geographically and organizationally dispersed extended manufacturing enterprises.

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Appendix 1:
The Existing Hard Core of Universal Statements

This appendix contains a set of 42 statements from the Axiomatic Design Theory as well as the two WDK-theories, the Theory of Technical Systems and the Theory of Domains. These statements are regarded as universal statements comprising the hard core of an existing theoretical system. This existing theoretical system is extended with the research results presented in this thesis.

Axiomatic Design

Some of the most important universal statements from Suh (1990) and Suh (2001) are:

1. Functional Requirements (FRs) are a minimum set of independent requirements that completely characterize the functional needs of the design solution in the functional domain.
2. Design Parameters (DPs) are the elements of the design solution in the physical domain that are chosen to satisfy the specified FRs.
3. Process Variables (PVs) are the elements in the process domain that characterize the process that satisfies the specified DPs.
4. Constraints (Cs) are bounds on acceptable solutions.
5. The Independence Axiom:
    - An optimal design always maintains the independence of FRs.
    - In an acceptable design, the DPs and the FRs are related in such a way that specific DP can be adjusted to satisfy its corresponding FR without affecting other functional requirements.
6. The Information Axiom: The best design is a functionally uncoupled design that has the minimum information content.
7. The Independence and Tolerance Theorem: A design is an uncoupled design when the designer-specified tolerance is greater than

$$\sum_{\substack{j \neq i \\ j=1}}^{n} (\partial FR_i/\partial DP_j)\ \Delta DP_j \qquad (1)$$

so that the nondiagonal elements of the design matrix can be neglected from design consideration.

8. The Design for Manufacturability Theorem: For a product to be manufacturable, the design matrix for the product, [A] (which relates the FR vector for the product to the DP vector for the product) times the design matrix for the manufacturing process[7], [B] (which relates the DP vector to the PV vector of the manufacturing process) must yield either a diagonal or triangular matrix. Consequently, when any one of these design matrices, that is, either [A] or [B], represents a coupled design, the product cannot be manufactured.
9. The Design-Manufacturing Interface Theorem: When the manufacturing system compromises the independence of the FR of the product, either the design of the product must be modified or a new manufacturing process must be designed and/or used to maintain the independence of the FRs of the product.

WDK: Theory of Technical Systems

Some of the most important universal statements from Hubka and Eder (1988) are:

10. The changes of state are termed transformations, and the oject that is being transformed is termed operand.
11. The transformations and partial transformations are realized by certain effects being exerted on the operand.
12. The effects are delivered by various operator systems – humans, technical systems, information systems, management systems, and the active environment.
13. The transformation system is defined as the set of all elements[8]

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[7] In this thesis, due to the modified terminology, the design matrix [B] and PVs do not characterize the manufacturing process, but the manufacturing system.

[8] Elements are constituents of various operator systems as specified in 12.

that participate in the transformation.

14. The process structure: what transformation processes take place *within* the TS; structure elements are the TS-internal processes;
15. The function structure: what internal capabilities does the TS have (it only uses these capabilities when it it actually operating); structure elements are the functions;
16. The organ structure: what active locations implement the capabilities; structure elements are the organisms and/or organs as function carriers;
17. The component structure (also morphological or anatomical structure): what physical (material) parts implement the organs; structure elements are the assembly groups, components (constructional elements).
18. A technical process (TP) is a special form of a transformation process in which technical systems are used by humans as artificial tools.
19. The structure of a TP consists of a set of partial processes or operations, and a set of intermediate states of the operand.
20. Each transformation process (the work process that transformes the operand) requires for its performance an additional set of processes: auxiliary, regulating and controlling, material and energy converting (propelling), and connecting and supporting processes. The need for these processes is evoked by the main working process. The representation of a TP includes (by convention and agreement) all these evoked processes.
21. The task (aim, purpose) of technical systems consists of exerting particular effects on the operands in the technical process. Consequently, the TS must have the ability to exert these particular effects.
22. The effect is achieved as the output of an action process (through an action chain) internal to the TS, in which the input measures are converted into the effects (output measures) of that TS. The

action process is a direct consequence of the structure of the TS, the term "mode of action" of the technical system is used to describe this relationship. The action process takes place after it has been initiated at the desired moment.

23. The action process (and the mode of action) is characterized by the TS-internal conversion of inputs of material, energy and information. These internal conversions are termed (technical) functions, and are linked by their relationships in the function structure of the TS.
24. The (technical) function describes the capability of the TS to transform an input quantity into an output quantity of different measure and/or form by natural phenomena that are deliberately caused to take place.
25. The functions (and function structures) are realized by organs (and organ structures) using certain action principles. Organs are means employed to fulfill the aims of the functions. Each function (function structure) can be realized by several existing action principles.
26. The organs (and organ structures) are realized by constructional elements (and component structures). The component structure realizes also all types of properties. Each organ (and organ structure) can be realized by several available component structures.
27. Each function, each organ or constructional element may be resolved into a system of partial functions, partial organs or partial constructional elements, resulting from the hierarchical character of technical systems.

WDK: Theory of Domains

Some of the most important universal statements from Andreasen (1980) and Andreasen (1992) are:

28. A technical process is an ordered set of transformations of an operand in space and time.
29. From the transformational point of view, processes may be regarded as systems (process systems), i.e.:

- Elements: Sub-processes (operations)
- Relations: Operands
- Structure: Process structure
- Function: Total transformation

30. The resulting transformations in a process system are determined by the system's process structure.
31. A function is a machine's ability to create an appropriate effect.
32. From the functional point of view, machines may be regarded as systems (function systems), i.e.:
    - Elements: Functions
    - Relations: Logical, causal
    - Structure: Function structure
    - Function: Effect
33. The resulting effects in a function system are determined by the system's function structure.
34. An organ is a concrete set of means, consisted of material areas, which by their properties and relations alter specific effects, i.e. functions.
35. From the organic point of view, machines may be regarded as systems (organ systems), i.e.:
    - Elements: Organs
    - Relations: Couplings, contrivances
    - Structure: Organ structure
    - Function: Effects
36. The resulting effects in a machine system are determined by the system's organ structure.
37. A machine component is an elementary consistuent in any machine, made in one material without assembly operations.

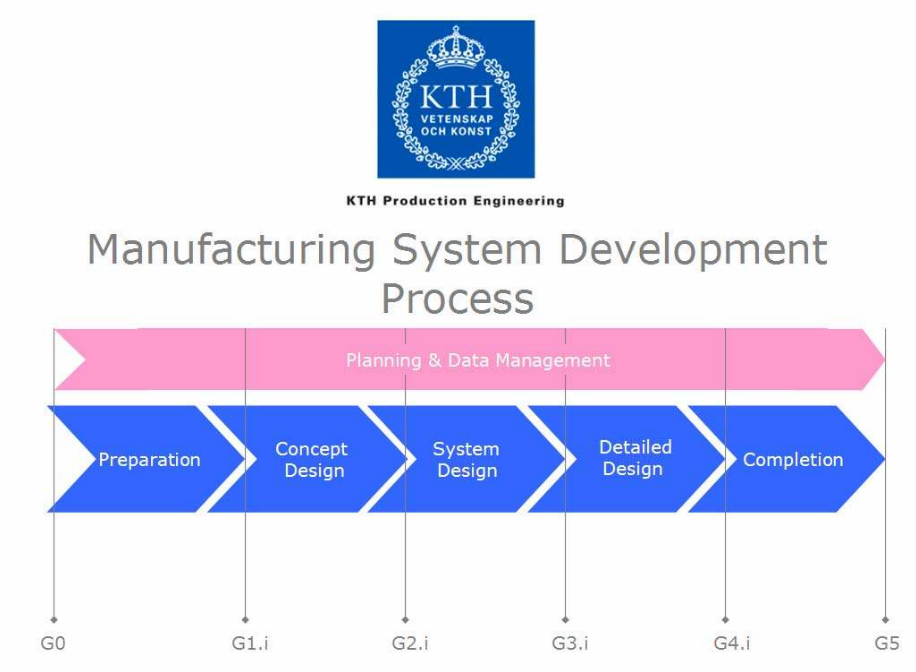
38. From the constructional point of view, machines may be regarded as systems (constructional systems), i.e.:
    - Elements: Machine components
    - Relations: Couplings, contrivances (e.g. assemblies)
    - Structure: Constructional structure
    - Function: Effects
39. The resulting effects in a machine system are determined by the system's constructional structure.
40. The working process and the effect-realizing processes in a machine are parts of a causal total system.
41. In a hierarchy of effects (functions), which contribute to the realization of working effects in a machine, there is the rule of causal relationships, determined by the organs (means), which realize the effects.
42. Relationships in the functional, the organic, and the constructional structure of a machine are determined by a causality chain mean/technology/effect/mode_of_effect/mean, where the term *mean* stands for a process, an organ, or a mode of construction.

Appendix 2:
Manufacturing System Development Process

In this appendix, the detailed description of the manufacturing system development process is presented. The description contains also a selection of document templates that are used to document specific activities within the manufacturing system development process.

Besides the material presented in this appendix, the internet application of the process contains links to the online tools for DFMA and PDM as well as links to the manufacturing resource databases, manufacturability guidelines databases, method manuals for IDEFØ, IDEF3, and DES, as well as a number standard project management document templates, e.g. assignment specification, project specification, progress report, risk analysis, milestone review. The internet application can be accessed from the KTH Production Engineering website www.iip.kth.se/ipm.

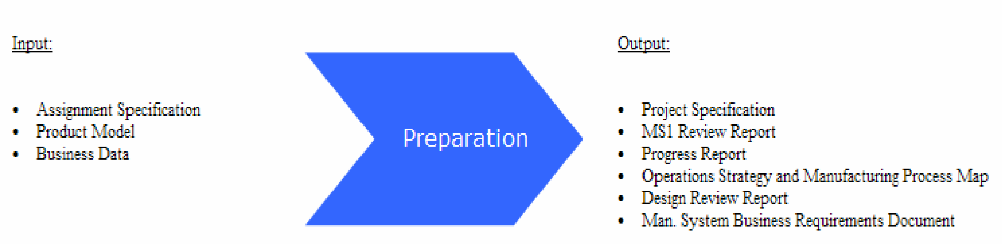
The Overall Process



KTH Production Engineering

Manufacturing System Development Process

Sub-process 1: Preparation



Input:

- Assignment Specification
- Product Model
- Business Data

Output:

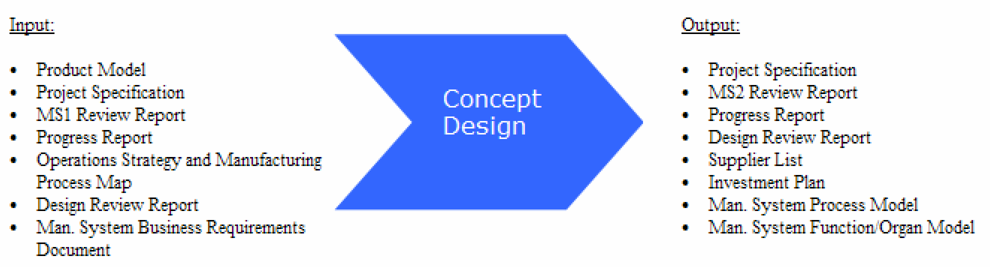
- Project Specification
- MS1 Review Report
- Progress Report
- Operations Strategy and Manufacturing Process Map
- Design Review Report
- Man. System Business Requirements Document

Tasks:

- Map the enterprise's operations strategy and corresponding business processes. Focus on detailed mapping of enterprise's manufacturing processes (i.e. existing process-, function- and resource structure).
- Perform functional analysis of the product that is going to be introduced (PP-PF-PO-PC mapping)
- Perform preliminary manufacturability analysis and create a preliminary design review report (append the functional analysis result). If needed, utilize the DFA2-tool and DFM-guidelines.
- Discuss whether to make or buy product components and create a preliminary supplier list.
- Based on the product plan create a manufacturing system increment plan. This will affect the project scope and the total number of stages and gates. Naturally, this impacts on e.g. the number of engineering hours in the project, project execution time, investment timing,…
- Create a business requirement document for the manufacturing system (append the m/b-decision and the increment plan). Based on volume-variety relationship and enterprise's long-term opera-

tions strategy decide on manufacturing system's performance objectives and specify the manufacturing process type.
- Develop Project Specification
- Perform Risk Analysis
- Carry out MS1-meeting
- Write a Progress Report that is to be presented on the G1-meeting

Sub-process 2: Concept Design



Input:

- Product Model
- Project Specification
- MS1 Review Report
- Progress Report
- Operations Strategy and Manufacturing Process Map
- Design Review Report
- Man. System Business Requirements Document

Output:

- Project Specification
- MS2 Review Report
- Progress Report
- Design Review Report
- Supplier List
- Investment Plan
- Man. System Process Model
- Man. System Function/Organ Model

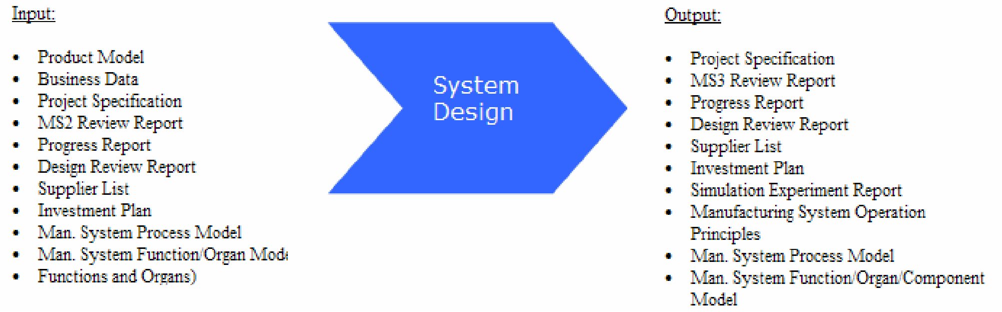
Tasks:

- Perform a manufacturability analysis and create a design review report. Utilize the DFA2-tool and DFM-guidelines. If needed, create a product shape prototype based on the proposed design changes using e.g. rapid prototyping techniques.
- Utilize the manufacturing system business requirements and technical requirements implied by the product (result of the functional analysis) to synthesize a set of alternative manufacturing system concepts:
  - Develop a process structure model for the manufacturing system, i.e. manufacturing processes (MPs) and their coupling to product components (PCs). Use IDEF3 and process flow charts as synthesis, analysis, and documentation tools. Create a Process Modelling Report.
  - Develop a manufacturing function (MF) and -organ (MO) structure model for the manufacturing system. When de-

veloping MO-structure, decide on the basic workshop layout type for the manufacturing system as well as on its basic control strategy. Use IDEF0 as synthesis, analysis, and documentation tool. Create a Function Modelling Report.

- Select a manufacturing system concept based on evaluation of concept's capability to fulfil specified tasks. Here, concept robustness can be assessed through examination of functional coupling. If needed, use Pugh's selection matrix.
- Update the supplier list.
- Create a preliminary investment plan.
- Update Project Specification
- Perform Risk Analysis
- Carry out MS2-meeting
- Write a Progress Report that is to be presented on the G2-meeting

Sub-process 3: System Design



Input:

- Product Model
- Business Data
- Project Specification
- MS2 Review Report
- Progress Report
- Design Review Report
- Supplier List
- Investment Plan
- Man. System Process Model
- Man. System Function/Organ Mod
- Functions and Organs)

Output:

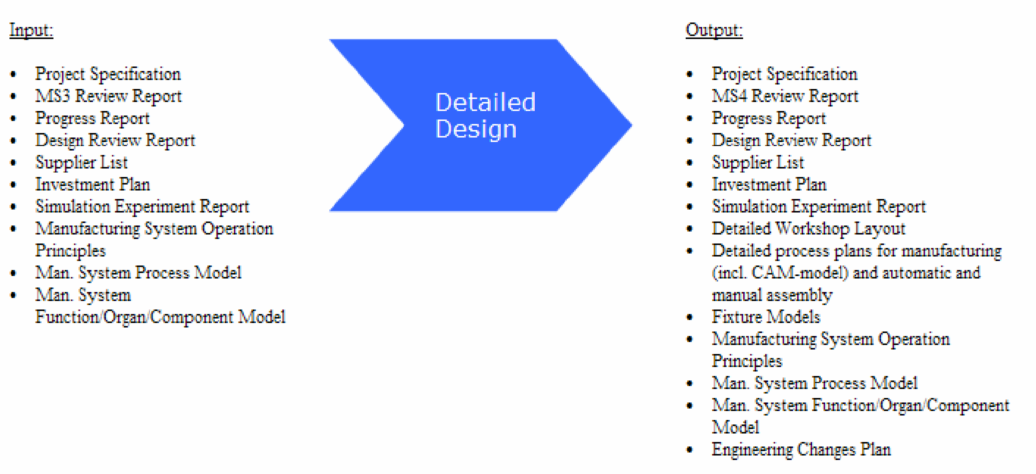
- Project Specification
- MS3 Review Report
- Progress Report
- Design Review Report
- Supplier List
- Investment Plan
- Simulation Experiment Report
- Manufacturing System Operation Principles
- Man. System Process Model
- Man. System Function/Organ/Component Model

Tasks:

- Receive product redesign feedback and evaluate the consequences. If needed, perform a manufacturability analysis and create a design review report. Utilize the DFA2-tool and DFM-guidelines. Freeze the product design on the system level, i.e. design on the detailed levels in the product's subsystems is still open.

- Based on the chosen manufacturing system concept, i.e. MO-structure, select the manufacturing components (MCs) that are going to implement the chosen concepts. Decompose the system (MP-MF-MO-MC) to the cell level. Utilize design and analysis tools, e.g. IDEF0 and IDEF3, to continue population of system structures.
- Create the detailed manufacturing workshop layout based on the decided layout type. Utilize layout design tools such as REL-matrix, trip-matrix, PFA-matrix, precedence diagram,…
- Select the system embodiment, i.e. manufacturing components and workshop layout, based on evaluation of system's capability to fulfil specified tasks. Here, system robustness can be assessed through examination of functional couplings. Check the consequences on MF-MO-relationship. If needed, use Pugh's selection matrix.
- Based on the manufacturing system business requirements and the proposed manufacturing system design create a simulation experiment plan, use a Discrete Event Simulation tool (Extend) to build the system model, and through experiments find and/or verify an optimal manufacturing system configuration. Generate a Simulation Experiment Report (append the manufacturing workshop layout).
- Based on the determined manufacturing system configuration create a document that in detail describes manufacturing system operation principles.
- Update the supplier list
- Update the investment plan.
- Update Project Specification
- Perform Risk Analysis
- Carry out MS3-meeting
- Write a Progress Report that is to be presented on the G3-meeting

Sub-process 4: Detailed Design



Input:

- Project Specification
- MS3 Review Report
- Progress Report
- Design Review Report
- Supplier List
- Investment Plan
- Simulation Experiment Report
- Manufacturing System Operation Principles
- Man. System Process Model
- Man. System Function/Organ/Component Model

Output:

- Project Specification
- MS4 Review Report
- Progress Report
- Design Review Report
- Supplier List
- Investment Plan
- Simulation Experiment Report
- Detailed Workshop Layout
- Detailed process plans for manufacturing (incl. CAM-model) and automatic and manual assembly
- Fixture Models
- Manufacturing System Operation Principles
- Man. System Process Model
- Man. System Function/Organ/Component Model
- Engineering Changes Plan

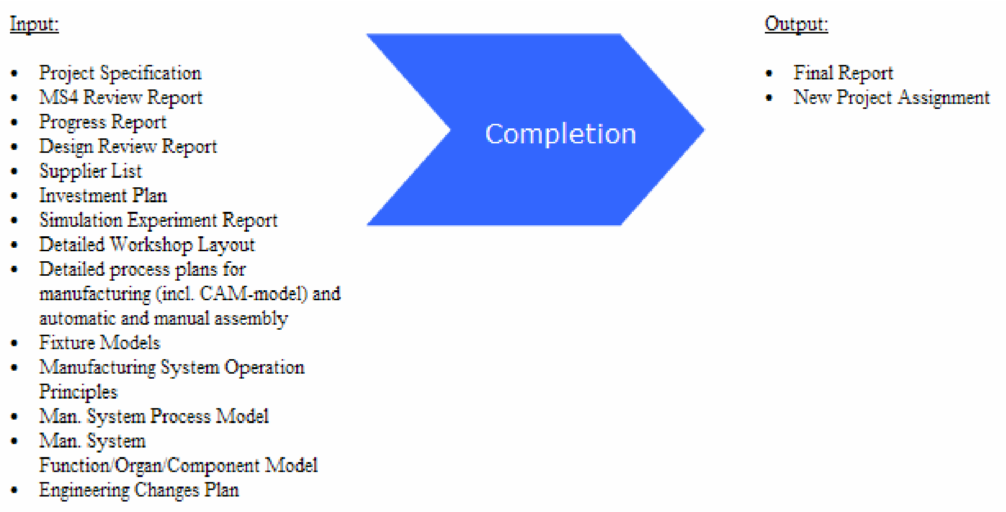
Tasks:

- If product design has changed (PCs has been modified and/or decomposed) or a physical prototype is available, perform manufacturability analysis (DFA2-tool and DFM-guidelines) and create a design review report.
- In system design phase the manufacturing system has been decomposed until the cell level. Now the cells should be decomposed into details (MP-MF-MO-MC). Utilize design and analysis tools, e.g. IDEF0 and IDEF3, to continue population of system structures. Alternative concepts should be generated and winners must be selected based on system capability to perform its tasks as well as on its robustness. This task is also supported by the activities below:

    - Develop detailed physical layout of discrete manufacturing and (automatic and manual) assembly stations.
    - Develop discrete manufacturing and (automatic and manual) assembly fixtures for parts and assemblies that are going to be manufactured in-house. Utilize 3-2-1 method and CAD-software (Solid Edge) as modelling tools.
    - Develop detailed process plans for all assemblies that are going to be assembled by in-house assembling resources. For creation of the process sequence for manual assembly, utilize MTM and operator process charts.
    - Develop detailed process plans for all parts that are going to be manufactured by in-house discrete manufacturing resources. Utilize CAD-models of product parts and use CAM-software (I-DEAS) to virtually verify the selected process plan and to generate the NC-code.
- Use detailed manufacturing subsystem models to assemble the total system model and evaluate its consistency and robustness.
- Use new timing information to update the Discrete Event Simulation model (Extend) of the manufacturing system. In needed, create a new simulation experiment plan and through experiments find and/or verify an optimal manufacturing system configuration.
- Based on the detailed manufacturing system configuration update the document that in detail describes manufacturing system operation principles. *Here, the work and maintenance instructions could also be created.*
- Update the supplier list.
- Update the investment plan.
- If possible, verify the manufacturing system design through manufacturing and evaluating physical product prototype and/or through conducting pre-series manufacturing. If needed, based on the verification, create an engineering changes plan for the manufacturing system.
- Update Project Specification
- Perform Risk Analysis
- Carry out MS4-meeting

- Write a Progress Report that is to be presented on the G4-meeting

Sub-process 5: Completion



Input:

- Project Specification
- MS4 Review Report
- Progress Report
- Design Review Report
- Supplier List
- Investment Plan
- Simulation Experiment Report
- Detailed Workshop Layout
- Detailed process plans for manufacturing (incl. CAM-model) and automatic and manual assembly
- Fixture Models
- Manufacturing System Operation Principles
- Man. System Process Model
- Man. System Function/Organ/Component Model
- Engineering Changes Plan

Output:

- Final Report
- New Project Assignment

Tasks:

- Act on the proposed engineering changes by either performing redesign, i.e. re-executing some of Concept Design, System Design, and/or Detailed Design activities, or by proposing a new project assignment.
- Create a final report, send it to the sponsor, adjust it according to the sponsor’s instructions and publish it.

Document Template 1: Operations Strategy

Operations Strategy for <OPERATION>

Enclosures

Process Map

Contents

Introduction

The Company

Briefly describe the company whose operation strategy you are going to map. What is the company's business idea? Is there any explicit business vision or policy stated?

Purpose

Describe the purpose of the operation strategy mapping.

Method

Briefly describe the used strategy mapping method, e.g. procedure, sources of evidence, etc. Describe also used process mapping methods.

Operation Strategy

The Market Perspective

The Customers

In this section, the structure of the customer space should be described. Which customers or types of customers are addressed by the company's products and services? How is the market segmented? What do customers require?

The Competitors

Here, the competitors and their strengths and weaknesses should be analysed. Which competitors are there and which market segments do they address? How do they compete?

Market Position

Based on the two previous sections formulate the market position for the company. What will make the company an attractive supplier to its customers? Why shouldn't they choose competitors' products instead? In other words, what is the differentiator, an order-winner?

Performance Objectives

Based on the three previous sections:

- <u>Define</u> operation's performance objectives, i.e. e.g. quality, flexibility, speed, dependability, cost.

- Which performance objectives are qualifiers? Which are order-winners?
- Discuss the trade-off relationship between them

The Resource Perspective

Operation's resources

Here, the existing tangible and untangible resources within the organization should be specified. Discuss if they are:

- Scarce
- Difficult to move
- Difficult to imitate
- Difficult to substitute

Operation's processes

List the operation's processes. Create the detailed maps of processes that will probably be affected by implementation of the results from the industrialization process. Append the process maps.

Operation's capabilities

Here, the distinctive capabilities, that shape the unique aspects of operations through which the company competes, should be stated. In other words, which set of core capabilities do operation possess in order to be able to successfully deploy its resources to execute its processes? These core capabilities give a sustainable competitive advantage to the company.

Decision Areas

Based on the three previous sections:

- Define operation's decision areas, i.e. e.g. capacity, supplier networks, process technology, development and organization.
- Describe the content of the defined decision areas

The Reconciliation: Operations Strategy Matrix

Express the operation strategy in terms of:

- The operation strategy matrix

- The description of the reasoning behind the matrix
- The required actions that company is/will/should undertake in order to be able to achieve and maintain the fit between the requirements and capabilities

Discussion

Discuss the implications of your results as well as pros and cons with the used mapping methods.

Conclusions

References

List documents referred to in this report.

Document Template 2: Design Review Report

Design Review Report for: <Product Name>

Enclosures

Contents

Introduction

Briefly introduce the product and describe the reason for the design review, e.g.:

- Functional analysis of the product in order to…
- Manufacturability assessment of a new product or new version…

Method

Briefly describe the used methodology, e.g. System Domain Mapping and/or DFMA.

Current Design

Functional Analysis

Here, the current product design should be decomposed into four interrelated structures: product process, -functions, -organs, and –components. The decomposition must be commented.

The structural decomposition will also lead to the establishment of design matrices and the assessment of functional dependence (i.e. axiom 1 in Axiomatic Design) between functional requirements and design parameters.

Manufacturability Assessment

Here, the results from the DFM and/or DFA analyses are to be presented. The method tables and/or printouts should be enclosed and clearly referred to. This section is therefore not reserved for pasting-in a set of tables but for commenting various product design features from the manufacturing and assembly point of view.

It is convenient to create subsections in which product components and/or assemblies are treated separately. In that case, a separate subsection discussing the overall product structure from the final assembly perspective is needed.

New Design

Proposal

In this section, a proposal for new product design should be presented. This, under the condition that the analyses of the current design have generated ideas about substantial product design changes. The proposal can be presented as a sketch, a CAD-model, and/or a FFF-model.

Functional Analysis

A new design or (even minor) changes to the current design imply the need for a new functional analysis in order to guarantee that the product will be able to perform the desired effects even after the redesign or a design change is implemented.

Manufacturability Assessment

Here, the manufacturability aspects of the new design should be discussed. A new DFM- and/or DFA-analysis can be performed or the aspects can be discussed within the context of the already performed current design analysis. This off-course depends on the nature and the extent of the proposed change.

Discussion

Discuss the implications of your results as well as pros and cons with the used modeling methodology.

Conclusions

References

List documents referred to in this report.

Document Template 3: Supplier List

Supplier List for: <Product Name>

Contents

Introduction

Briefly describe the product.

In-house Manufactured Components

List the components that will be manufactured within the company's factory. State the reason why these components must be manufactured in-house.

Bought Components

List the components that will be manufactured by the external suppliers. For every component following must be stated: (i) the external supplier name, (ii) the reason for outsourcing to the external supplier (iii) outsourcing type, i.e. development, manufacturing or both

Discussion

Discuss the implications of your results.

Conclusions

References

Document Template 4: Business Requirements

Business Requirements on the Manufacturing System for: <Product Name>

Enclosures

Contents

1 Introduction
2 Method
3 Business Requirements and Constraints
4 Discussion
5 Conclusions
6 References

Introduction

Briefly describe the company and the products that are going to be manufactured. Explain why the business requirements need to be explicitly stated.

Method

Explain how the business requirements are generated, e.g. operation strategy mapping activities.

Business Requirements and Constraints

Clearly define the business requirements, e.g.:

- Total capacity needed
- Capacity increments
- Capacity flexibility

- In-house manufacturing
- Throughput times
- Cost limits
- Cost structure of the existing manufacturing resources that must be used
- Product- and variant flexibility
- etc

Discussion

Discuss the implications of your results as well as pros and cons with the used methodology.

Conclusions

References

List documents referred to in this report.

Document Template 5: Process Modeling Report

Process Modeling Report for: <Project Name>

Enclosures

Contents

Introduction

Problem

Describe the problem that the process modelling is going to help you to solve.

Method

Briefly describe the used process modeling method.

Process Model

Preparation

Prepare your modeling activity by deciding on:

- Purpose with the model
- Modeling perspective
- Intended use of the model

Explain the procedure for information gathering.

Process and Object List

List major objects (operands), their states and major process operations. Every object and every process operation must be explicitly defined.

Diagrams

Present diagrams on all hierarchical levels.

Discussion

Discuss the implications of your results as well as pros and cons with the used modeling methodology.

Conclusions

References

List documents referred to in this report.

Document Template 5: Activity/Function Modeling Report

Activity/Function Modeling Report for: <Project Name>

Enclosures

Contents

Introduction

Problem

Describe the problem that the activity modeling is going to help you to solve.

Method

Briefly describe the used activity modeling method.

Activity Model

Preparation

Prepare your modeling activity by deciding on:

- Purpose with the model
- Modelling perspective
- Intended use of the model

Explain the procedure for information gathering.

Data and Activity List

List major data classes and major activities. Every data class and every activity must be explicitly defined. Use the ICOM-code to define all the components of the activity model.

Diagrams

Use ICOM and present diagrams on all hierarchical levels.

Discussion

Discuss the implications of your results as well as pros and cons with the used modelling methodology.

Conclusions

References

List documents referred to in this report.

Document Template 6: Concept Selection

Concept Selection Report for: <Project Name>

Enclosures

Contents

Introduction

Problem

Introduce the problem that the concept selection is going to help you to solve.

Method

Briefly describe the used concept selection method.

Concept Selection

Selection Criteria

Here, the concept selection criteria are defined. The criteria are based on the stakeholder requirements, i.e. functional requirements and constraints.

The relative weight of the concept selection criteria should be decided and clearly stated.

Alternative Concepts

In this section, a set of alternative concepts is presented. Every concept is unambiguously presented both textually and graphically.

Selection Matrix

Based on the previous two sections, a selection matrix is presented. When a reference concept is selected, the alternative concepts are compared with the reference concept based on the selection criteria.

Final Concept Ranking

Reiterations are executed until all the alternative concepts are ranked and a feasible concept is selected.

Discussion

Discuss the implications of your results as well as pros and cons with the used concept selection methodology.

Conclusions

References

List documents referred to in this report.

Document Template 7: Investment Plan

Investment Plan for: <Product Name>

Enclosures

Contents

Introduction

Briefly describe the company and the products that are going to be manufactured.

Describe why the investment plan is made.

Method

Briefly describe the investment calculation method, i.e. the financial model that is going to be used. Preferably, an investment calculation method that considers the interest effects should be selected.

Investment Plan

Investment Data

Here, the reason for making an investment should be presented. The investment data should include:

- Description of the manufacturing resource that is to be purchased
- The investment reason, e.g.:
    - new product (variant),
    - new manufacturing process,
    - replacement of an existing resource because of …,
    - multiplication of an existing resource because of …,
    - etc
- Capacity increments, i.e. if the whole investment is not made all at once but is distributed over the time

Profitability Requirements

Here, the company specific financial prerequisites and preferences should be stated. The most interesting prerequisites are the calculation interest and the required pay back time.

Payments

Outpayments

In this section, outpayments should be stated. Outpayments include:

- Detailed specification of the basic investment, e.g. the machine, tools, installation, education.
- Detailed specification of the running outpayments, i.e. operation costs.

Inpayments

In this section, inpayments should be stated. Inpayments include:

- Detailed specification of the running inpayments, i.e. operation revenues.

- Remaining value, i.e. the purchased machines second-hand value at the end of the calculation period (mandatory).

Result

Here, the investment calculation is carried out according to the selected calculation method and the recommendation is presented.

Discussion

Discuss the implications of your results as well as pros and cons with the used methodology.

Conclusions

References

List documents referred to in this report.

Document Template 8: Simulation Experiment Report

Simulation Experiment Report for: <Project Name>

Enclosures

Contents

1 Introduction
1.1 Problem
1.2 Method
2 Simulation Experiment
2.1 Modeling
2.2 Experiment Design
2.3 Results
3 Discussion
4 Conclusions
5 References

Introduction

Problem

Describe the problem that the simulation experiment is going to help you to solve.

Method

Briefly describe the used modelling and simulation method.

Simulation Experiment

Modeling

- Define the manufacturing process that is going to be analysed. The manufacturing process should be presented as a process flow chart.
- Define the manufacturing functions needed to execute the process. The manufacturing functions should be presented as a high-level IDEFØ-model.
- Use a DES-tool to build a simulation model of the defined system.

Experiment Design

- Identify input parameters and their levels.
- Present the experimentation plan, i.e. design matrix including factors and responses.

Results

- Present the results of simulation runs.
- Infer the conclusions, i.e. present the solution for the problem

Discussion

Discuss the implications of your results as well as pros and cons with the used modeling and simulation methodology.

Conclusions

References

List documents referred to in this report.

Appendix 3:
RDF-schema

In this appendix, the lexical description of the RDF-schema, representing the fraction of a STEP AP233-subset, is presented.

```
<?xml version="1.0"?>
<rdf:RDF xml:lang="en"
xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#" >

<rdfs:Class rdf:ID="general_function_definition"/>

<rdfs:Class rdf:ID="composite_function_definition">
<rdfs:subClassOf rdf:resource="#general_function_definition"/>
</rdfs:Class>

<rdfs:Class rdf:ID="general_functionality_instance"/>

<rdfs:Class rdf:ID="function_instance">
<rdfs:subClassOf rdf:resource="#general_functionality_instance"/>
</rdfs:Class>

<rdfs:Class rdf:ID="general_physical_definition"/>

<rdfs:Class rdf:ID="physical_node_definition">
<rdfs:subClassOf rdf:resource="#general_physical_definition"/>
</rdfs:Class>
```

```
<rdfs:Class rdf:ID="physical_instance"/>

<rdfs:Class rdf:ID="context_physical_relationship"/>

<rdfs:Class rdf:ID="system_view"/>

<rdfs:Class rdf:ID="partial_system_view">
<rdfs:subClassOf rdf:resource="#system_view"/>
</rdfs:Class>

<rdfs:Class rdf:ID="partial_system_view_relationship"/>

<rdfs:Class rdf:ID="engineering_process_activity"/>

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rdf:ID="engineering_process_activity_element_assignment"/>

<rdfs:Class rdf:ID="engineering_process_activity_relationship"/>

<rdfs:Class rdf:ID="property_assignment"/>

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```

```
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<rdfs:Class rdf:ID="property_definition"/>

<rdfs:Class rdf:ID="property_relationship"/>

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"http://www.w3.org/1999/02/22-rdf-syntax-ns#Literal"/>
<rdfs:domain rdf:resource=
"http://www.w3.org/1999/02/22-rdf-syntax-ns#Resource"/>
</rdf:Property>

<rdf:Property rdf:ID="definition">
<rdfs:range>
<rdf:Alt>
<rdf:li rdf:resource="#general_function_definition"/>
<rdf:li rdf:resource="#general_physical_definition"/>
<rdf:li rdf:resource="#property_definition"/>
</rdf:Alt>
</rdfs:range>
<rdfs:domain rdf:resource="#function_instance"/>
<rdfs:domain rdf:resource="#physical_instance"/>
```

```
<rdfs:domain rdf:resource="#property_value"/>
</rdf:Property>

<rdf:Property rdf:ID="assigned_to">
<rdfs:range>
<rdf:Alt>
<rdf:li rdf:resource="#general_functionality_instance"/>
<rdf:li rdf:resource="#general_physical_definition"/>
</rdf:Alt>
</rdfs:range>
<rdfs:domain rdf:resource="#property_assignment"/>
</rdf:Property>

<rdf:Property rdf:ID="property">
<rdfs:range rdf:resource="#property_value"/>
<rdfs:domain rdf:resource="#property_assignment"/>
</rdf:Property>

<rdf:Property rdf:ID="specified_value">
<rdfs:range rdf:resource="#value_with_unit"/>
<rdfs:domain rdf:resource="#property_value"/>
</rdf:Property>

<rdf:Property rdf:ID="related">
<rdfs:range>
```

```
<rdf:Alt>
<rdf:li rdf:resource="#property_definition"/>
<rdf:li rdf:resource="#partial_system_view"/>
<rdf:li rdf:resource="#engineering_process_activity"/>
</rdf:Alt>
</rdfs:range>
<rdfs:domain rdf:resource="#property_relationship"/>
<rdfs:domain rdf:resource="#partial_system_view_relationship"/>
<rdfs:domain
rdf:resource="#engineering_process_activity_relationship"/>
</rdf:Property>

<rdf:Property rdf:ID="relating">
<rdfs:range>
<rdf:Alt>
<rdf:li rdf:resource="#property_definition"/>
<rdf:li rdf:resource="#partial_system_view"/>
<rdf:li rdf:resource="#engineering_process_activity"/>
</rdf:Alt>
</rdfs:range>

<rdfs:domain rdf:resource="#property_relationship"/>
<rdfs:domain rdf:resource="#partial_system_view_relationship"/>
<rdfs:domain
rdf:resource="#engineering_process_activity_relationship"/>
```

```
</rdf:Property>

<rdf:Property rdf:ID="relation_type">
<rdfs:range rdf:resource=
"http://www.w3.org/1999/02/22-rdf-syntax-ns#Literal"/>
<rdfs:domain rdf:resource="#property_relationship"/>
<rdfs:domain rdf:resource="#partial_system_view_relationship"/>
</rdf:Property>

<rdf:Property rdf:ID="description">
<rdfs:range rdf:resource=
"http://www.w3.org/1999/02/22-rdf-syntax-ns#Literal"/>
<rdfs:domain rdf:resource="#property_relationship"/>
<rdfs:domain rdf:resource="#partial_system_view_relationship"/>
</rdf:Property>

<rdf:Property rdf:ID="physical_instance_relationship">
<rdfs:range rdf:resource="#physical_instance"/>
<rdfs:domain rdf:resource="#context_physical_relationship"/>
</rdf:Property>

<rdf:Property rdf:ID="part_in_physical_context">
<rdfs:range rdf:resource="#system_view"/>
<rdfs:domain rdf:resource="#context_physical_relationship"/>
</rdf:Property>
```

```
<rdf:Property rdf:ID="activity">
<rdfs:range rdf:resource="#engineering_process_activity"/>
<rdfs:domain
rdf:resource="#engineering_process_activity_element_assignment"/>
</rdf:Property>

<rdf:Property rdf:ID="element">
<rdfs:range>
<rdf:Alt>
<rdf:li rdf:resource="#general_function_definition"/>
<rdf:li rdf:resource="#general_physical_definition"/>
</rdf:Alt>
</rdfs:range>
<rdfs:domain
rdf:resource="#engineering_process_activity_element_assignment"/>
</rdf:Property>

</rdf:RDF>
```