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Information Modeling of Manufacturing Processes: Information Requirements for Process Planning in a Concurrent Engineering Environment

Johan Nielsen

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Abstract

The innovation process is an important process for our prime motor of welfare, manufacturing. During this process, the prerequisites for manufacturing are set. To set the best possible prerequisites consideration about products, manufacturing processes, and manufacturing resources must be made concurrently, which also means involving several different disciplines in a collaborative effort.

As a consequence of involving different disciplines, the communication of engineering information may be hindered. The reason is that different disciplines use different terminology for the same concept and sometimes have the same terminology for different concepts. This may result in difficulties understanding each other, which may, in turn, result in unnecessary loss of quality and productivity.

The main objective of this thesis is to identify information concepts (i.e. information requirements) for process planning in a concurrent engineering environment, and to formally define the corresponding terminology. The work is based on case studies at Volvo Car Corporation, involving management of weld spot and location system information, and at ABB Body-in-White, involving tender preparation information.

The results are presented in the thesis in terms of an information model, the Product-Process-Resource (PPR) information model, and two corroborated hypotheses. The PPR information model define the identified information requirements in the scope of the thesis whereas the hypotheses concern how, e.g., modularization can be used in information modeling.

The PPR information model provides the base for an information platform in a concurrent engineering environment. The PPR information model enable model based documentation and, thus, traceability of the evolution of the product, process, and manufacturing resource designs, and their interrelations.

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Chapter 1

Introduction

The purpose of this chapter is to give context and motivation to the thesis. In addition, the scope, objectives, and delimitation of the thesis will be presented.

1.1 Product Innovation

One of the principal means by which welfare is created is manufacturing (Bollinger et al., 1998; Sohlenius, 2000). Sohlenius (2000) mean that there are three reasons for manufacturing to be the *prime motor of welfare*, the need for products by the customers, the need for return on investments by the share holders, and the need to earn a living by the employees. That is, manufacturing fulfills the need of the customers by providing products, which, when sold with profit, fulfills the need of the share holders, and it fulfills the need of its employees by providing employment and income.

Although manufacturing is considered to be the prime motor of welfare by Bollinger et al. (1998) and Sohlenius (2000) it is only one of the activities in the product realization process, cf. Figure1.1. Another activity that can be identified is the *innovation* activity, the focus of this thesis.

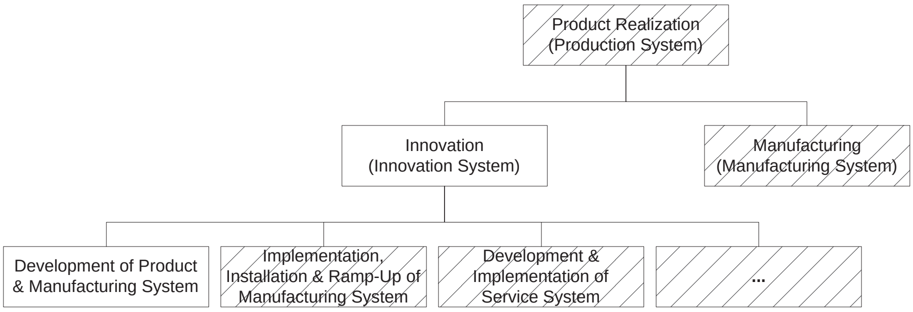

Figure 1.1. Relationship between the innovation process, the focus area of thesis, and the product realization process.

Innovation is here considered as, in similarity with Cooper (2001); Davenport (1993); Hubka and Eder (1988), and Sohlenius (2000), the transformation of ideas into new products ready for the market. As such it also includes, but not limited to, the development and implementation of a manufacturing system that can manufacture these products. Hence, innovation is the process where many of the prerequisites for manufacturing are set, cf. Figure 1.2 where innovation is represented by the product development, the development and implementation of manufacturing system, and the development and implementation of service system.

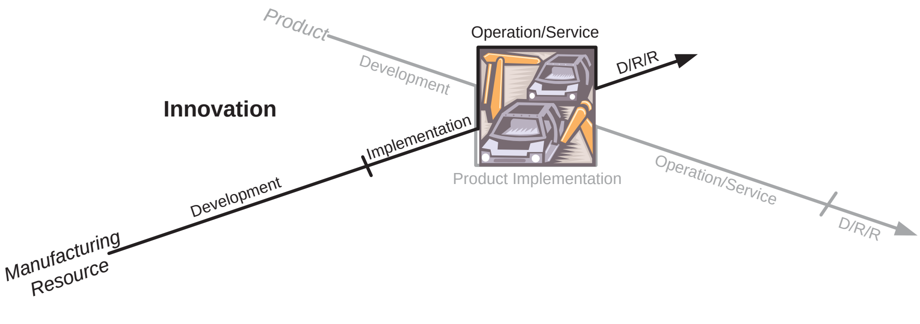

Figure 1.2. Prerequisites for manufacturing are set during the innovation process, the activities to the left.

These prerequisites include prerequisites for product quality and productivity. Product quality refers to the satisfaction of customers in terms of, e.g. features, functionality, and aesthetical perception of the product (Sohlenius, 2000; Taguchi et al., 1989), whereas productivity refers to the measuring of efficiency[1] in manufacturing (Sohlenius, 2000).

The two concepts, product quality and productivity, are closely related and highly interdependent. To manufacture high quality product a manufacturing system needs to be effective, i.e. it needs to manufacture products that are needed by customers. Another view is that a manufacturing system that cannot manufacture products with the wanted quality is not efficient.

The loss of quality, and thus of productivity, occur, according to Taguchi et al. (1989), in three different activities, the product design, the process design, and the production phases. These activities correspond to the innovation (product development and manufacturing system development), and the manufacturing activities in Figure 1.1. In addition, the implementation of the manufacturing system could be considered a source for poor quality, i.e. the manufacturing of the manufacturing system.

Naturally, these activities have different criteria for decision making, and there is a clear risk for conflicts between, e.g., the product development and the manufacturing system development activities. On the one hand, the product need to fulfill the needs of the customers and, on the other hand, these needs need to be fulfilled at a reasonable cost. Hence, innovation could be described as a struggle to find the best possible balance between fulfilling the needs of the customers and the manufacturing cost.

[1]Efficiency is here considered to be the quality of being efficient, which is acting effectively with a minimum of waste.

1.1.1 Concurrent Engineering

Traditionally, different needs like these have been considered separately in a sequential manner. This have resulted in redesigns of the product when it has been found out that, e.g., reasonable costs, and/or quality could not be maintained with that particular design of the product. Consequently, the rework have resulted in unnecessary long lead-times, sometimes poor quality, and unnecessary high cost.

However, lead-times and costs can be reduced, and quality can be increased by considering more than one aspect of a system[2] during its development (Krause et al., 1993; Liker et al., 1995; McGrath, 1996; Sohlenius, 1992). This is usually called concurrent, or simultaneous, engineering, and it implies an extensive communication of engineering information (Fagerström et al., 2002) between different disciplines.

As a consequence of involving different disciplines, the communication of engineering information may be hindered. The reason is that different disciplines use different terminology for the same concept and sometimes have the same terminology for different concepts. This may result in difficulties understanding each other, which may, in turn, result in unnecessary loss of quality and productivity.

1.1.2 Collaboration in the Extended Enterprise

Concurrent engineering is an important aspect of a company to stay or increase its competitiveness. Another important aspect to stay or increase the competitiveness of a company is its collaboration with other companies. This can be seen as a network of competences that are needed to provide products to the market, usually called an extended enterprise.

As with concurrent engineering, collaboration in an extended enterprise implies communication of engineering information. Naturally, the same

[2] System is here considered to consist of the product and its manufacturing system.

problems of using different terminology may occur in the extended enterprise too. In fact, the problem may be increased because not only does the terminology depend on the different disciplines involved, but also on the different companies. That is, the same disciplines may use different terminology if they are part of different companies.

1.1.3 Communication and Management of Engineering Information

So far one problematic aspect of concurrent and collaborative engineering have been identified, that of difference in terminology. This may result in poor communication because the receiver of the engineering information does not interpret the message as it was intended by the sender (Davenport and Prusak, 1998; Schenck and Wilson, 1994).

The core of the problem, though, is that terminology is *just* a reference to a concept, cf. Figure 1.3. Terms and concepts are associated with each other during the interpretation of a message. As the receiver interprets the message she, or he, associates a term with its concept and, thus, understands the message. This, however, is only the case if the sender and the receiver associate the term with the same concept.

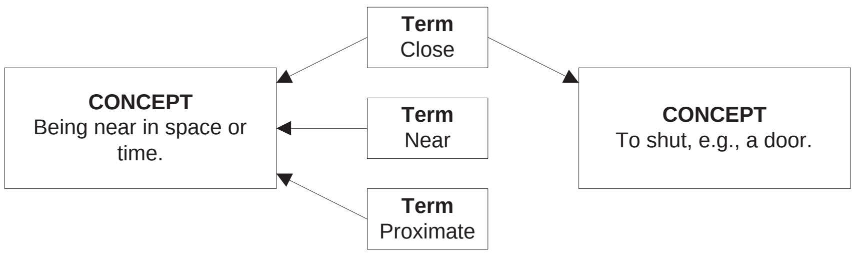

Figure 1.3. Example of how a concept can be referenced by different terms and how a term can reference different concepts.

Usually the problems with different concepts and terminology can be solved by informal agreements on the concepts, and the terminology to represent these concepts, e.g. through discussion and reasoning on a meeting. However, this is only the case when humans are involved.

Computer applications are not as adaptable as humans, nor as intelligent, and, thus, cannot discuss and reason with each other to reach an informal agreement on terminology to use in the communication process. Therefore, communication between computer applications need to be based on formal agreements on terminology (Schenck and Wilson, 1994).

In addition, difference in terminology/concept is not the only cause for poor communication. Other causes are that of not knowing what to communicate, and not knowing where to find what to communicate. Both causes are important issues of information management, and will affect both the quality of the product and the productivity of the innovation process.

These issues can be solved by: (i) understanding the activities, (ii) understanding the need for information in the different activities, and (iii) understanding how this information is related. Doing this and formally documenting it will provide maps of required information.

Hence, there are needs to formally define concepts and terminology, and to formally define a map of the required information. Activity and information models are important to formally represent these definitions.

Activity and Information Models - Maps of Required Information

An activity model captures activities and the information flow between activities. Hence, it is a tool to formally document the operations of an organization. The documentation can then be used to analyze the operations of the organization in terms of what the organization does and what information that is necessary to do this.

As a result an activity model provides a requirements specification for an information model (Al-Timimi and MacKrell, 1996) in two aspects. First it provides a scope for the information model, i.e. it states activities the information model is to support. Second, it provides the high level information types that are needed in the operations of an organization.

An information model then provides a detailed description of the information types. That is, it defines data that represents the information, it defines the relationships between different data, and it defines the interpretation rules of data.

Information Models - Formal Definitions of Terminology

An information model provides, besides a map of required information, formal representation of the interpretation rules of the terminology, i.e. an information model defines the terminology and its associated information concepts. These formal rules of interpretation is then used to implement import and export interfaces to the computer applications that are to participate in the communication. If the information model is computer interpretable much of this work can automated (Schenck and Wilson, 1994).

Standardization for Increased Quality and Productivity

Standardization of information models is a way to establish world wide common agreements on interpretation rules. Such standardization have resulted in ISO10303 and complementary standards such as ISO 15296 (EPISTLE), and ISO 13584 (Parts Library). A wide usage of standards like these would decrease the cost and effort for collaboration, and increase competitiveness. Gallaher et al. (2002) report that the transportation equipment industry in USA, i.e. automotive, aerospace, ship building, and special tool and die industries, save $156 million (2001 currency) annually by using ISO10303 enabled CAx applications. This report also estimates a potential benefit of $928 million annually.

Gallaher et al. (2002) categorize the benefits to: (i) decreased avoidance costs, decreased mitigating costs, and (iii) decreased delay costs. Included in avoidance costs are purchasing of redundant CAx systems, train and maintain engineering skills in redundant CAx systems, and productivity loss due to engineers working with less familiar CAx systems, i.e. costs to avoid communication problems. Mitigating costs are costs that arise due to problems in an actual communication process, i.e. costs of reworking CAx models, and costs of reentering data in CAx systems. Delay costs include profit loss as a result of delays due to communication problems.

Note that the benefits, current and potential, only include CAx applications. Hence, the benefits are potentially much higher if standards are used for all types of information exchange, e.g. PDM information, process planning information, and other types of project information.

1.1.4 Process Planning

Process planning, as it is considered in this thesis, play an important role in the innovation process. It is the interface between product development and manufacturing system development. It is in this activity that the product specification is interpreted and translated to manufacturing requirements. Hence, in this thesis, process planning is considered to be an active part in the concurrent development of products and their manufacturing systems, not only an activity where manufacturing resources are selected.

Problem Areas of Process Planning

As an interface between product development and manufacturing system development, the process planning activity deals with problems of managing information about products and manufacturing resources, as well as manufacturing processes. Not only does this result in communication problems, but it also result in increased complexity as a multitude of versions of product solutions, process plan solutions, and manufacturing system solutions must be managed.

The communication problems arise because information from different disciplines are involved in the communication process. This in combination with the increased complexity requires information models that defines terminology of different information concepts and that relate the different concepts.

Usually the process planning activity occurs too late in the product realization activity. The later the process planning activity is carried out, the less freedom the engineers have to plan, and the less they can affect the total cost positively, cf. Figure 1.4.

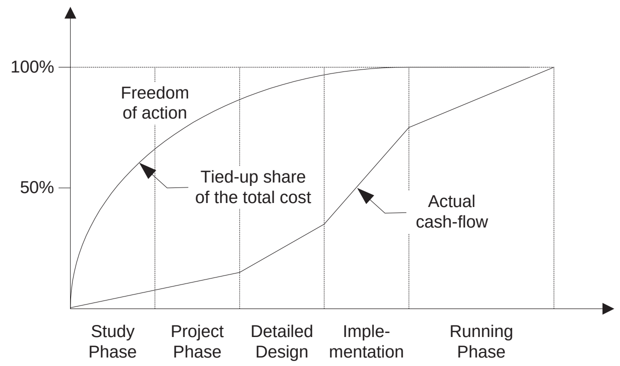

Figure 1.4. The impact of the early decisions on the total cost of development, adapted from Schaub (1990) and Vallhagen (1996).

A conclusion is to focus the efforts where they affect the total cost the most, i.e. in the early phases, cf. Figure 1.5. Process planning is an important part of the product realization process as it is here the product specification is interpreted and understood from a manufacturing perspective. Hence, process planning should start as early as possible in the product realization process, which, in turn, affect the requirements on information that is needed.

If process planning aspects were considered in the early phases, and related decision making was documented, these aspects would be considered when they can affect the total cost the most. In addition, process planning would be a more active part of the total innovation process. An activity where manufacturing requirements where defined rather than only selecting manufacturing resources.

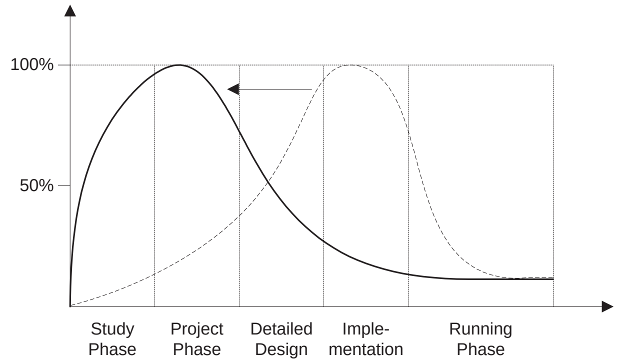

Figure 1.5. Work efforts should be focused where they affect the total cost most.

The agility[3] in process plans has also been poor. Most process plans have static relationships relating products to manufacturing resources via the process plan, i.e. the process plans represent a particular type of, or a particular, manufacturing resource that should carry out a particular manufacturing process. At most this concept have the ability to represent a portion of flexibility[4].

1.1.5 Related Research and Research Gap

In Section 1.1.4 some of the problems within the innovation process was identified. These problems concern the following areas:

- information requirements (information models),
- process planning (conceptual and detailed), and
- agility in process plans.

Schenck and Wilson (1994) discuss information modeling in general and information modeling with EXPRESS in particular. Their approach

[3]Agility is the ability to adapt to unforeseen events.
[4]Flexibility is the ability to adapt to foreseen events.

may be used for any application area where there is a need to capture information requirements and to formally define the interpretation rules of data.

One such application area is process planning, which Juran (1988) mean can be described as a process where goals are reviewed, processes are chosen, facilities capable of meeting the goals are provided, and methods are provided. Similar, but more specific, descriptions are provided by Curtis (1988); Eversheim et al. (1991); Feng and Song (2000); Ham and Lu (1988); Salomons (1995); and van Houten (1991).

Compared to the other, Feng and Song (2000) add an interesting aspect of process planning, the conceptual process planning. With conceptual process planning, Feng and Song (2000) mean the planning of processes at a phase in the innovation process when the detailed design of the product is not established. They also provide an information model describing the information requirements for conceptual process planning.

Other have also worked in the field of conceptual process planning, e.g. Haudrum (1994) consider production methods during the design stage, and Boothroyd et al. (2002); Boothroyd and Radovanovic (1989); and Mileham et al. (1993) estimate the cost of manufacturing processes in the early design stages before design details are available.

Related to process planning is the representation of capability. Whereas Bergman and Klefsjö (1998) and Curtis (1988) discuss bot machine and process capability, Algeo (1994); Gindy and Ratchev (1992); and Juran (1988) mainly focus on process capability.

Close related to process planning is the research area of features and feature technology. A large amount of research effort have been put in this area, e.g. van Houten (1991) describe the use of features in the PART computer aided process planning system, Salomons (1995) also use a feature based approach to support design of mechanical products, Dürr and Schramm (1997) make use of features to feedback manufacturing knowledge to the early design stages, and Wingård (1991) describe how form features can be used in CAD/CAM systems.

However, information management in process planning, where process planning is part of the concurrent development of products and their manufacturing systems in the extended enterprise, is not considered. This means that typical problems in this area, such as how to define and represent information that are relevant for process planning, have not been considered to its full extent.

In addition, conceptual process planning have not fully been elaborated as an activity where conceptual requirements on the manufacturing system can be identified and documented. Many of the approaches related to conceptual process planning either consider a traditional way of planning only earlier, or focus on evaluation-method aspects of process planning. Hence, the documentation-of-manufacturing-requirements aspect is forgotten.

Finally, a future aspect of process planning is forgotten as well. The aspect of eliminating the need of a static coupling between a manufacturing process and its executing manufacturing resources by having a dynamic relationship based on requirement and capability. This would increase the agility of the process plan and postpone the point in time when the final decision on what particular manufacturing resource that has to execute a particular manufacturing process, e.g. even as late as at the actual execution of the on-the-fly generated production plan.

1.2 Objectives of the Thesis

Considering the identified gap in research, one main area of interest is to identify and define information requirements for process planning in the context of concurrent engineering. In particular the information requirements concerning the early stages of the innovation process-Naturally, these requirements include the important connections between products, manufacturing processes, and manufacturing resources as well. Hence the following objectives were set:

Research objective 1. *Identify and define information requirements for process planning in the context of concurrent engineering.*

Research objective 2. *Identify and define important connections between product, process and manufacturing resource information for process planning.*

These objectives have been the base to formulate relevant research questions to guide the project work:

Research question 1. *What information is needed for process planning?*

Research question 2. *What information is needed to describe the relationships between products, manufacturing processes, and manufacturing resources?*

Research question 3. *How can the information be structured in an information model?*

1.3 Delimitation of the Thesis

The innovation process is by nature complex and include a vast amount of aspects. Therefore the work of limiting the scope of the thesis has been an important, and difficult, activity.

Naturally, the scope has been dependent on available case study objects at participating project partners. Since the project partners have been Volvo Car Corporation, ABB Body-in-White[5], and Scania, it has been natural to limit the scope to automotive industry. Particularly the body-in-white operations, and more specific weld spot operations.

Hence, the scope of the thesis concern weld spot process planning as part of the concurrent development of manufacturing systems in the extended enterprise.

[5] Although ABB Body-in-White has changed their name to ABB Automation Technologies (ABB ATRM/AM) since the study they will still be referred to as ABB Body-in-White throughout this thesis.

1.4 Structure of the Thesis

The structure of the thesis is as follows:

Chapter 1 give context and motivation to the thesis, as well as objectives and research questions.

Chapter 2 discuss research methodology in general and present the method of the work for this thesis in particular.

Chapter 3 give relevant theory for activity and information modeling, as it is used in this thesis. The chapter also deals with the relationship between activity and information modeling.

Chapter 4 give the main theoretical framework for the thesis. It is within this framework the result has been developed and hypotheses tested.

Chapter 5 present the main result and hypotheses. The result is presented in terms of an information model, the PPR information model. This work have also resulted in two hypotheses, which are also presented in this chapter.

Chapter 6 discuss the testing of hypotheses and relevance of the result in terms of validity.

Chapter 7 give a critical discussion of the results in terms of hypotheses and information model, as well as indicate further work and conclude the thesis.

Chapter 2

Research Methodology

The purpose of this chapter is to introduce the reader to the author's view on research and science, and to describe the research method that was used. The hope is that this introduction will provide the reader with what Ödman (1994) and Westin (1973) call pre-understanding of the research approach, which will help the reader to understand and interpret the research results.

Pre-understanding is the historically given understanding that is necessary to understand an observation (Ödman, 1994). Pre-understanding gives the *direction* of a search and determines the *view* from which an object is observed. Considering these two aspects of pre-understanding, it is obvious that describing the author's view on research and science, as well as the research method, will help the reader to interpret and understand the results in their intentional meaning.

However, as this thesis is not about research methodologies, the theories presented and discussed in this chapter will, mainly, be the ones that have had major impact on the methodology of this research project.

2.1 Research and Science

A reasonable question for a doctoral candidate to ask is, what is research and science? Føllesdahl et al. (1993) mean that the main objective of research and science is to acquire knowledge and understanding. Here, research is considered to be the process where knowledge and understanding about objects and phenomena in the Universe is acquired, whereas science is considered to be the framework of valid methods that are used to acquire the knowledge and understanding. In natural science, for instance, researchers want to understand natural phenomena such as nuclear fission.

A contrast to natural science is engineering science. In engineering science the concerned objects and phenomena are those created and initiated by humans to fulfill human needs. Hence, research in engineering science is the process of understanding the principles of creating and controlling these objects and phenomena. For instance, the effort made by, e.g., Andreasen (1991); Pahl and Beitz (1996); and Suh (1990) to understand and describe the principles of design.

2.2 Development of Theories

A description of, e.g., the principles of design is called a theory, which can be used to explain the behavior of objects, or to predict phenomena and their consequences. That is, the theory can be used to answer questions about the concerned objects and phenomena. Fagerström and Moestam-Ahlström (2001) describe the entities and activities that are involved in the creation of a theory, as well as the direction of information, in the *Model of Research*, cf. Figure 2.1.

It is clear that Fagerström and Moestam-Ahlström (2001) have an entity focused approach describing research. Objects are the things, physical or non physical, in the Universe that are of concern for the research, e.g. the design process. Subjects are those who conduct the research,

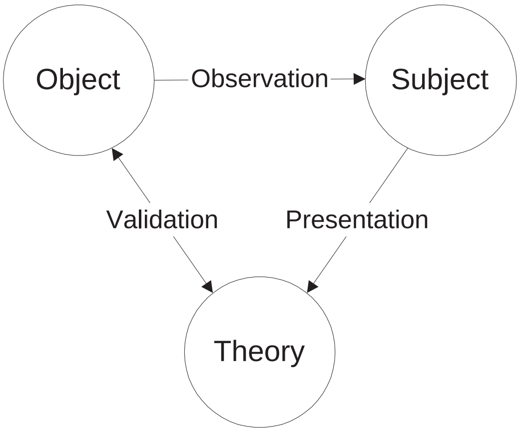

Figure 2.1. The *Model of Research* (Fagerström and Moestam-Ahlström, 2001).

i.e. the researchers. Theories are the result of the research, e.g. the law of gravity.

The subordinated activities describe what is happening in the research. Mainly this is an interaction between the subject and the two other. That is, the subject observe the object, the subject present the theory as a result of its observation, analysis, and synthesis, and the subject validate the theory to assure that it is a correct reflection of the object within its Universe of discourse.

As indicated in the previous paragraph, analysis and synthesis are also part of the research. These activities are not part of the *Model of Research*, but if they are to be included they should probably be arrows going out of and into the subject. This to indicate that the information is still at the subject during these activities.

The validation activity is one of the most important activities in the development of a theory. In Section 2.2.2 two fundamentally different approaches to develop and validate theories are discussed, but first hypotheses are discussed.

2.2.1 Hypotheses

Popper (2003) call the result of an observation for a singular statement. It is a statement about a particular object in a particular place at a particular time. That is, it is not a statement about swans in general, but a statement about the color of a particular black swan in a particular park in Sydney, Australia, at noon August 1, 2001.

Definition 2.1. A singular statement is a statement that accounts of results from observations or experiments.

(Popper, 2003)

In contrast to singular statements are universal statements. Popper (2003) mean that theories are universal statements. Hence, a universal statement is a statement that can be used to explain or predict a singular statement. Another universal statement is the hypotheses, a tentatively anticipated universal statement that is the subject of testing.

Definition 2.2. A universal statement is a statement in terms of a theory or a hypotheses.

(Popper, 2003)

Definition 2.3. A hypotheses is a tentatively anticipated universal statement that is the subject of testing.

From (Popper, 2003)

2.2.2 The Way to Prediction - Induction or Deduction?

There are two fundamentally different types of inference, induction and deduction. These two inferences constitute two fundamentally different approaches to create and validate theories.

Inference is called inductive if it passes from singular statements to universal statements (Popper, 2003), cf. Figure 2.2. That is, the development of a theory is called inductive if it is concluded that the theory is true because of the singular statements it is based on.

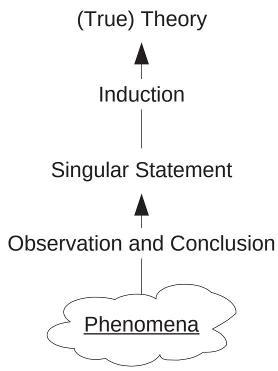

Figure 2.2. When inference passes from singular statement to universal statements it is called inductive.

Both Chalmers (1999) and Popper (2003) dispose inductive inference by arguing that no matter how may observations that are made, there is always the possibility that the next time an observation is made it will prove that the theory does not hold. A classical example is the observation of white swans resulting in the theory that all swans are white. Independent of the thousands and millions of observations of white swans, the first time a black swan was observed it proved that the theory did not hold.

Popper (2003) further emphasize the shortcomings of an inductive approach by referring to history, which show that all theories have been proven to not hold. This is obvious because a theory only reflect the observers interpretation of a phenomena in the Universe, and as the knowledge of the observers increase the understanding of the particular phenomena changes and, thus, so do the theory.

A deductive method also depend on induction to develop universal statements, i.e. universal statements are developed by observing singular phenomena, draw conclusions from the observation, and generalize these conclusions. However, in a deductive method it is not concluded that universal statements are true because of the singular statements they are based on.

On the contrary, Popper (2003) mean that a theory can never be established as true, merely corroborated. This is done by critically testing the theory, cf. Figure 2.3. A critical test is conducted by establishing singular statements by means of deduction, and then comparing the singular statements with one another and other statements to find their logical relationships. Four different approaches to testing may, according to Popper (2003), be distinguished.

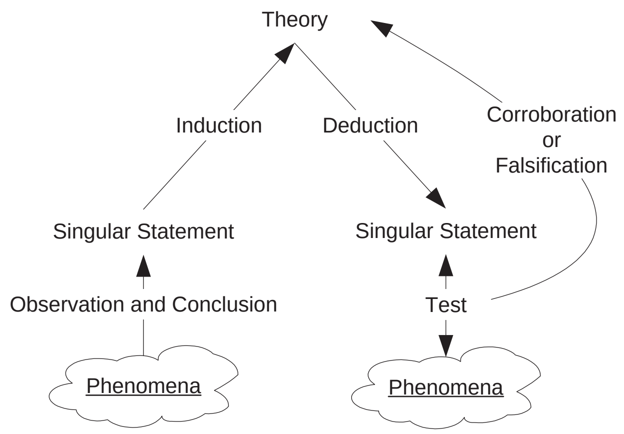

Figure 2.3. In a deductive approach a theory is never considered true only corroborated or falsified.

First, a logical comparison of the deduced singular statements can be made. This is done to evaluate logical consistency between the singular statements, e.g to find equivalence, similarities, and contradictions.

Second, the logical form of a theory can be tested. That is, a test can be conducted to find out whether the theory is of empirical or scientific nature, or if it is, e.g., tautological.

Third, a theory can be compared with other theories. The aim is to determine whether the theory have a scientific contribution or not.

That is, to determine if the theory constitute a scientific advancement compared to already established and justified theories.

Fourth, a deduced singular statement can be compared with practical applications and experiments. If the test verify a singular statement then the theory has passed its test for time being and, thus, the hypothesis has become more likely to be a reflection of the world within its universe of discourse. If, on the other hand, the test falsify a singular statement then the hypothesis, from which the singular statement was logically deduced, is falsified and, thus, the hypothesis is not valid.

2.3 Influences on the Research Result

It is natural to believe that research and the result of the research are influenced by the environment in which they exist. Three such influences, identified by Ejvegård (1996), are the research problem, the method and the objects of observation, cf. Figure 2.4.

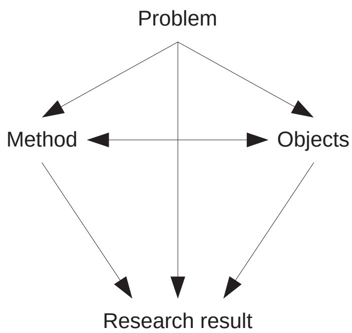

Figure 2.4. The choice of problem, method and objects influence the result of the research, adapted from Ejvegård (1996).

It is obvious that the choice, and wording, of the problem is a major influence because the problem is the starting point for all research. When the problem is defined a suitable research method and suitable objects of observation can be chosen (Yin, 1994). They in turn, influence each other (Chalmers, 1999) as well as the result of the research. These influences and their relationships are shown in Figure 2.4.

A fourth influence can also be identified, namely the researcher. The researcher choose and define the problem, as well as method and objects to observe. All observations will be colored by the researcher and, thus, influence the result (Chalmers, 1999).

Again, Ödman (1994) and Westin (1973) call this pre-understanding. It is the pre-understanding that gives direction in a search and determines the perspective that is put on the objects of observation. All interpretation of events and things in an environment will be colored by the assumptions and understanding the researcher already have of that environment, or that the researcher have acquired during the research.

Therefore it is important to describe not only the environment in which the observation have been made, but also the researchers view of that environment, the objects of observation, and, perhaps most important, the procedure of conducting the research, i.e. the research method.

2.4 Research Method

As discussed in Section 2.2, it is important to use a systematic and structured method for research. In this research project a method consisting of three phases were used. This phases were the preparation, the creation, and the presentation phases, cf. Figure 2.5.

2.4.1 Preparation Phase

The setup of the research project was made in the preparation phase by defining the research problem, defining the objectives and research questions, and by configuring the research methodology. The purpose of these activities was to define the necessary means to control and guide the research.

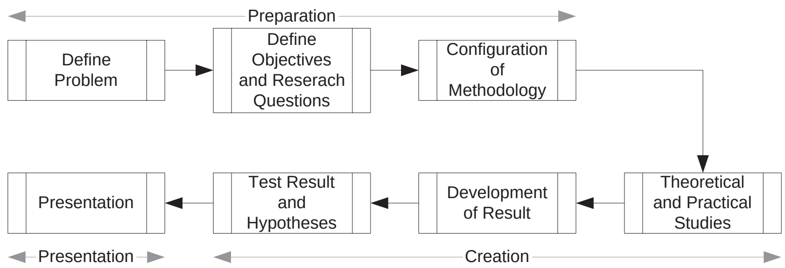

Figure 2.5. A procedural description of the used research method.

The main prerequisite for everything in the research project has been to identify and define a problem. Without understanding that there was a problem, and what the problem was, there was no need to conduct the research.

The objectives and research questions have, mainly, served as a control of the research project. In other words, activities that have not contributed to (i) fulfillment of the objectives or (ii) the answers of the research questions, have not been part of the research project. As a consequence, the focus and aim have been maintained throughout all the activities.

The configuration of the methodology was made by identifying suitable methodologies, combining them and adapting them to the needs of the research project. These needs were derived from a need of understanding the innovation process as a whole. A whole that is dependent on the interaction with, and between, its parts.

Considering these needs of understanding the whole and its parts, the hermeneutics research method (Ödman, 1994) and, more specific, the hermeneutics circle (Føllesdahl et al., 1993; Ödman, 1994) was used as the overall research method. As a consequence, the incremental aspect of the hermeneutics circle was introduced, cf. Figure 2.6.

In *D1* a decision is made whether the new experience from the theoretical and practical studies have affected the earlier understanding of problem. If the earlier understanding of the problem was affected a new

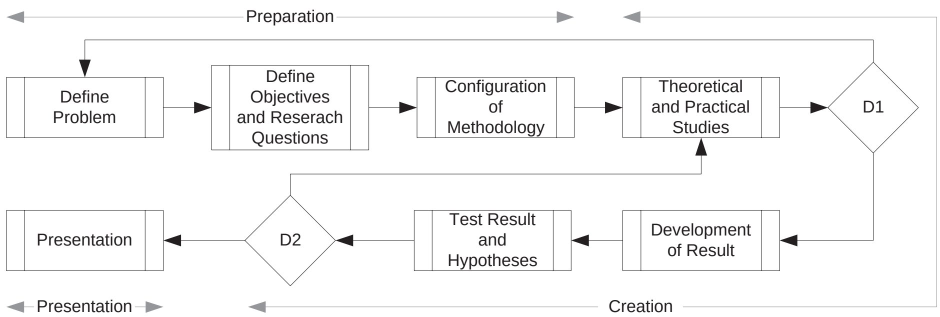

Figure 2.6. The incremental aspect of the hermeneutics circle, with decision points *D1* and *D2*, was introduced in the model of the research method.

definition of the problem was made, research questions and methodology was refined.

The *D2* was the starting point for the main incremental loop. If the result was found to be *not satisfactory*, further work had to be done to study theory and practice, and to develop and test new results.

In addition to the hermeneutics circle, literature studies, case studies, activity modeling[1], and information modeling[2] were also used.

The different methods were used for different purposes in different phases of the project. The hermeneutics method influenced the overall research strategy. As a complement, the other methods influenced the more practical approach of understanding the research problem, observing the research objects, and creating, documenting and verifying the result.

2.4.2 Creation Phase

The development of result was carried out in the creation phase by theoretical and practical studies, development of result, and test the

[1]See Section 3.2.
[2]See Section 3.3.

result and resulting hypotheses. The purpose of these activities was to identify the requirements for information about manufacturing processes in the innovation process, and to develop an information model that capture these requirements.

The theoretical studies were carried out as literature studies, whereas the practical studies were carried out as case studies. Thus, the innovation process in general, and the process planning activity in particular, was studied from two perspectives. First, from theories and experiences of other researchers, such as Andreasen and Hein (1987); Clausing (1994); Hubka and Eder (1988); Kjellberg (1982); Pugh (1998); Schenck and Wilson (1994); Suh (1990, 2001); Ueda et al. (2001); Ulrich and Eppinger (2000); van Houten (1991). Second, from experience within the research project itself in terms of case studies at Volvo Car Corporation, and ABB Body-in-White.

Considering the identified requirements, an information model was developed. This activity mainly involved the analysis of what was found in the studies, the synthesis to develop an information model and the presentation of the information model in EXPRESS[3]/EXPRESS-G[4], cf. Section 3.3.

Furthermore, the result was verified by populating the information model with data from fictive and real cases. The final verification and test of hypotheses was made by data from the PDTnet project, cf. Mårtensson et al. (2002).

To summarize and clarify, the hermeneutics circle was used in two aspects here. First, in the overall process of the creation phase, i.e. the iteration between the analysis, synthesis and verification activities. Second, in the synthesis activity for the iteration between the activities of modeling, population and verification of part of the information model.

[3]EXPRESS is a lexical modeling language.
[4]EXPRESS-G is a graphical subset of EXPRESS.

2.4.3 Presentation Phase

As a last activity of the research project, the result was presented by writing this thesis. In addition to the text and illustrations of the thesis, the main findings were presented in an information model by using the EXPRESS/EXPRESS-G modeling language.

Chapter 3

Activity and Information Modeling

The purpose of this chapter is to provide a theoretical background to what a model is in general, and what an activity and an information model is in particular. In addition, several related terms such as data, information, and knowledge will be elaborated and defined.

3.1 Model and Modeling

The term *model* have many definitions. The least common denominator seems to be that it is a simplification, an abstraction of something (Booch et al., 1999; Edlund and Högberg, 1997; Fishwick, 1995; Føllesdahl et al., 1993; Mäntylä, 1988; Schenck and Wilson, 1994), which may not be real; it can be an imaginary thing such as a model of a product that has never been designed before. As a simplification a model will not represent the whole, but merely some perspectives of interest of what is being modeled at a certain level of detail. Hence, the model is only valid for those perspectives, and to the level of detail, it claim to represent (Ross, 1977).

In addition, Booch et al. (1999); Fishwick (1995) and Schenck and Wilson (1994) mean that the overall purpose of a model is to provide a way to better understand a particular perspective of the thing being modeled, such as the shape of a product represented in a 3D CAD-model. Obviously, the model must be able to answer questions about, e.g., the shape of a product in order to help an observer understand it.

Combining the reasoning about simplification and understanding, a model can be described as an abstraction that must be able to answer questions about the thing being modeled. The answers are only valid within the perspective and level of detail the model claim to represent. Hence, the following definition of a model is used:

Definition 3.1. M is a model of a system S if M can answer questions about S with an accuracy of A.

(Marca and McGowan, 1988)

Consequently, a theory is a model because it describes some phenomena in the real world, i.e. it can answer questions about the real world phenomena such as the relationship between energy, mass and the speed of light ($e = mc^2$).

When a model is created it is called modeling or, in other words, modeling is the action of creating a model.

3.2 Activity Modeling

As this thesis focus on information modeling, a reasonable question to ask is - why activity modeling? The answer to that question will be elaborated in this section. However, before this answer are provided it is important to understand what the term *activity* mean.

3.2.1 Activity

Of course, the definitions of the term activity are numerous. Nevertheless, words like happening, changing, and action are usually part of the definitions.

Both ISO/TC184/SC4 (1999) and Ross (1977) mean that an activity is something happening in a system. A difference between the two definitions of an activity is that ISO/TC184/SC4 (1999) explicitly define that the *happening* (a process) makes a change to the universe, whereas Ross (1977) does not.

Nevertheless, the two definitions are essentially the same. When something is *happening* in a system there is actually a *change* to the system, which is part of the universe. This may not be a visible change, but merely a change of the state of the system.

Both definitions are similar to the definitions by ISO/IEC/JTC1/SC7 (2001) and ISO/TC184/SC4 (2002). However, one important difference exists; ISO/IEC/JTC1/SC7 (2001) emphasize that an activity always consumes time and can, thus, never be instantaneous. This clearly separates the activity from an event, which is instantaneous.

Definition 3.2. An event is an instantaneous happening that have an effect on the universe.

Yet another difference is that whereas ISO/TC184/SC4 (1999) place an activity on an equality with a process, ISO/IEC/JTC1/SC7 (2001) does not. ISO/IEC/JTC1/SC7 (2001) mean that a process is a set of interrelated activities that transform an input to an output, cf. the term transformation process as it is used by Hubka and Eder (1988).

Instead ISO/IEC/JTC1/SC7 (2001) uses the term *action* to define an activity, meaning that an activity is a set of actions. American Heritage (2000) define an action as the state of acting or doing, indicating that an activity need some kind of active participation to make the change.

Definition 3.3. An action is the state of acting or doing.

(American Heritage, 2000)

Obviously, this indication limits the use of the term to describe changes to the universe that are due to an active participation from some part, e.g. humans or machines. This limitation makes the use of the term activity more clear, as the purpose of this thesis only concern activities that are part of a transformation process, cf. Chapter 4, which always involve an active participation of some resource.

Following the reasoning above, in this thesis an activity will be regarded as something that consumes time while it makes a change to the universe. The start and end of the activity are events, which may be triggered by other events.

Definition 3.4. An activity is a set of actions that consumes time while it makes a change to the universe.

Adapted from ISO/TC184/SC4 (1999)
and ISO/IEC/JTC1/SC7 (2001)

3.2.2 Rationale Behind the Use of Activity Modeling

The rationale behind the use of activity modeling in this thesis is that it exists a strong interrelationship between activities and information. Activities, as they are considered in this thesis, use[1] information while they make a change to the universe.

In addition, as the activities change the universe they create information that itself contribute to the change of the universe. This information may be used by other activities. In fact, it should be used by,

[1]Naturally, it is not an activity itself that uses and creates the information but rather the resources that carry out the activity.

at least, one other activity. Otherwise the creation of the information would have been a waste.

What, then, is the information used for in an activity? The answer is simple and straight forward, the information is used for decision making (Fagerström et al., 2002; Fagerström and Moestam-Ahlström, 2001). Hence, following from the previous paragraph, the creation of information that is not used for decision making is a waste[2].

Obviously, in order to minimize the waste it is necessary to understand what information that is needed in an activity. Consequently, understanding the activity is a necessity. Activity models will aid in the process of understanding an activity by representing the identified activities and the flow of information between them.

Since an activity model captures the information flow between activities it provides a requirements specification for an information model (Al-Timimi and MacKrell, 1996). As a requirements specification it also provides the scope for an information model.

3.2.3 Activity Model

Then, what are the requisites of an activity model? It is clear form Definition 3.4 that the purpose of an activity is to make a change to the universe. Hence, the ability to represent a change to the Universe is a necessity for an activity model.

In most activity models this is done by describing the change as an output of the activity. In a graphical presentation it is usually an arrow going out of a box, where the arrow correspond to the output and the box correspond to the activity. This can be seen in, e.g., the Structured Analysis and Design Techniques (SADT) (Ross, 1977).

As in any design, activity modeling is a type of design, once it is understood *what* to accomplish it is needed to know and control *how* to

[2]The term waste is used with the assumption that specific effort have been put into create this particular information.

accomplish it (Ross and Schoman, 1977; Suh, 1990). This is not often considered in most activity models. Nevertheless, an important capability of an activity model is the capability to describe the control of how to achieve the outputs, the goals, of the activity.

In addition, it is sometimes important to describe the resources that are used to create the outputs of an activity (ISO/TC184/SC4, 2002; Marca and McGowan, 1988). Marca and McGowan (1988) mean that resource can be classified in two different types of resources, resources that are consumed or manipulated during an activity, and resources that are not.

These four aspects of activity models are all representable in the SADT as output, control, input, and mechanism respectively, cf. Figure 3.1 or a description of SADT by, e.g., Ross (1977). Many other activity models does not include these aspects in their models, e.g. UML Activity diagrams (Booch et al., 1999). The reason is the difference in purpose of the activity models.

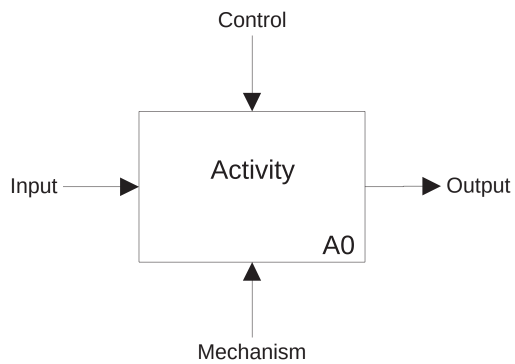

Figure 3.1. Under control, an activity transforms its input into output with its mechanism (Marca and McGowan, 1988).

Whereas SADT have the purpose of describing the activities and the flow of things between the activities, other activity models, including UML activity diagrams, tend to focus on the sequencing of activities instead. Hence, for the purpose of this thesis the SADT is more suitable.

3.3 Information Modeling

The central theme of this thesis is the modeling of information about manufacturing processes. But what is information? And what is information modeling?

Davenport and Prusak (1998) describe information as a message sent to inform a receiver, and indeed, information is created to be communicated. A similar interpretation of information is made by Kent (1978) and Schenck and Wilson (1994). Schenck and Wilson (1994) even consider the possibility of sender and receiver being the same, and that storage of information is only a special case of communication. In addition, Schenck and Wilson (1994) mean that "information is knowledge of ideas, facts and/or processes".

However, the interpretation of a message, as it was intended by the sender, can only be ensured if there is an agreement between the sender and the receiver of how to interpret the message (Kent, 1978; Scheller, 1990; Schenck and Wilson, 1994). A base for such agreements, or rules of interpretation, is the information model.

3.3.1 Data, Information, Knowledge and Competence

The term *interpret* seems to be vital in the description of information. The meaning of interpret is to conceive the significance of something (American Heritage, 2000), and this something is what is called data.

Kjellberg (1982); and Schenck and Wilson (1994) define data as being signs or symbols that, based on the rules of interpretation, can represent information. A slightly different definition is made by Davenport and Prusak (1998); and Holmer et al. (1990), who mean that data is discrete facts about the real world. Despite the difference in the definition, the essence of data as being the raw material, building blocks, or representation of information is a least common denominator. Hence, the following definition of data is used:

Definition 3.5. Data are symbols which represent information for processing purposes, based on implicit or explicit interpretation rules.

Adapted from Schenck and Wilson (1994)

Obviously, data itself has little or no meaning, and says nothing about its own importance or irrelevance (Davenport and Prusak, 1998; Ignizio, 1991; Scheller, 1990). Data is merely the representation of a concept, and it is the concept that brings meaning to the data. That is, when data is interpreted it is associated with a concept that has a particular meaning for the receiver of the data. When the association between the data and the concept is made the data is understood and becomes information.

What, then, if the data is associated with another concept than the originator intended? Is it still information? For simplification, information will here be considered as data interpreted in its original meaning.

Definition 3.6. Information is data interpreted in its original meaning.

Definition 3.6 differ from the definition of information that Schenck and Wilson (1994) uses. Schenck and Wilson (1994) mean that information is knowledge, whereas Davenport and Prusak (1998); Hicks et al. (2002); Holmer et al. (1990) mean that knowledge originates and is applied in the mind of people. Indeed, knowledge is created through a cognitive process when an individual, or group of individuals, interpret and understand information, both formal[3] and informal[4].

Hicks et al. (2002) call this process the knowledge inference process and it results in the creation of knowledge elements. The knowledge elements are merely perspectives of information, which depend on factors such as knowledge of a person, the role of a person in an organization, environment and goals (Hicks et al., 2002). The division of

[3]Formal information is structured information that provides a context and measure so that the same knowledge may be inferred (Hicks et al., 2002).

[4]Informal information is unstructured information, such as verbal, expressions and memory information (Hicks et al., 2002).

knowledge into process and elements is similar to how Davenport and Prusak (1998) describe knowledge as being both process and stock. In addition, both Davenport and Prusak (1998); and Hicks et al. (2002) mean that the knowledge stock, or elements, is derived from information as information is derived from data. Considering this discussion the following definition of knowledge seem adequate:

Definition 3.7. Knowledge form the sum of experiences and information a person have collected and more or less consciously structured for its needs.

(Holmer et al., 1990)

The ability to use the acquired knowledge and information to make appropriate decisions and actions is here called competence. Competence is not only knowledge about how to make decisions and how to act, but also include the will and drive to make a change, cf. Figure 3.2. Bergman and Klefsjö (1998) describe this as possessing the right skills and knowledge to perform the service. Without the competence, and underlying knowledge, no good decisions and actions would be made.

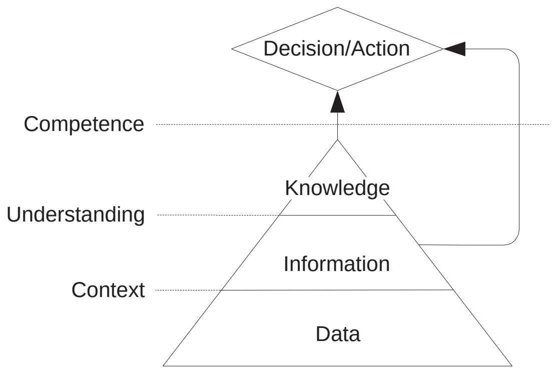

Figure 3.2. The relationship between data, information, knowledge and competence.

Definition 3.8. Competence is the ability to use the acquired knowledge to make appropriate decisions and actions.

3.3.2 Information Model and Information Modeling

For a company it is important that individuals, and groups of individuals, create the same knowledge from the same information. However, it may be impossible to create the same knowledge from the same information because of different pre-understanding. Similar knowledge creation can only be assured if the individuals have access to formal information, which means that the elements of information are structured, provide a specific context, measure, and rules of interpretation. Structure, context, measure, and rules of interpretation are what the *information model* provide.

From Definition 3.6 (definition of information) and Definition 3.1 (definition of model) the term *information model* mean a model of how data should be interpreted to information. What does this mean? To interpret the data correctly, implicit or explicit interpretation rules are needed. That is, rules to control how to interpret the data. An information model provides the explicit interpretation rules of data in a formal way. A guide in the interpretation of an information model is the two basic rules that must always be stated for an information model (any model actually), namely the purpose of the model and the viewpoint of the model. This distinguish the usage and the user of the model, and supports a correct interpretation.

Schenck and Wilson (1994) uses a formal approach to describe the interpretation of data to form information, letting I and D stand for information and data respectively. Then let R be the set of explicit interpretation rules that produce information from data. Then formally

$$R(D) \mapsto I \tag{3.1}$$

mean that data is transformed into information by applying the interpretation rules. The opposite is also possible, by applying the inverse rules R_{-1} to information, data is produced. This is formally expressed as

$$R_{-1}(I) \mapsto D \tag{3.2}$$

Furthermore, if R is invariant then information can be exchanged without a loss. This is formally described as

$$R(R_{-1}(I)) \mapsto I \tag{3.3}$$

This reasoning is important in explaining the purpose of the information model and information modeling, as will be shown by introducing the interpretation rules of a sender (indexed by s) and a receiver (indexed by r) in the description. Then formally

$$R_r(R_{-1_s}(I_s)) \mapsto I_r \tag{3.4}$$

mean that the information of a sender is transformed to data, which in turn is interpreted and transformed to information by the receiver. However, $I_s = I_r$ only if R_{-1_s} is the inverse of R_r and, thus, $R_s = R_r$. In other words, information can only be exchanged fully and with preserved meaning if the rules of interpretation is the same for both the sender and the receiver. The information model is a set of explicit interpretation rules to ensure that the intended meaning of information is always preserved.

Definition 3.9. An information model is a formal model of data and its interpretation rules.

Schenck and Wilson (1994) distinguish between two different types of information models, a conceptual and a concrete information model. A conceptual information model is independent of any particular instantiation method. That is, it has not been constrained by any limitations imposed by an instantiation method. In contrast, the concrete information model is developed with a particular instantiation method in mind and, thus, constrained by the limitations of that particular method.

This thesis will mainly concern conceptual information models. The rationale for using conceptual models is to limit the influence and constraints by having a particular instantiation method in mind. Such influence would, of course, limit the usability of the result presented in this thesis.

Finally, information modeling can be summarized by the following quotation:

> The ultimate goal of information modeling is 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.
>
> (Schenck and Wilson, 1994)

3.3.3 Representation of Information Models

An information model can be represented by using different techniques, such as the EXPRESS-G (Schenck and Wilson, 1994), the Unified Modeling Language (UML) (Booch et al., 1999), the Entity-Relationship (ER) (Chen, 1976), and the Nijssen's Information Analysis Method (Nijssen and Halpin, 1989), as well as the EXPRESS (ISO/TC184/SC4, 1994; Schenck and Wilson, 1994) and the DAPLEX (Shipman, 1981) among others.

The different techniques can be divided into graphical (EXPRESS-G, UML, ER, NIAM) and lexical (EXPRESS, DAPLEX) representation techniques. Whereas a graphical technique utilizes symbols or icons to represent the major items in a model a lexical technique uses words and mathematical symbols (Schenck and Wilson, 1994). The strength of a graphical representations is their ability to visualize the structure of a model. In contrast, the strength of a lexical representation is their ability to formally represent the details and constraints of a model, as well as being computer processible.

A model constraint is a particular type of property that put restrictions on properties, relationships and entities as a whole. Two examples of common constraints are the *cardinality* and the *data type*. These constraints are so commonly used that they are usually possible to represent in both lexical and graphical languages. In Example 3.1 an attribute *salary* is constrained to only represent values larger than or equal to 1000. This type of constraint is usually only possible to represent in lexical languages.

Example 3.1.

```
ENTITY Employed INTEGER;
  salary :  INTEGER;
WHERE
  {salary >= 1000};
END_TYPE;
```

In this thesis the EXPRESS-G and EXPRESS techniques have been used for information modeling, cf. Schenck and Wilson (1994) for a description of the basic syntax. The rationale behind this decision is that EXPRESS-G and EXPRESS in combination provide the strengths of being both graphical and lexical. This can be achieved because EXPRESS-G is a sub-set of EXPRESS. In other words, what can be represented in EXPRESS-G can also be represented in EXPRESS. Usually, available EXPRESS-based modeling tools utilize EXPRESS-G for graphical modeling, but the output for computer processing purposes is EXPRESS. In addition, it is usually possible to define details and constraints by using EXPRESS in these tools.

Chapter 4

The Innovation Process: A Collaborative Effort

The purpose of this chapter is to provide a definition of the innovation process as the term is used in this thesis. Furthermore, an overview of the innovation process, from the viewpoint of the research, is also given.

From this viewpoint, four characteristics have been identified as the core characteristics of the innovation process, namely (i) decision making, (ii) information, (iii) design methods and (iv) collaboration. If mastered, they will have a great and positive impact on the result of the innovation process and the performance of the company. The organization in which this process is executed is called the innovation system.

4.1 Innovation

In the late 1970s the Japanese automotive industry, assuming the energy crisis to continue, had made large investments in engine plants for small four-cylinder engines (Womack et al., 1990) to cope with demand for small cars. The drop of fuel prices in the beginning of the 1980s resulted in an unexpected increase in demand for large cars with more power.

Instead of investing in new engine plants for V6-engines, the Japanese companies developed four-cylinder engines with technical features, such as fuel injection, four valves per cylinder, turbochargers and double overhead camshafts. Non of these features were new in itself, the 1924 Bentley had double camshafts, but the way they were combined and, most important, the way they were adapted in terms of manufacturability were new.

This adaptation resulted in a much higher quality of each feature than had been possible before. The increased quality enabled the new engines, using the combination of features, to run as smoothly and with as high reliability as engines without the features did.

Womack et al. (1990) end their example of the four cylinders motor emphasize the weaknesses of the engineering system of a mass-producer. This weakness was exposed when the rest of the automotive industry tried to add the same features to their four cylinders motors. It took, for instance, GM four years to introduce the features and two more years to refine the design so that the engines could run without any drivability problems. Still, GM was only able to provide these engines in a narrow range of GM cars.

It is clear, from the example above, that not only does the product design impose requirements and constraints on its manufacturing system, but it is also driven and, perhaps more often, limited by the capabilities of the same. The example also indicates that there is a strong interdependency between the properties of the product and the capabilities of its manufacturing system, which must be considered during the process of bringing new products to the market.

What the Japanese automotive industry did was to understand the need of the customer, it was more power not V6-engines they needed, in order to create a new solution that fulfilled the needs without compromising the requirements on cost and quality. In addition, they were more skilled in terms of understanding the interdependency between the product and its manufacturing system, i.e. that either one can impose constraints on the other, and in terms of organizing the work to deal with this interdependency.

This process of understanding the needs, creating a new solution and providing the solution to the customers is the innovation process, what Davenport (1993) describes as the *introduction of something new*. Similarly, Cooper (2001); Hubka and Eder (1988), and Sohlenius (2000) describe innovation as *bringing new products to the market*, with the emphasis on *bringing*. It is clear that innovation does not involve the continuous process of producing products, but rather the process of bringing products to the market. In this thesis the following definition of innovation will be used:

Definition 4.1. Innovation is the transformation of customer needs into new products on the market, from idea until a stable manufacturing process is established.

It is important to remember that innovation, as it is considered here, involves the development and realization aspects on two design objects; the development and realization of (i) products, and (ii) processes and manufacturing system. Furthermore, innovation involves the activities of bringing a product to the market, up and until a stable manufacturing process is established.

In a general aspect innovation can be seen as a process that transforms, among other things, ideas, raw material and equipment to descriptions of products and their manufacturing system, as well as stable manufacturing processes, physical products and their physical manufacturing system. That is, things, e.g. raw material, are inputs to a process, which then transforms them and releases them as outputs, e.g. products, cf. Figure 4.1.

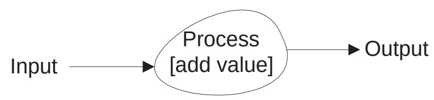

Figure 4.1. Input is being transformed to output in a process.

Essential for this transformation is, as it is created and initiated by humans to fulfill human needs, that value is being added as the input is transformed to output (Hitomi, 1979; Hubka and Eder, 1988; Slack et al., 1998; Sohlenius, 2000; Wu, 1992). The input is transformed to satisfy the needs of the customers.

Hence, the following definition is used:

Definition 4.2. A transformation process transforms an input to an output by adding values to satisfy previously declared needs.

Adapted from Hubka and Eder (1988)

Of course, for a transformation process to take place, it needs to be carried out by someone or something, e.g. humans, machines and computers. The humans, machines, computers or other resources that carry out or participate in a transformation process are all part of a system, called a transformation system (Hitomi, 1979; Hubka and Eder, 1988).

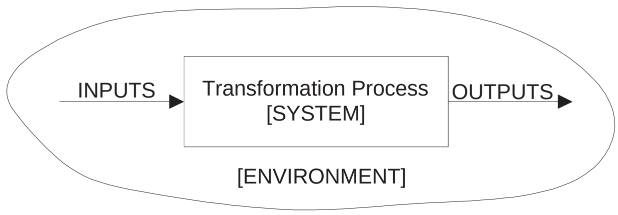

Figure 4.2. A transformation system transform inputs to outputs (Hitomi, 1979).

Hitomi (1979) describe a transformation system as a system that "receives input from its environment, transforms them to outputs, and releases the outputs to the environment", cf. Figure 4.2. Wu (1992) on the other hand do not explicitly describe a transformation system, but his description of a system is similar. That is, it receives inputs and delivers outputs.

In their description, Hubka and Eder (1988) decompose the transformation system into sub-systems. They mean that a transformation system consist of the human system, the technical system, the information system, and the management and goal system. Hubka and Eder (1988) also provide a clearer separation of the components of a transformation system and its process, cf. Figure 4.3.

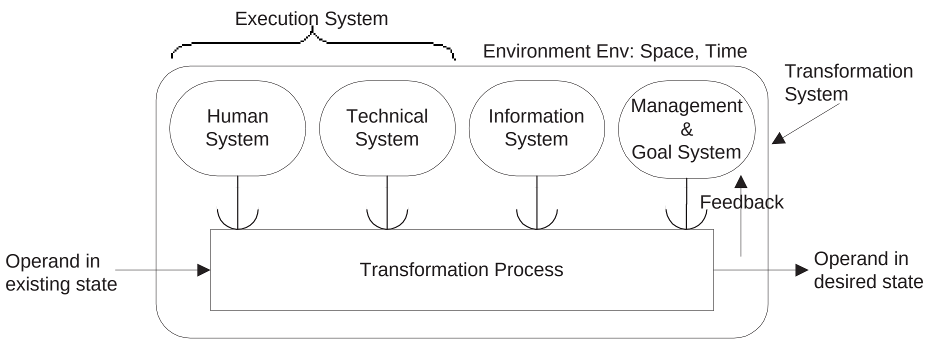

Figure 4.3. A transformation system rely on several sub-systems to execute the transformation process (Hubka and Eder, 1988).

Accordingly, a transformation system can be defined as follows:

Definition 4.3. The sum of all elements and influences (and their relationships among them and to their environment) that participate in a transformation is collectively termed a transformation system.

(Hubka and Eder, 1988)

Hitomi (1979); Hubka and Eder (1988); and Wu (1992), all mean that the transformation system encapsulates the transformation process. That is, the process is carried out within the system. This view can be applied on all levels of a transformation system, from the level of large enterprises to machine tools.

In addition, with their reasoning, Hitomi (1979); Hubka and Eder (1988); and Wu (1992) provide two important perspectives of transformation, the process and the system, or function, perspective. Depending on the purpose, either perspective can be used to analyze a transformation.

4.2 Successful Innovation

As mentioned in Section 4.1, innovation is a particular instance of a transformation process. It transforms ideas to products, which are ready for the marketplace, and their corresponding manufacturing system with stable manufacturing processes. Of course, companies that make the best use of their innovation process will have an advantage against their competitors. But what makes an innovation process successful?

Cooper (2001) mean that there are two fundamental principles for successful innovation, "doing the right projects" and "doing the projects right", effectiveness and efficiency respectively. This relates to making the right decisions and act upon those decisions in the best possible way. Thus, a good innovation process model must support the organization to make the best decisions and actions in all situations.

Naturally, skilled people have the necessary prerequisites to make better decisions than less skilled people. However, independent of the level of skill, people, and machines, involved in a decision making process need information as a base for their decisions. This information need to be correct, at the right level of detail, and available at the right time (Fagerström and Moestam-Ahlström, 2001; McGrath, 1996).

Skilled people and information are, however, not enough to ensure a good decision making process. What is missing is the decision criteria, a guideline that supports the decision maker to make decisions that meet its objectives (CEN/TC310, 2002; Fagerström and Moestam-Ahlström, 2001). Note that decision criteria are part of a method that describe a structured way, for humans or machines, to create and use information for decision making.

4.3 The Innovation Process

There are different ways in which an organization can coordinate and organize its operations. The toll-gate model is an often used and successful way to structure and organize the innovation process (Cooper, 2001; McGrath, 1996).

In the toll-gate model the innovation process is divided into discrete and identifiable phases, or stages, with the purpose to gather and create information to progress to the next toll-gate. At the toll-gate the critical characteristics of the project are reviewed. These characteristics are judged against criteria to decide whether to (i) continue (go), (ii) terminate (kill), (iii) hold, or (iv) redirect the project, cf. Figure 4.4. Both Cooper (2001) and McGrath (1996) mean that the gates, in combination with well defined objectives, are one of the keys for successful product innovation.

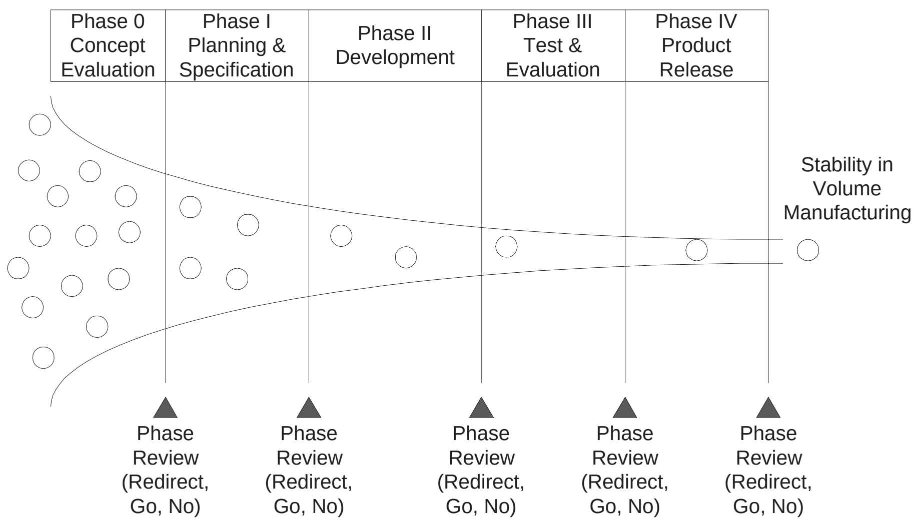

Figure 4.4. The phase review process funnel (McGrath, 1996).

The design and definition of the phases are usually specific to the particular organization or company. Pahl and Beitz (1996) have described four phases, namely (i) the clarification of task, (ii) conceptual design, (iii) embodiment design, and (iv) detail design. These phases, as described by Pahl and Beitz (1996), have a product design focus and only consider the development of the manufacturing system in peripheral.

Hitomi (1979) and Sohlenius (1998) have similar phase descriptions. The innovation process start with the develop product and production phase, continues with the process planning phase, and ends with the produce product phase. The main difference here is that Sohlenius (1998) clearly state that development of production is part of innovation, cf. Figure 4.5, and Hitomi (1979) does not. That is, the first stage of Hitomi (1979) does not include development of production, but merely define the development of a product.

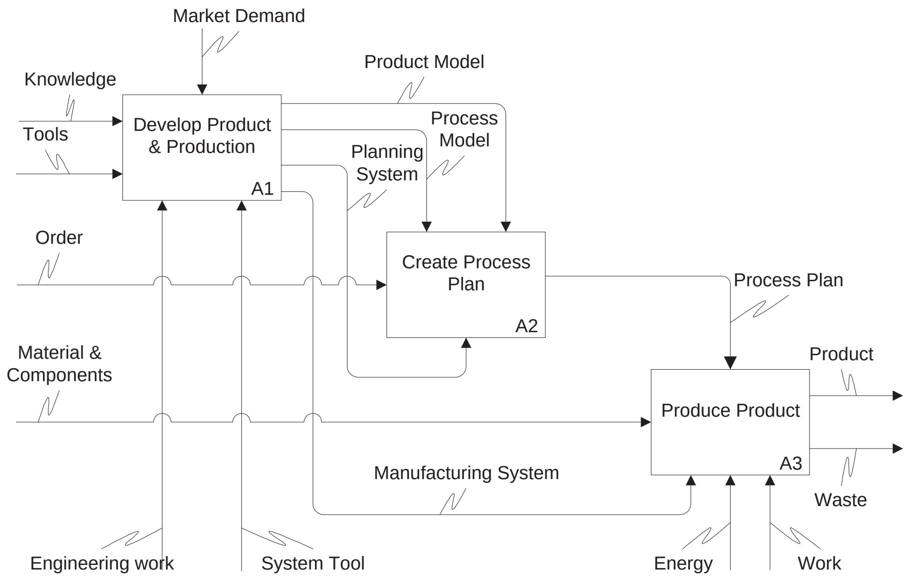

Figure 4.5. The innovation process according to Sohlenius (1998).

A more detailed description is provided by Prasad (1996) where the innovation process is divided into seven phases, (i) definition of objectives, (ii) product planning, (iii) design, (iv) production planning, (v) production, (vi) manufacturing and assembly, and (vii) delivery and service. The three first phases correspond to the first phase of Hitomi (1979) and Sohlenius (1998). The fourth phase correspond to second of Hitomi (1979) and Sohlenius (1998). The fifth and sixth phases of Prasad (1996) correspond to the third phase of Hitomi (1979) and Sohlenius (1998). The seventh phase that Prasad (1996) describe must be seen as out of the scope of the models that Hitomi (1979) and Sohlenius (1998) provide. It is also clear that service, as an activity, is out of the scope of the innovation process.

Several other also tend to describe the innovation process in similar ways, e.g. Askin and Stanridge (1993); Cooper (2001); Hubka and Eder (1988); ISO/TC184/SC4 (2001); ISO/TC184/SC5 (2002a,b); Mårtensson (2000); McGrath (1996); Pugh (1998); Ullman (1992); Ulrich and Eppinger (2000); and Wu (1992). These descriptions of the innovation process are also similar to the innovation process of several companies, e.g. Carlsberg (1997); Ericsson (2001); and Scania (1998).

In Fagerström et al. (2002) a functional view of an innovation system is presented. This view has been adapted[1] to present the activities of the innovation process, cf. Figur 4.6.

It is interesting to see that Fagerström et al. (2002) have put more emphasis on the development and realization of manufacturing systems than usual. It is clear that the development of the product and the development of the manufacturing system are interdependent, which is symbolized by the open product model and the open manufacturing system model. This interdependency between the two activities consists of constraints that are imposed by one activity on the other. Usually these two activities are carried out in collaboration involving several different organizations from different companies.

If the *Develop Manufacturing System* activity is decomposed it consists, schematically, of three activities, cf. Figure 4.7. These activities are (i) *Create Process Plan* (A21), (ii) *Create Manufacturing System Solution* (A22), and (iii) *Validate Manufacturing System Solution* (A23).

Naturally, this decomposition of activities can be argued. As this thesis main theme is manufacturing processes in the application of manufacturing system development, the choice was to include the *Create Process Plan* as a separate activity in the *Develop Manufacturing System* activity.

[1]The adaption have included changes according to comments made by SAAB Automobile and Dario Aganovic.

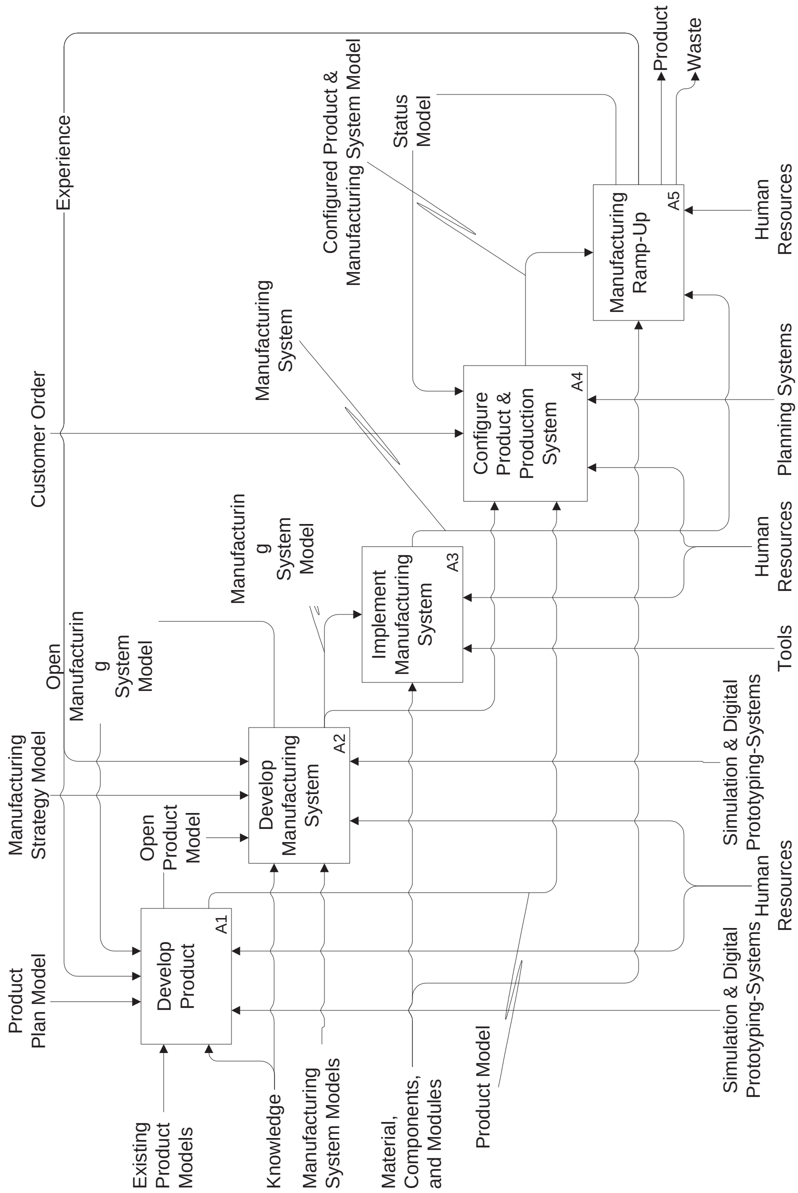

Figure 4.6. Activities in the innovation process, adapted from Fagerström et al. (2002).

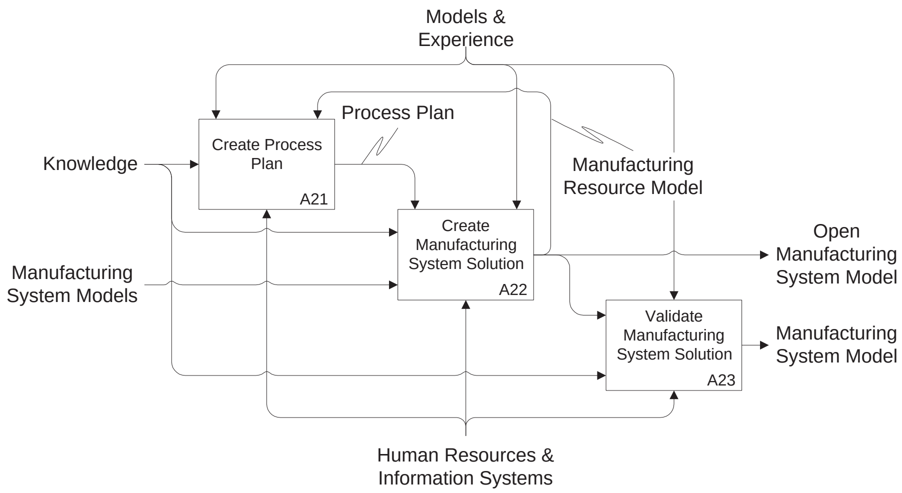

Figure 4.7. Schematic view of activities in the develop manufacturing system activity.

In addition, the *Create Process Plan* and the *Create Manufacturing System Solution* activity are thought of as being interdependent. This interdependency consists of the *process plan* and the *manufacturing resource model* that are used to control respectively process, and it indicates that the process plan and the manufacturing resources are developed concurrently. It may also be that a new product is introduced into an existing manufacturing system, i.e. that the manufacturing resource model represent the manufacturing resources that already exist in the manufacturing system. The process plan describe the plan of how to manufacture a product, including selected resources or requirements on resources, whereas the manufacturing resource model describe the available resources or resources that are being developed.

This is clearly a different view than, e.g. Hitomi (1979); McGrath (1996); and Sohlenius (1998) have. The main difference is that process planning is not considered at all, or it is considered to take place when all manufacturing resources are available. That is, the manufacturing resources only need to be selected and do not need to be developed.

4.3.1 The Create Process Plan Activity

Juran (1988) mean that a general process planning activity consists of four activities. These activities are: (i) review goals, (ii) choose process, (iii) provide facilities capable of meeting the goals, and (iv) provide methods.

First, in the *review goals* activity the goals of process planning is reviewed to understand them and their attainability. The result of the activity, Juran (1988) mean, is a set of attainable goals, which are often represented in terms of, e.g., manufacturing features, tolerances, surface finish, and materials (Azari, 1990; Eversheim et al., 1991).

Second, in the *choose process* activity the process to conduct, manufacture, the product is chosen, or designed. The result of the activity is a specification of economic and feasible processes. The specification consists of sequenced processes that are assigned to fulfill one or more attainable goals.

Third, in the *provide facilities capable of meeting the goals* activity the objective is to provide facilities, manufacturing resources, that are capable of meeting the attainable goals. This include the specification of capability requirements as well as physically providing the facilities, e.g. make or buy the facilities. The result is, naturally, the capable facilities.

Finally, in the *provide methods* activity the methods that are needed to control human resources, machine tools, and robots are developed and documented. The result of the activity is information required by the resources, e.g. machine tools and human resources, to perform the process.

The description by Juran (1988) above is a general description of a process planning activity and can be applied to explain the process planning activity as it is described by Azari (1990); Curtis (1988); Eversheim et al. (1997, 1991); Nielsen and Kjellberg (2000); and van Houten (1991), as well as the activities in Figure 4.8.

The *Prepare Product Model & Prepare Strategy* (A211) activity clearly corresponds to the more general *review goals* activity, and its attainable goals are represented in the *prepared product model*. An additional result of the activity is a *process plan strategy model*, which represent the manufacturing strategy in an applied strategy considering the goals and resources for a specific process plan. The strategy is used to control the rest of the create-process-plan activities.

The *Engineer Process Methods* (A212) and *Establish Sequence of Processes* (A213) together correspond to the *choose process* activity. The result, a specification of economic and feasible processes, is represented by the *structure of processes*.

The *Specify Resource Requirements or Select Resources* (A214) activity partly correspond to the *provide facilities* activity. The difference is that the actual development and implementation of facilities, e.g. plants and machine tools, are carried out in the *Create Manufacturing Solution* (A22) activity, cf. Figure 4.7. Instead of capable facilities, the activity result in a *preliminary process plan* that specify requirements on facilities, types of facilities, or the actual facilities.

The *Validate Process Plan & Create Control Information* (A215) activity partly correspond to the *provide methods* activity. The difference is that this activity emphasize the importance of validating the process plan before creating the control information, represented by the *process plan*.

To summarize, the process plan activity is an activity where the product requirements are interpreted and translated to manufacturing requirements. That is, the language that are used to define the design of a product is translated to the language that are used to define the manufacturing of the same product. This may be done at a macro or micro level of planning, but the principles of interpreting the product requirements and translate these to manufacturing requirements

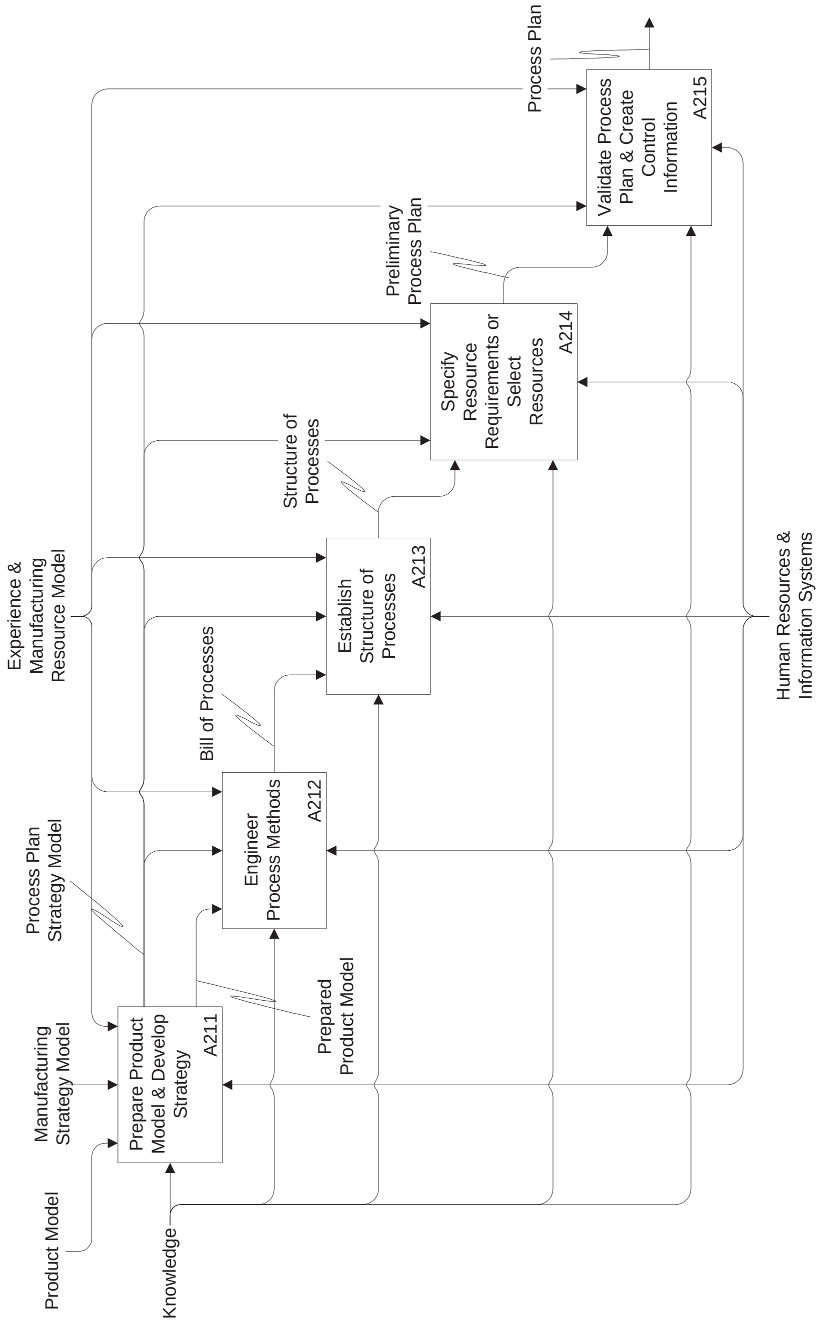

Figure 4.8. Activities in the create process plan activity.

remains.

4.4 Organization of the Activities in the Innovation Process

As mentioned in Section 4.3, the innovation process does not involve only one organization, and activities are often carried out in parallel. The degree of parallelism of the activities is, to a large extent, affected by the dependencies between the activities.

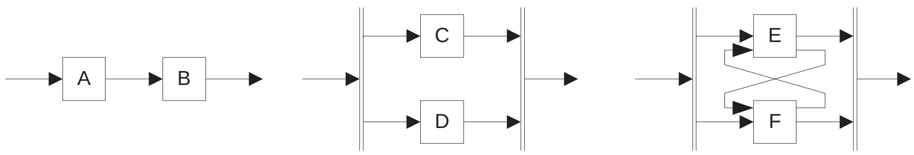

Figure 4.9. Activities in the innovation process, adapted from Eppinger et al. (1994) and Tátray (1998).

For instance, in Figure 4.9 activity *B* is dependent on the result of activity *A* and, thus, *A* must precede *B*. Activities *C* and *D*, on the other hand, have no dependency and can, thus, be carried out in parallel without any interaction. An interdependency is much more complex, activities *E* and *F* in Figure 4.9, and must be carried out incrementally. An example of an interdependency is the dependencies between the activities *Develop product* (A1) and *Develop Manufacturing System* (A2) in Figure 4.10.

In general terms, the dependency between the develop product and the develop manufacturing system activities originates from decision making. A decision making that impose constraints not only on the activity in which the decision was made, but also on the dependent activity. In Figure 4.10 the constraints are implicitly and/or explicitly represented in the *Open Product Model* and the *Open Manufacturing System Model*.

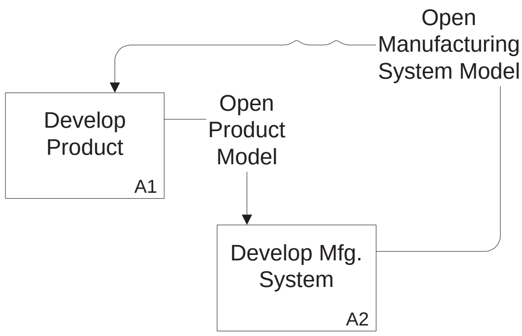

Figure 4.10. Dependencies between the *Develop Product* and *Develop manufacturing system* activities.

The more activities that are involved in an interdependency, the more complex are the information flow between the activities. For instance, if four activities are coupled, e.g. activities A, B, C, and D there will be twelve different communication paths that need to be maintained, cf. Table 4.1.

$A \rightarrow B$	$B \rightarrow A$	$C \rightarrow A$	$D \rightarrow A$
$A \rightarrow C$	$B \rightarrow C$	$C \rightarrow B$	$D \rightarrow B$
$A \rightarrow D$	$B \rightarrow D$	$C \rightarrow D$	$D \rightarrow C$

Table 4.1. Communication paths between the coupled activities A, B, C, and D (McGrath, 1996).

Typically, this intense information exchange between activities occur for activities organized according to the concurrent engineering philosophy (Fagerström et al., 2002).

4.4.1 Concurrent Engineering

The term concurrent engineering refers to simultaneously consider more than one aspect of a system during its design phase (Krause et al., 1993; Liker et al., 1995; McGrath, 1996; Sohlenius, 1992), cf. Figure 4.11. Like lean production, concurrent engineering is mainly an invention by

Toyota, who began moving to simultaneous development in the 1960s (Liker et al., 1995).

Definition 4.4. Concurrent engineering is the simultaneous consideration of more than one aspect of a system during its design phase.

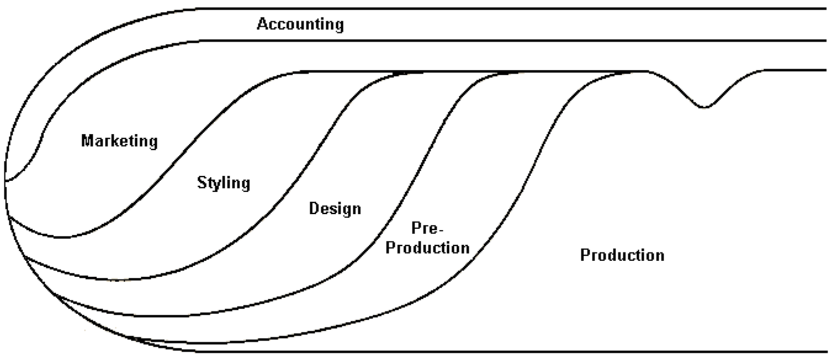

Figure 4.11. Concurrent engineering at Toyota (Liker et al., 1995).

The effect of concurrent engineering on the design of a system is decreased innovation process lead-time and increased product quality (Liker et al., 1995; Sobek et al., 1998; Sohlenius, 1992; Womack et al., 1990). The cause for the effect is that problems are identified and highlighted earlier in the design phase. These problems have a base in a conflict of interests between different objectives and functional areas (Sobek et al., 1998). The conflict is then solved by a compromise between the conflicting functional interests. An engineer at Toyota put this into words by meaning that "lots of conflict" makes a good car (Sobek et al., 1998).

4.5 Managing Information in the Innovation Process

As mentioned in Section 4.1, a key to a successful innovation process is good decision making. Good decision making is dependent on the availability of the right information at the right time. Thus, managing information is vital for the success of the innovation process.

This is especially true for an organization that have organized their innovation process according to the concurrent engineering philosophy. The reason is, as Kimura et al. (1992) describe it, that concurrent engineering implies information sharing. This view is also shared by Brunnermeier and Martin (1999) and Fagerström et al. (2002).

How then, can an effective and efficient information sharing be established? Naturally, there are different approaches to solve this problem. In Japanese automotive industry, for instance, a black-box sourcing is used for subsystem suppliers (Liker et al., 1995). This approach reduces the need for communication by specifying clear and stable interface requirements along with the subsystem requirements. Consequently, the subsystem supplier can rely on the requirements and work independently without any unnecessary communication. Thus, using a suitable method for the innovation process can minimize the need for information sharing. Nevertheless, even companies using black-box sourcing need to share information across functional boarders.

Information seems to be a common denominator that binds different organizations together. However, the different organizations usually use different terminology or have different definitions for the same terms. The difference in terminology complicates the communication process, independent of if it is between humans, computers, or a mix of the both. To overcome these difficulties common definitions need to be agreed upon. Such agreements are defined and documented in an information model, cf. Section 3.3.

4.6 Information Models in the Innovation Process

As ideas are transformed to ready-for-the-market products, information about, and rationale behind, the design of the product and its manufacturing system is created. This information must, in order to support the innovation process, represent several different aspects of the product and its manufacturing system throughout their life cycles (Kimura, 1993; Krause et al., 1993).

In addition to different aspects, the product and its manufacturing system can also be divided in three main domains of information. The three domains hold information about the product, the manufacturing process, and the manufacturing resource respectively, cf. Figure 4.12. This view is, to some extent, also shared by, e.g. Azari (1990); Eversheim et al. (1991); Eversheim and Westekemper (2001); Johansson (2001); Kulvatunyou and Wysk (2000); Onosato and Iwata (1993); Ray (1989) and Young et al. (2000). The three domains can also be identified in the structure of ISO 10303-214 (ISO/TC184/SC4, 2001) and other standards.

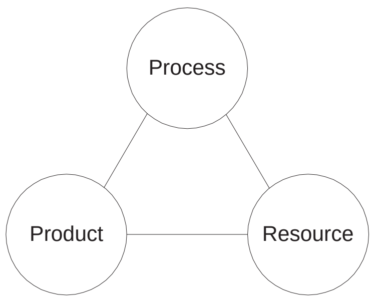

Figure 4.12. Three main domains of information: the product, the manufacturing process and the manufacturing resource domains.

On the one hand, each domain need to capture its own design information and rationale in its own information model. On the other hand, as the different domains interact, it is important that design information about, and design rationale behind, the interaction can be captured as well (Krause et al., 1993).

The interaction between the different types of models could provide a description of the products, how they should be manufactured, and what manufacturing resources that should be used. This would provide an information platform upon which several different computer based tools to support the innovation process can be built.

4.6.1 The Product Model

A product model represents all relevant information about a product throughout its life cycle (Kjellberg, 1982; Krause et al., 1993). The phrase *all relevant information* implies that the content of a product model may differ. In fact, whereas Kjellberg (1982) only include information describing the product itself in the concept of a product model, Krause et al. (1993) also include information describing how and with what resources the product is manufactured. In this thesis, the view of the former is applied.

This is done to clearly separate different types of information for easier interpretation and better understanding. Nevertheless, different organizations still consider different information about their product being of different relevance. The relevance of the information about a product depend on the scope and methods of concerned organizations.

Consequently, several different aspects in several different life cycle stages must be representable in a product model. In general the aspects range from abstract, *why*, to concrete, *how*, representations of the product, a view shared by Andreasen (1991); Krause et al. (1993); Pahl and Beitz (1996); Ross and Schoman (1977); Suh (1990); and Ulrich and Eppinger (2000). These aspects can be grouped in four main categories:

- requirements,
- functions,
- concepts, and
- concrete solutions.

In addition, Andreasen (1991); Ross and Schoman (1977); and Suh (1990) mean that a product can be described in more or less detail.

That is, each aspect may describe the product from low to high level of detailing.

How, then, does this affect the product model? It affects the product model in terms of general requirements of what type of information the product model must be able to represent, and to what detailing level. Of course, this is related to the questions the model is supposed to answer, which, in turn, is related to the scope and methods of the organization.

Different Types of Product Models

As already mentioned, in order to support different scopes and methods, different aspects of a product must be represented in a product model. These aspects can be represented in different types of product models. Krause et al. (1993) have identified an incomplete list of different types of product models:

- structure-oriented product models,
- geometry-oriented product models,
- feature-oriented product models,
- knowledge-based product models, and
- integrated product models.

Structure-oriented product models represent some aspects of a product from a product breakdown perspective Krause et al. (1993). For instance, a product can be broken down in functions and components (Hubka and Eder, 1988; Krause et al., 1993; Pahl and Beitz, 1996), in terms of, e.g. function trees, bill-of-materials, and assembly structures.

Geometry-oriented product models represent the shape of a product (Kjellberg, 1982; Krause et al., 1993). Naturally the shape of a product can be described in different ways depending on the purpose of the description. Kjellberg (1982); Krause et al. (1993); and Salomons (1995) have identified wire frame, surface, solid, and hybrid models. In addition, Kjellberg (1982) have identified graph and lamina models.

Feature-oriented product models represent a product in terms of features, cf. the next section for further discussion on feature-oriented product models.

Knowledge-based product models formally represent accumulated knowledge about a product (Krause et al., 1993). The accumulated knowledge can then be used to guide the design and constrain the design space (Holmer et al., 1990; Krause et al., 1993; McMahon and Browne, 1998). Consequently, a knowledge-based product model is used to guide and control a designer in her, or his, use of other type of product models, rather than representing some aspect of a product itself.

Integrated product models represent a product by combining different types of product models (Krause et al., 1993). An example of an integrated product model is ISO 10303-214 (STEP AP214), which combine structure-, geometry-, and feature-oriented product models (ISO/TC184/SC4, 2001).

Of course, there are additional types of models that could be considered, e.g. material-oriented product models and kinematic-oriented product models.

Feature-Oriented Product Models

As mentioned above, feature-oriented product models represent the product in terms of features. A feature, though, is defined in several different ways. The essence, however, is similar, describing a feature as something that provides engineering meaning, or application-dependent semantics, to a product.

Eversheim et al. (1991); Krause et al. (1993); and Wingård (1991) mean that a feature is a form feature, which represent a shape, in combination with application-dependent semantics. This definition introduce two aspects of a feature, the shape aspect and the application-dependent semantic aspect. That is, the application-dependent semantics provide an user-oriented view of the application-independent geometric shape (Dürr and Schramm, 1997; Nyqvist and Nielsen, 2001).

Brown et al. (1992); McMahon and Browne (1998); and Salomons (1995) extend the definition of a feature to include any information that is useful to reason about the function, behavior, performance, and manufacture of a product. In addition, they mean that this information need not necessary be associated with some shape of a product. Instead it can be associated with some other application-independent information, such as a function of a product.

Consequently, a feature consists of two parts: (i) a part that is application independent, and (ii) a part that is application dependent. This provides a strong concept where different engineering applications can share application-independent information and customize it for a particular purpose by adding application-dependent semantics.

In this thesis the following definition of a feature will be used, provided that what is perceived is represented by both an application-independent and application-dependent part:

Definition 4.5. A feature is a perceived geometric element, functional element, or property of an object useful in understanding the function, behavior, performance, or manufacture of that object.

Adapted from Brown et al. (1992)

4.6.2 The Manufacturing Process Model

A Manufacturing process model represents all relevant information about manufacturing processes throughout their life cycle. Here a manufacturing process is considered to be a process that transforms a physical object from one state to another.

Definition 4.6. A manufacturing process is a process that transforms a physical object from one state to another.

Then, what is a process? ISO/IEC/JTC1/SC7 (2001) describe a process as a set of interrelated activities that transform inputs to outputs. This is what Hitomi (1979); and Hubka and Eder (1988) call a transformation process. American Heritage (2000) and Juran (1988) add goal orientation, meaning that a process is a set of actions directed to the achievement of a goal. Here the following definition is used:

Definition 4.7. A process is a systematic series of actions directed to the achievement of a goal.

(Juran, 1988)

Consequently, a manufacturing process is a systematic series of actions directed to the achievement of a goal. In this case the goal is to transform inputs to outputs, i.e. transform raw material to finished products and subassemblies.

Kulvatunyou and Wysk (2000) mean that information necessary to describe the transformation is represented by the manufacturing process model. This include information that specify operations, resources, and skills. A view that Kulvatunyou and Wysk (2000) share with Hubka and Eder (1988); Johansson (2001); Nielsen and Kjellberg (2000); and Tönschoff and Zwick (1998).

Whereas Hubka and Eder (1988); Johansson (2001); Kulvatunyou and Wysk (2000); and Nielsen and Kjellberg (2000) clearly separates the process representation from the resource representation, Tönschoff and Zwick (1998) does not. Tönschoff and Zwick (1998) mean that the manufacturing resources are represented by the process model as well. This view is not representative for the view represented by the work of this thesis. Here there is a clear separation between product, process, and resource (PPR) data.

Nevertheless, Tönschoff and Zwick (1998) emphasize other aspects of the process model that are important. These aspects, which are also identified by Hubka and Eder (1988); Johansson (2001); Kulvatunyou and Wysk (2000); Nielsen and Kjellberg (2000); and Ray (1989), include:

- process structures - structural relationships between processes, e.g. decomposition, alternative, and parallel,
- process sequences - sequential relationships between processes, and
- process parameters - parameters and properties of processes, e.g. process time, process temperature, and feed rate.

In addition, Tönschoff and Zwick (1998) mean that this information is product independent. That is, the type of product does not change how processes are represented. Having separated the representation of products and processes, thus, makes it possible to reuse the representation of processes for many types of products. For the same reason, it is important that the representation of processes and resources are separated as well.

4.6.3 The Manufacturing Resource Model

Similar to a product model, cf. Section 4.6.1, a manufacturing resource model represents all relevant information about a manufacturing resource throughout its life cycle. The type of information is, in general, the same as for the product. Johansson (2001) mean that the same model can be used for the development of both products and manufacturing resources.

This is supported by Hubka and Eder (1988) that draw no distinction between different types of technical systems. That is, a car, which is most often seen as a product, is a technical system and so is a machine tool, which is most often seen as a resource.

However, both a car and a machine tool can be considered being both a product and a resource. If the product is not needed, i.e. is not useful (a resource) for someone, it will not be a successful product. Hence, product and resource seem to be two different viewpoints of the same object.

Usually the different viewpoints are related to the *manufacturer/vendor* of the product, and *user* of the resource. Consequently, the same object, e.g. a car, is a product from a manufacturer/vendor viewpoint and a resource from a user viewpoint.

Definition 4.8. A product is an object intended to be sold to, or leased by, a customer.

Definition 4.9. A resource is an object that is used, or consumed, to fulfill some need of the user.

Hence, for the purpose of manufacturing, categories of resources include material, equipment, humans, and information. A view that, to some extent, is shared with Hubka and Eder (1988); Kulvatunyou and Wysk (2000); and Ray (1989).

To conclude this reasoning, in this thesis only one model will be considered to represent information about both products and manufacturing respurces. That is, the product model, cf. Section 4.6.1.

However, as different types of information is considered important in the different views, the information that is important in the resource view will be elaborated further here.

In contrast to the product view information that are used to support decisions concerning the development and realization of an object, the resource view information is used to support decisions concerning the operation and support of the object, e.g. capabilities, performance, operative expenses, and costs of maintenance.

In addition, the hierarchical nature of a manufacturing system is often represented in structures with particular naming conventions for each level of the hierarchy. Formalized manufacturing system structure models are provided by the National Institute of Standards and Technology (NIST) and the International Organization of Standardization (ISO) respectively, cf. Figure 4.13. Both these models can be used to classify and structure the manufacturing resource model (Johansson, 2001).

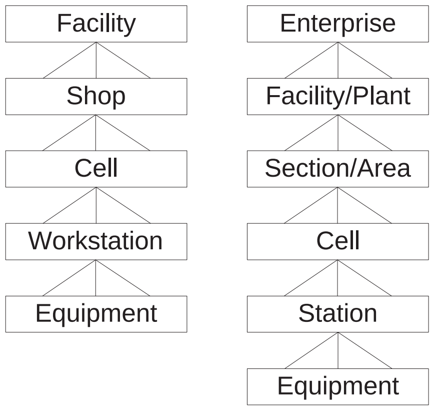

Figure 4.13. The NIST-model, left, and the ISO-model, right, (Bauer et al., 1991).

Capability Representation

American Heritage (2000) mean that capability is the quality of being capable. Similarly, Bergman and Klefsjö (1998); and Curtis (1988) mean that capability is the ability of a machine, or process, to repeat and hold tolerances. The three can be summarized by Juran (1988) who define capability as the inherent ability to perform. Hence, the following definition is used:

Definition 4.10. Capability is the inherent ability to deliver performance.

Adapted from Juran (1988)

Notable is that inherent ability to deliver performance indicate that there is a difference between capability and performance. Juran (1988) mean that the difference is that capability is what something could do whereas performance is what something did do. Naturally, the performance of, e.g., a machine tool depend on such things as operator, variance in air temperature, variance in material properties of workpiece, and tool that is used.

There are usually two types of capability discussed in literature, process and machine capability. Sometimes they refer to different capabilities and sometimes they refer to the same. The confusion certainly stem from a careless use, or misunderstanding, of the term *process* for both manufacturing processes and manufacturing resources. For instance, Bergman and Klefsjö (1998); and Juran and Gryna (1988) do make a difference between process and machine capability whereas Curtis (1988) does not.

Bergman and Klefsjö (1998); and Juran and Gryna (1988) mean that process capability refers to the ability to perform over a long period of time considering normal changes in workers, materials, and other process conditions. Machine capability, on the other hand, is defined by Bergman and Klefsjö (1998); and Juran and Gryna (1988) as the ability to perform considering one set of process conditions, e.g. one operator and no changes in material properties.

Definition 4.11. Machine capability refers to the reproducibility under one set of process conditions.

(Juran and Gryna, 1988)

Definition 4.12. Process capability refers to the reproducibility over a long period of time with normal changes in workers, material, and other process conditions.

(Juran and Gryna, 1988)

Although agreeing with the differentiation of machine and process capability, for the purpose of this thesis the process is not considered to have any capability itself, cf. Figure 4.14. It is the resources that are used to carry out the process that have capabilities to perform the process and achieve the goals that are set. In addition, the method that are used to control how the process is carried out is also considered to have capabilities.

Usually, capability is represented in mathematical and numerical models (Kulvatunyou and Wysk, 2000). The mathematical representation

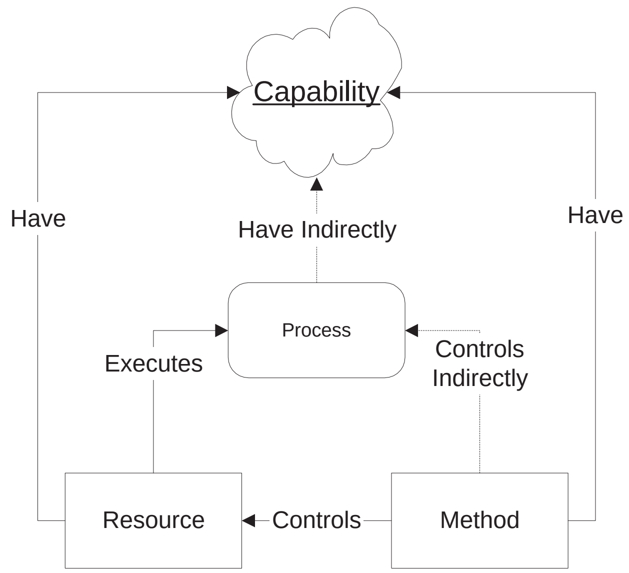

Figure 4.14. The process capability is determined by the executing resources and the method that controls the execution.

is often in terms of 6 σ, or six standard deviations (Juran, 1988), but can also be represented by other mathematical models such as the loss function (Taguchi et al., 1989). Several other capability representations, both mathematical and non mathematical, have been identified by Algeo (1994), e.g. machine tool capability model by Gindy and Ratchev (1992).

However, the mathematical and numerical models does not say if a manufacturing resource is able to make, e.g., a particular shape or a particular joint. A process engineer has to select manufacturing resources both on the assumption on what they can perform, e.g. a hole, and how well they can perform, e.g. in terms of 6 σ. This could be considered to be a higher level of capability representation related to shape and functional aspects of the manufacturing resource capability, and would support the process engineer in the selection process.

In addition, and perhaps more important, it would also provide a mean for early feedback on how to make the detailed design of a product. For instance, in the early phase of product development it might only be decided that there is a need for a joint with some characteristics on strength, surface finish, and so on. When manufacturing resources with the capability of joining are considered, aspects of detailed design, such as the shape aspect affect of clinching or spot welding, is highlighted and can easily be considered as well, cf. Figure 4.15.

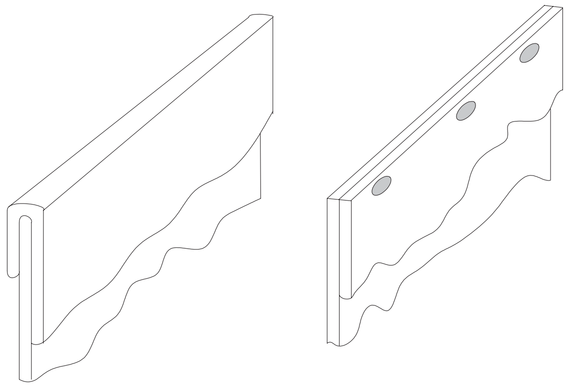

Figure 4.15. The detailed design of a product will be affected differently when using clinching and spot welding.

Chapter 5

Information Requirements for Process Planning

The purpose of this chapter is to present and discuss requirements for a process model that support the create process plan activity, cf. Section 4.3.1. The requirements have been identified in case studies at Volvo Car Corporation, cf. Appendix C, ABB Body-in-White (ABB BiW), cf. Appendix D, and Scania. and literature studies, e.g. Al-Timimi and MacKrell (1996); Andreasen (1991); Boothroyd et al. (2002); Hubka and Eder (1988); ISO/TC184/SC4 (1996, 2000, 2001); Slack et al. (1998); Suh (2000); and Wu (1992).

5.1 Hypotheses

Several different process information models exists today, including international standards, standards under development, company specific models, and computer application specific models. They all claim to have different scopes and intention to justify their individual existence, and, indeed, many have different scope and intention. However, there are several components that are similar between the different process information models.

The similarities between the models are, in general, the way products and manufacturing resources are related to processes, cf. Figure 4.3. That is, products are seen as inputs and outputs of processes, and manufacturing resources are seen as executers of the processes. In addition, the way process objects are related to other process objects are similar, i.e. there is also a similarity in the process plan structure. Hence, it seems that there are generic information concepts that are common between the different process models and that there are specific information concepts that are not.

A generic information concept is an information concept that are generic within the scope of the information model whereas a specific information concept add specific meaning within the scope of the information model. For instance, the term *turning process*, which is commonly used in information models for process planning, references two information concepts, the concept for turning and the concept for process. The turning concept is a specific information concept because it adds specific meaning to the generic information concept of a process, in this case which type of process it is.

The reasoning about the generic and specific information concepts came from an idea of how to develop information models that will not be obsolete as soon as, e.g. a new type of process is developed or if not all types of processes where though of when developing the model. The idea is to use the generic information concepts as the building blocks to create an information model that can remain stable over time. The specific information concepts add specific semantical meaning to the generic information concepts. Whereas the domain and structure of the generic information concepts are to be stable the domain and structure of specific semantical concepts may vary.

The specific semantical meaning to a generic information concept is then set when an information model is instantiated. If a turning process, for instance, are to be represented in an instantiated process information model then the representation of the generic information concept for a process is used and added to this generic information concept is the specific information concept for turning, which define in the instantiated model that it is a turning process. The same generic information concepts would be used to represent a milling process and the specific information concept for milling would define that it is a milling process. Naturally, the information concepts for representing a specific information concepts is a generic information concept.

This idea have resulted in the following hypothesis:

Hypothesis 5.1. *Any information model is, within the scope of its generic information concepts, made independent of the information it represents by (i) separating generic and specific information concepts, and (ii) provide generic information concepts for defining specific information concepts.*

This is thought of to affect the longevity of any information model positively. Are there complementary ways to increase the longevity? Thinking about this question ended in thoughts about product modularization.

In product modularization there are a number of module drivers that have been identified by, e.g., Erixon (1998). Some of these module drivers are *carry over*, functional separation, technology development, variety, and quality. Companies want to carry over developed modules between existing product families and to the next generation, they may plan to introduce new technology in to an existing product family, and so on.

In fact, these module drivers, and the reasons behind them, seem relevant for information modeling too. For instance, if an organization change their information requirements for information about employees then only that module of the information model must be changed. Consequently, only that part of the information system must change too. Different departments of the organization may share information modules, but may also have specific information modules for their specific needs.

This idea of modularization have resulted in the following hypothesis:

Hypothesis 5.2. *Modularization will have the same effect on information models as on products.*

This effect is reuse of information concepts, i.e. carry over, possibility to update information concepts without effecting other information concepts, i.e. technology development and functional separation, and quality, e.g. that the different information-concepts modules can be tested separately.

5.2 The PPR Information Model

The two hypotheses, Hypothesis 5.1 and Hypothesis 5.2 have been the base for the development of the information model in this thesis, the product-process-resource (PPR) information model. In Figure 5.1 is a schematic illustration of the (PPR) information model that consist of three modules, the product module, the process plan core model module, and the manufacturing resource module.

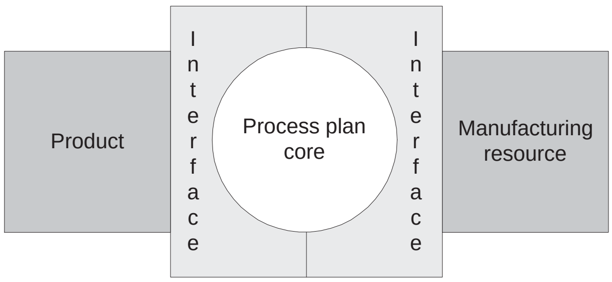

Figure 5.1. The product-process-resource information model with its process plan core.

The purpose of the process plan core model is to represent information that describe the process structure independent of any other information, e.g. product information, manufacturing resource information, documents, and properties. This is the generic information concepts related to process planning. The differences between different types of process plans, e.g. macro and micro, and different types of processes, e.g. spot welding and turning, are defined by the information that are related to the process plan core model. Naturally, the interfaces in Figure 5.1 can be extended to include interfaces for external reference data libraries, document information, property information, etcetera.

5.3 Requirements on Process Plan Core Model

The main purpose of the process plan core model is to represent information that solely describe processes and their structure for process planning purposes. This include information to identify the manufacturing process necessary to manufacture a particular product, how these processes are structured and how they are defined.

5.3.1 Representation of Process Plan

Perhaps the most basic requirement on a process model is the ability to identify a set of processes that describe how a particular product is, or should be, manufactured. The structured set of processes will here be called a *process plan*, cf. Figure 5.2.

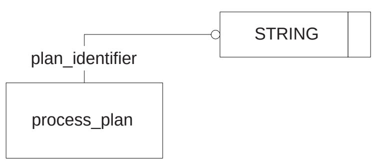

Figure 5.2. The representation of a process plan.

A *process plan* have a unique identity which distinguish it from other process plans. This is represented by the *plan identifier* attribute in Figure 5.2.

In addition, a *process plan* may have relationships to other process plans. Typically these relationships indicate that a *process plan* may be used as an alternative for another, or that a *process plan* is substituted by another.

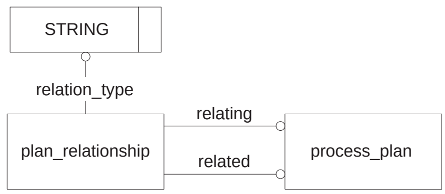

Figure 5.3. The representation of a process plan relationship.

Figure 5.3 show how a relationship between two *process plan* objects is represented. The attribute *relation type* specify the type of relationship between two *process plan* objects, i.e. *alternative* and *substitution*. The *related* specifies the *process plan* that are used as an alternative or is a substitute for the *process plan* specified by the *relating*.

Naturally, a *process plan* also have a relationship to the product, which manufacturing processes the *process plan* identify. However, this relationship is not part of the process plan core model and will be discussed in Section 5.4.15.

5.3.2 Representation of Process Plan Version

The rationale behind the requirement for a process plan version is that of keeping track of changes to a process plan. Although it is not the only way to keep track of changes it is the most commonly used and the process plan version mechanism, cf. Figure 5.4, may be used with other ways to keep track of changes, e.g. by effectivity.

Figure 5.4 show the representation of a *process plan version* and its relation to a *process plan*. Each *process plan version* must be associated with a particular *process plan*, the *associated plan* relation. The inverse (INV) *associated version* relation indicates that a *process plan* may not exist without having at least one version specifying it as the associated

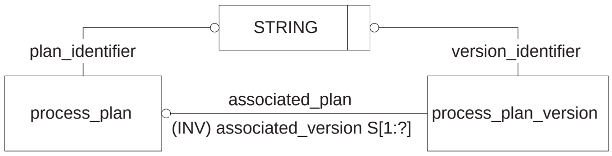

Figure 5.4. The representation of a process plan and its version.

plan. Furthermore, the unique identification of a particular *process plan version* is maintained by the use of the attribute *version identifier*.

In order to relate a *process plan version* to its successor and alternatives the process plan version relationship mechanism in Figure 5.5 was added. The mechanism has a similar functionality as the process plan relationship mechanism. That is, the semantical meaning of the relationship is defined by the attribute *relation type*, and the *related* specifies the predecessor version of the *relating* version.

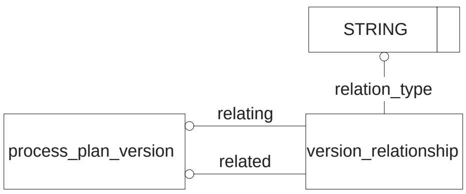

Figure 5.5. The representation of a process plan version relationship.

Typically, the attribute *relation type* can take the values *sequence* and *alternative*. The value *sequence* indicate that the related version is the successor of the relating version, whereas the value *alternative* indicate that the related version may be used as an alternative for the relating version. In addition, the values *derivation* and *hierarchy* may also be used. The value *derivation* implies that the related version is based on the relating version. The value *hierarchy* is used to indicate a hierarchy between versions, e.g. the relationship between *version 1* and its revision, *revision 1.1*.

5.3.3 Representation of Processes in a Process Plan

To be useful, a set of processes must be identifiable. The identification of a set of processes is provided, as mentioned, by the process plan mechanism. Each *process*, in a particular set of processes, identify a particular version of a particular *process plan* to which all processes in the set belong, cf. Figure 5.6.

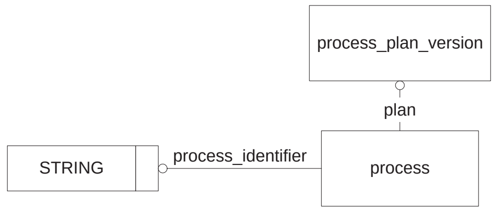

Figure 5.6. The representation of a process in a process plan version.

The *plan* attribute identify the particular *process plan version* to which the *process* belong. Each *process* also have its own identification represented by the attribute *process identifier*.

5.3.4 Reuse of Processes in Process Plans

An important requirement for a process model is the ability to reuse the definition of a process at different places in a process plan or in different process plans. There are at least two aspects of the reuse of the definition of a process.

First, library of available processes can be used to control the design of a product. That is, by defining a set of standardized processes, a company may use these definitions to decide if a particular product feature is possible to manufacture in the existing manufacturing system.

Second, manufacturing companies with many manufacturing sites may develop a generalized process plan that describe how a particular product should be manufactured, e.g. in terms of process sequence, and manufacturing resources. If the definition of a process can be reused the generalized process plan may be adapted to fit a particular manufacturing site without creating a new definition.

The ability to reuse the definition of a process in a process plan is provided by separating the process and its definition in the process core model. A process is, thus, represented by a non reusable chunk of information, the *process*, and a reusable chunk of information, the *process definition*, cf. Figure 5.7. The process and its definition together provide the information for a particular process in a particular process plan.

Figure 5.7. The representation of a process definition in a process plan.

Figure 5.8 show information related to a *process definition*. The attribute *definition identifier* represents the identifier of a particular *process definition*. In addition, the type, i.e. class, of process that is defined is also important information to represent. In fact, so important that each process definition must have a classification associated with it. However, this information has not been considered to be in the process core model and, thus, it will not be discussed here but in Section 5.4.3.

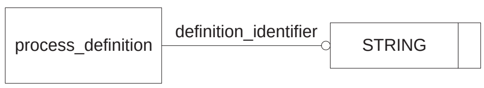

Figure 5.8. The representation of a process definition.

Finally, the process relationship mechanism to relate two different process definitions, cf. Figure 5.9. The attribute *relation type* define the semantical meaning of the relationship. An example of such a relationship is the *substitution*, where the *relating* definition is substituted by the *related* definition.

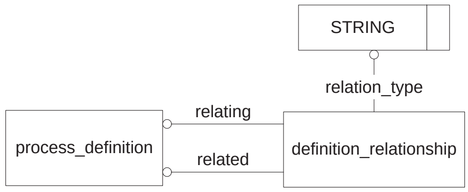

Figure 5.9. The representation of a process definition relationship.

5.3.5 Representation of Process Sequence

The most common relationship between two processes is the sequence relationship. A sequence relationship define that a process is executed before or after another. Figure 5.10 show the *process relationship* that provides a mechanism to relate processes in sequence.

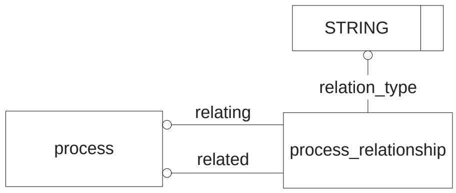

Figure 5.10. The representation of process sequences.

The attribute *relation type* should have the value *sequence* to define the correct semantical meaning of the relationship. The semantical meaning of the relationship is, then, that the *related process* is a successor of the *relating process*. Naturally, two processes in a sequence relationship may not have an overlap in their time of execution. That is, a process may not start until the execution of the predecessor has ended.

5.3.6 Representation of Process Hierarchy

Another common relationship is the decomposition relationship. This is used when a more detailed description of a process is necessary, e.g. when a process is decomposed to describe each sub-process for a particular machine tool. Often a decomposition of a process is called operation, a decomposition of an operation is called task and so on. However, here they are all considered as a process at different levels of detail.

Figure 5.10 show the representation of a *process relationship*. The attribute *relation type* should have the value *decomposition* to define the correct semantical meaning of the relationship. The meaning of a decomposition relationship is that the *related process* is a decomposition of the *relating process*. As such, the *related process* provides more detailed information than the *relating process*, e.g. in terms of product realization information.

5.3.7 Representation of Alternative Processes

Yet another common process relationship is the alternative relationship. An alternative relationship specify that a process may be used as an alternative for another process. The process plan core model make use of the *process relationship* in Figure 5.10 to represent an alternative relationship.

The attribute *relation type* should have the value *alternative* to define the correct semantical meaning of the relationship. This, then, define that the *related process* may be used as an alternative for the *relating process*.

Notable is that two alternative processes may not have a common *process definition*. The meaning of processes that have a common process definition is that these processes are the same and, thus, not alternate processes. In the case where two alternative processes have a common process definition it should be interpreted as being alternative resources instead. This may be controlled by the following rules:

1. two alternative processes may not have a common definition, unless
2. the two processes are executed by different resources.

Thus, the alternative relationship can be used to define alternative processes, different process definitions, and alternative resources, common process definition but different resources. See Section 5.4.21 for a discussion on alternative resources.

5.3.8 Representation of Arbitrary Ordered Processes

A not so common relationship between two processes are the arbitrary order relationship. The meaning of such a relationship is that the order of execution of the processes does not matter. That is, either one of them may be executed first. The only restriction is that they may not have an overlap in their time of execution.

Even though the relationship is not used as often as a sequence relationship it could still be useful when it is necessary to define the processes needed to manufacture a product, but not their order of execution. The decisions about the order may then be left until later when more information is available. For instance, during production planning, or even at the time of the execution.

Arbitrary ordered processes are grouped together by the process grouping mechanism in Figure 5.11.

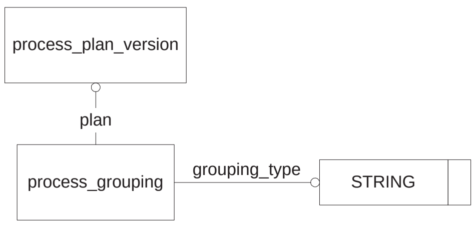

Figure 5.11. The representation of a group of processes.

The attribute *grouping type* should have the value *arbitrary order* to define the correct semantical meaning of the grouping. With an *arbitrary order* value the meaning is that the processes belonging to the *process group*, i.e. the processes that are associated to the *process group* with a decomposition relationship, may be executed in any order.

5.3.9 Representation of Parallel Processes

In a similar way as arbitrary ordered processes, parallel process are also a set of processes grouped together to define that they are executed in parallel. Hence, a major difference is that while arbitrary ordered processes may not have an overlap in their time of execution, parallel processes not only may have but must have an overlap in their time of execution.

The process grouping mechanism in Figure 5.11 represent a grouping of parallel processes. The attribute *relation type* must have a value of *parallel* to define the correct semantical meaning of the grouping, which is that the processes specified by the *processes* are, or should be, executed in parallel.

5.3.10 Representation of Process Grouping Relationship

There is no significant difference between an ordinary process and a group of processes when it comes to relationship to other processes, including groups of processes. Consequently, a process grouping must in a similar way have the ability to be related with other processes in terms of sequence, decomposition, and alternative relationships.

Figure 5.12 show a mechanism that provide the ability to relate a process object with another process object. Since the *process object* entity itself is abstract it can only exist in terms of its subtypes, i.e. in terms of a process or a process grouping. Hence, a process structure can be created containing any number or variants of process and process grouping objects.

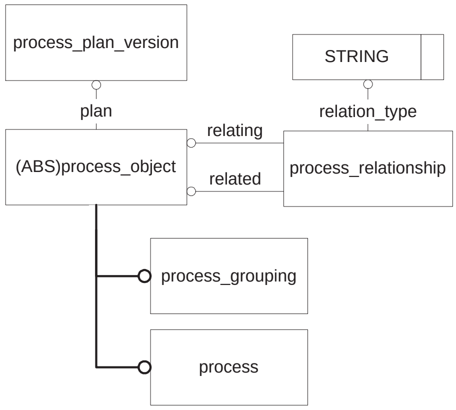

Figure 5.12. The representation of process object relationship.

The semantical meaning of the process relationship is, as usual, defined by the attribute *relation type*. Applicable values for the *relation type* attribute are: (i) alternative, (ii) decomposition, and (iii) sequence. The *relating* and *related* have the same semantical meaning as described in Section 5.3.5 to Section 5.3.7.

However, the meaning of the relationship is, perhaps, easier to interpret if another construct is used. Figure 5.13 show the complex process and process constituent mechanism. Here it is obvious that *process grouping* as well as *process* are types of both *complex process* and *process constituent*, meaning that they can be specified by the *relating* as well as the *related.*

5.4 Requirements on Outer Part of the PPR Information Model

The purpose of the outer part of the PPR information model is to represent information that can be used to define and describe, or are related to, processes, but could not fulfill the requirements for information represented in the process plan core model.

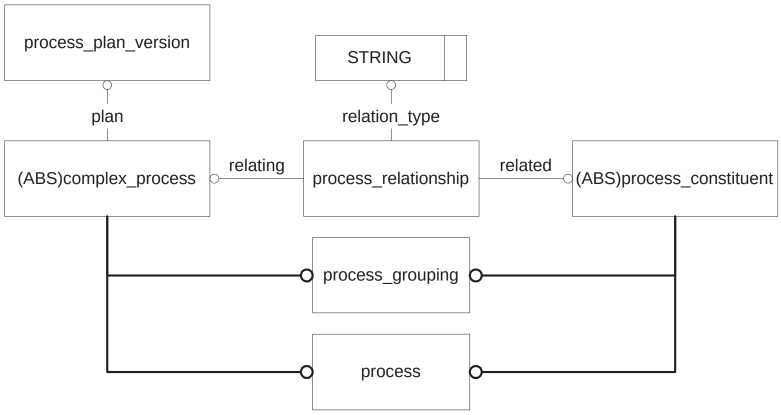

Figure 5.13. A mechanism to represent process structures.

Therefore this information have been separated by adding an interface model that separates the representation of non core information from the representation of core information.

An example of a mechanism in the interface model that relates core information with non core information is presented in Figure 5.14. This shows how a process is related with non core information, e.g. information defining a product in terms of input to a process.

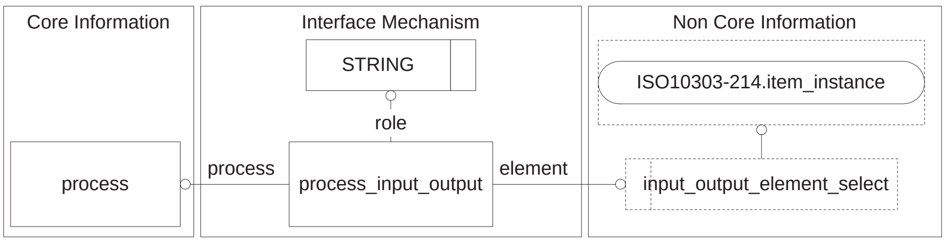

Figure 5.14. An example of an interface mechanism relating core information with non core information.

Similar interface mechanisms will be used to relate core information with other non core information, e.g. classification, document, and organization.

5.4.1 Representation of Process Definition Attribute

The purpose of using a process definition is to define a process. Not only need a process definition provide a classification for a process, cf. Section 5.4.3, it must also define the properties that characterizes a process and the values that are allowed for those properties. Such a mechanism is presented in Figure 5.15.

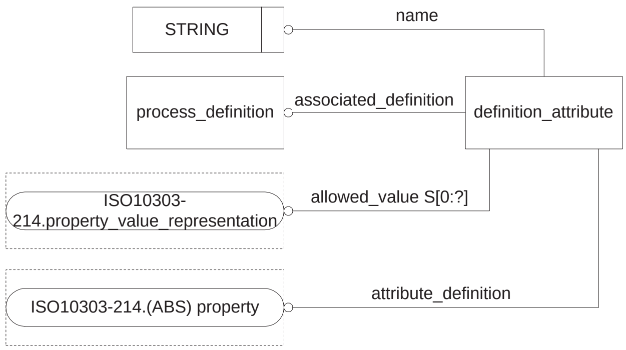

Figure 5.15. Representation of process definition attribute.

The semantical meaning of the mechanism in Figure 5.15 is that a *process* must have a minimum set of properties according to the set of *definition attributes* associated with the definition. That is, if a *process definition* have a *definition attribute* named *cycle time* associated with it, then the *process* must have a property called *cycle time* associated with it as well. In addition, the property must be defined according to the *definition attribute* and must be assigned values that do not contradict the allowed values of the *definition attribute*.

5.4.2 Representation of Process Property

An important aspect of a process model is its ability to represent process properties, such as cycle time, feed rates, and costs. Typically, properties are associated with a single process or a set of processes.

Figure 5.16 show the representation of a property and the association of it to a process element. Typical process properties are, e.g., cycle time and feed rates.

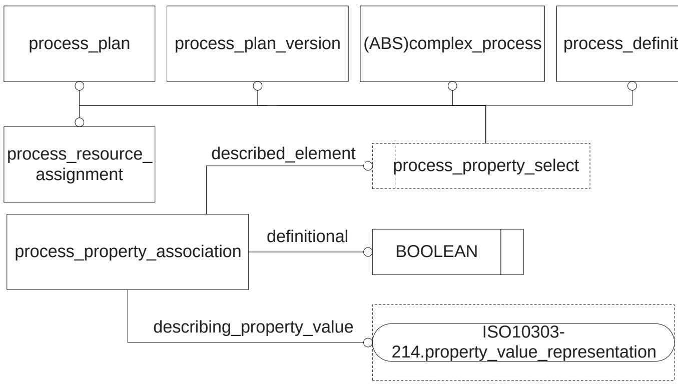

Figure 5.16. The representation of process properties.

The *process property association* is used to associate a process related element with a property. If the *definitional* is assigned a value of *true* then the property define the process related element. Definitional properties may be used to distinguish process related elements of the same kind from each other.

The semantical meaning of an associated property depend on the process related element it is assigned to. For instance, if a mean time between failure property is assigned to a process, it means that all manufacturing resources that are used to carry out the process have the same mean time between failure. On the other hand, if the same property is assigned to one of the manufacturing resource it means that the particular manufacturing resource have the same mean time between failure in all processes it carries out. A better solution, thus, is to assigned a mean time between failure property on the process resource assignment object, which would indicate that the particular property is dependent on the combination of process and manufacturing resource.

5.4.3 Representation of Process Classification

As mentioned above, the classification of a process is so important that each process definition must have a classification associated with it. Naturally, the classification may differ between different organizations. Hence, a classification mechanism must be able to represent all types of classifications.

Figure 5.17 show how a classification is associated to a *process definition*. The actual representation of the classification is provided by the general classification mechanism in ISO10303-214 (ISO/TC184/SC4, 2001).

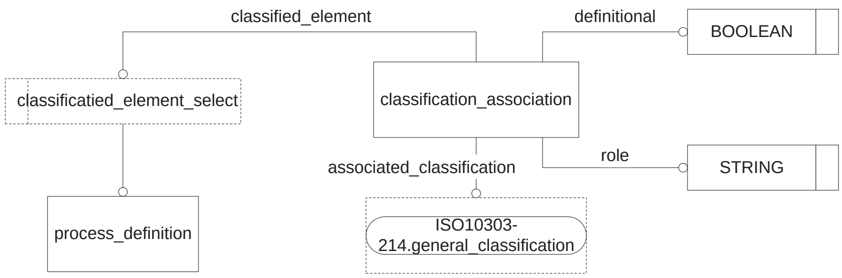

Figure 5.17. The representation of process classification.

The use of the classification system may be to represent definitional classifications and non definitional classifications. The former concern classifications that define particular process definitions whereas the latter concern classifications that add useful classification information to a process definition.

A definitional classification may define, e.g., the type of process, what the process is capable of doing, and its capability requirements on manufacturing resources. For instance, the classification system may be used to classify the basic process definitions in a process library, e.g. in terms of basic shapes they remove. These basic process definitions define the available basic shapes that can be made at the manufacturing sites of a company. Thus, it helps controlling the product development process in terms of available shape solutions.

In addition, the basic process definitions may be used to generate control programs for, e.g., CNC-machines. The interpretation of a basic process definition, and combinations of basic process definitions in a process plan, to generate control programs may be implemented in a rule based system. In combination with parameterized and feature based product models, the basic process definitions would provide a powerful base for on-the-fly generation of control programs for manufacturing of customizable product parts.

Even though the reasoning above is on process definitions for removal processes it may as well be used for other types of processes. For a weld process the removal shapes cannot be used. However, the shape of the joint and/or weld seam may be part of the classification. Other parts of a definitional classification of a weld process may be surface finish of the welded area and/or restrictions in current.

Nevertheless, the classification mechanism provides the means to choose the most suitable process definitions to manufacture the product. It may also be used to understand what process definitions that are available in the existing manufacturing system and adapt the product design accordingly.

5.4.4 Representation of Capability

In Section 4.6.3 capability and its use were discussed. There it was also stated that the process itself did not directly provide capability. Instead the capability is provided by the manufacturing resources. Nevertheless, there is an implicit relationship between a process and a manufacturing resource via the capability. The manufacturing resource provides the capability, which the process requires, cf. Figure 5.18.

The required capability is represented by the *product function*[1], cf. Section 5.4.13, and the *capability*. A *process*, or a *process definition*, is related to a *product function* via the *process function association*

[1]Here the product function represents a requirement on a manufacturing resource.

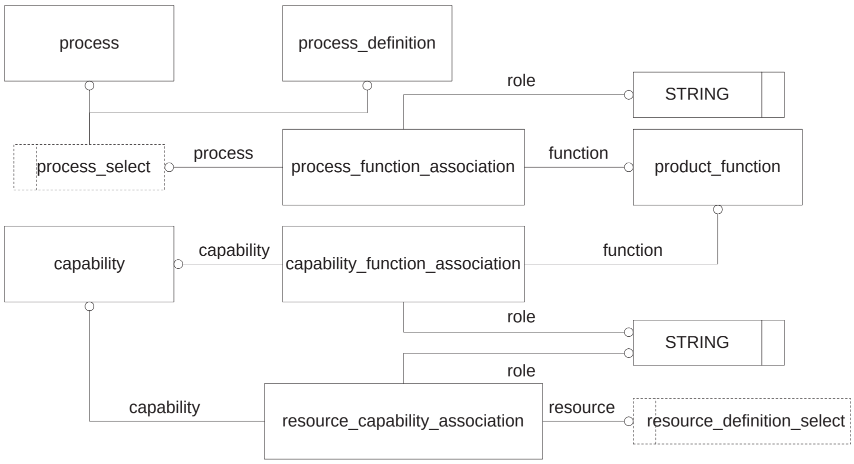

Figure 5.18. The representation of relationships between capability and requirer or provider of capability.

with the value *required* assigned to the *role* attribute. The semantical meaning of this is that the origin of the functional requirement on the manufacturing resource is required by the *process*, or the *process definition*.

The *product function* itself is, in this case, defined by the *capability*, which is related to the *product function* by the *capability function association*. That it is a definition relationship is defined by the *role* attribute by assigning a value of *definition*.

The provided capability is distinguished from the required capability by relating it to the manufacturing resource via the *resource capability association*. The semantical meaning of provided capability is defined by assigning a value of *provided* to the *role* attribute. The entities representing manufacturing resources will be discussed in Section 5.4.20.

Figure 5.19 show the actual mechanism for representing capability. In the center is the entity that represents the capability. The definition of a capability is provided by an external reference data library mechanism, e.g. P-lib and Epistle (ISO/TC184/SC4/WG3, 1999). Hence, the actual definition is represented externally.

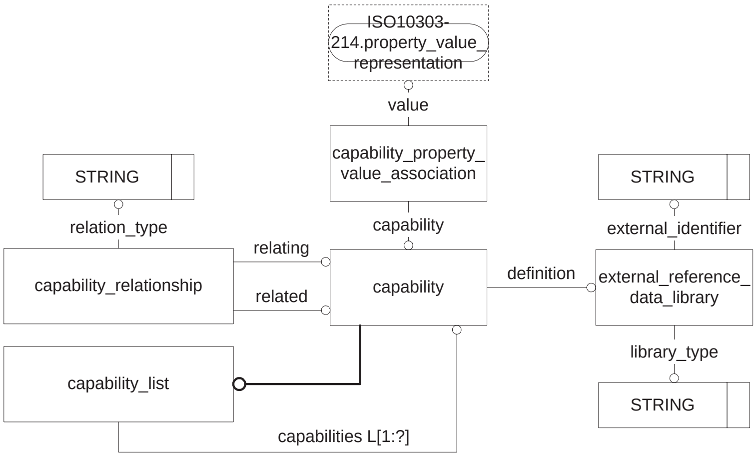

Figure 5.19. The representation of capability.

Besides the main entities the *capability relationship* and *capability property value association* also are part of the capability mechanism. The former is used to relate two capabilities with each other and the latter is used to relate different properties to a capability.

The semantical meaning of a relationship between two capabilities is defined by the *relation type* attribute. The possible attribute values are: (i) *decomposition*, (ii) *dependency*, (iii) *equivalence*, and (iv) *substitution*.

The advantage of using a reference data library is that such an mechanism provides an open environment for defining concepts without changing anything in the information model. That is, the reference data library enables the definition of concepts that can be referenced from an instantiated information model. Hence, enabling the use of different terminology in different organizations for the same concept. Anyone who needs to know the definition of a capability may access it from the reference data library by using the *external identifier* and *library type*. Hence, the structure and basic semantics of the model can remain the same whereas the specific semantics of a particular, e.g., capability may be updated.

For further reading on reference data libraries the reader is kindly asked to await the forthcoming doctor's thesis by Olof Nyqvist at the Kungliga Tekniska Högskolan, department of Computer Systems for Design and Manufacturing. The thesis is planned to be finished in 2004.

5.4.5 Representation of Process Condition

The ability to have a condition on sequential relationship between processes is a not so often occurring requirement. However, it is a way to control the execution of processes until a particular condition is fulfilled, e.g. a process may not be executed until a particular period of time have elapsed since a painting process was finished, and may be useful for production planning purposes.

Figure 5.20 show the mechanism to represent conditions to control the flow of processes.

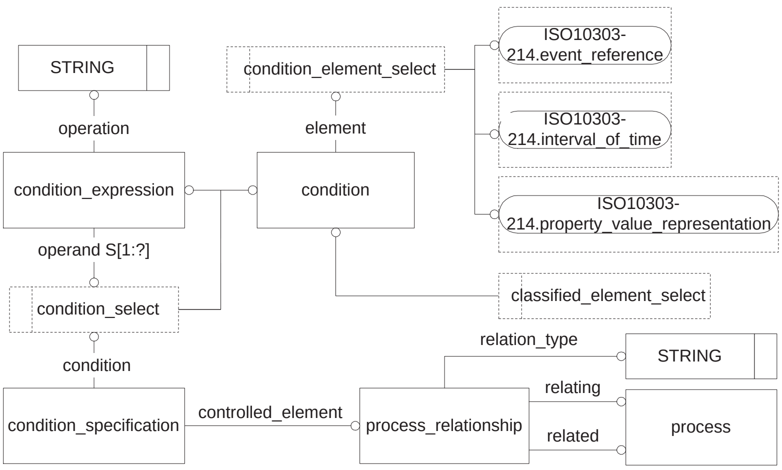

Figure 5.20. The representation of a process condition.

The main functionality of the condition mechanism is the *condition specification*. It provides the mean to control the relationship between two processes, if the *relation type* of a process relationship has been assigned the value of *alternative*, *sequence*, or *substitution*. A condition specification assigned to a process relationship must evaluate to true before the related process may be executed.

A *condition specification* specify a *condition* or a *condition expression*. The *condition* is the representation of the actual condition that must be fulfilled, whereas a *condition expression* represents an expression of conditions, e.g. that condition A, B, and not C $(and(A, B, not(C)))$ must be fulfilled.

The semantics of a *condition expression* is defined by the *operation*. The *operation* may be assigned the values *and*, *or*, *xor*, and *not*. An *and*-operation defines that the conditions and/or condition expressions specified by the *operand* all must be fulfilled. An *or*-operation defines that at least one of the conditions and/or condition expressions specified by the *operand* must be fulfilled, whereas in contrast, a *xor*-operation defines that one, and only one, must be fulfilled. Lastly, a *not*-operation defines the inversion of the Boolean value of its operand, which may be only one.

Each condition use the ISO10303-214 mechanisms event reference, interval of time, and property value representation to represent the value of the condition. In addition, each condition may be classified with the general classification mechanism, cf. Section 5.4.3.

5.4.6 Representation of Configuration Control of Process Structures

Most manufacturing companies today have highly customizable products. Many companies do not consider a variant of a product to be a different product with different identification. They control the product variants by configuration mechanisms in their information systems.

However, depending on the configuration of the product the manufacturing of it will differ, i.e. process plans for variants of the product will differ. Consequently, the number of process plans for a product will be, at least, the same as the number of variants of the product.

The variant process plans will, to a great extent, have common process definitions, sequence, properties and so on.

If instead one process plan was used, a lot of work could be reduced. That is, work such as creating the same process plan information again and again, and work of updating every single process plan whenever a change need to be made that affect the common parts.

Not only does this type of work consume time directly, it also consumes time due to its error prone nature. Humans tend to make errors in this type of repetitive work. Each error may affect the quality of the final product, resulting in time consuming activities tracing the source of the error and then correcting the error. All while an unsatisfied customer waits for her, or his, high quality product.

If instead the configuration specification of the product could be reused to configure the process plan as well. Then the variants of a product would be manufactured according to the variants of the same process plan. Any changes would be made to the same process plan and, thus affect all the variants of the processes. Not only would the initial work of making the change consume less resources, the potential risk of having product variants manufactured according to an old process plan is eliminated.

Figure 5.21 show how the model make use of the configuration mechanism in ISO10303-214 (ISO/TC184/SC4, 2001) to configure process plans, process plan versions, complex processes, and a manufacturing resources.

In principle, the configuration will state which *complex process*, i.e. *process* or *process group*, that is valid in a particular part of the *process plan*. This statement depend on, as already mentioned, the configuration of the product.

The configuration mechanism may also be used to control the use of a particular *process plan*, or *process plan version*, depending on the configuration of the product. This, however, correspond to the principle of one process plan for each variant of a product. Consequently, this does not reduce the work of creating the same information again and

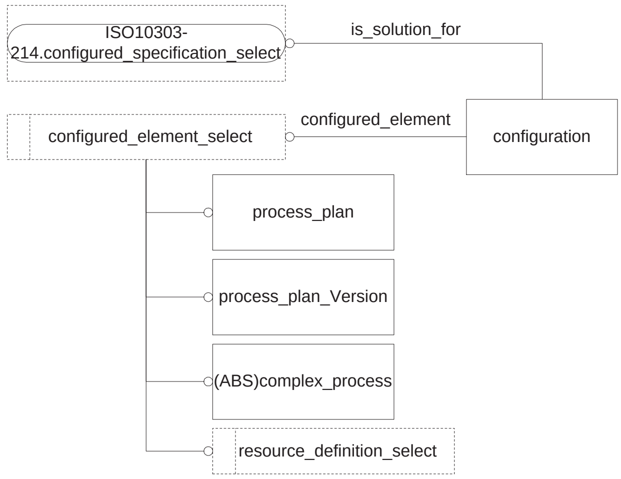

Figure 5.21. The representation of a process and its configuration.

again, nor does it eliminate the need for updating each process plan when a change that affect common parts is made.

Which approach to use must depend on the type of production of the particular company and their available process planning system. That is, the effect of using the product configuration to configure the process plan is higher if several variants are involved and the production volume is high. In addition, the company must have a process planning system that can manage product and process plan configurations, or the complexity will probably be too extensive for the process planner to handle.

In addition, the same mechanism may be used for configuration of the manufacturing resources as well. Then the configuration of the product will determine not only the configuration of the process plan, but also the configuration of the manufacturing resources used to carry out the process plan. For instance, variant A of a car make use of the same assembly robot, robot R, as variant B of the same car. However, at the particular point in the process plan where they both use robot R, they need different tools for the robot, e.g. weld guns or grippers. The configuration of the product is then used to control the configuration of robot R, so that variant A uses robot R and weld gun A in process

A, whereas variant B uses robot R and weld gun B in process B.

5.4.7 Representation of Process Constraint

During the design of a process, or a product, particular prerequisites must be considered, e.g. that a particular vendor is preferable. These prerequisites can be referred to as design constraints, because they constrain the design by limiting the domain of solutions that can be considered.

Naturally, it is important to document design constraints in such a fashion that it can be communicated with concerned engineers. Figure 5.22 show the mechanism to represent design constraints.

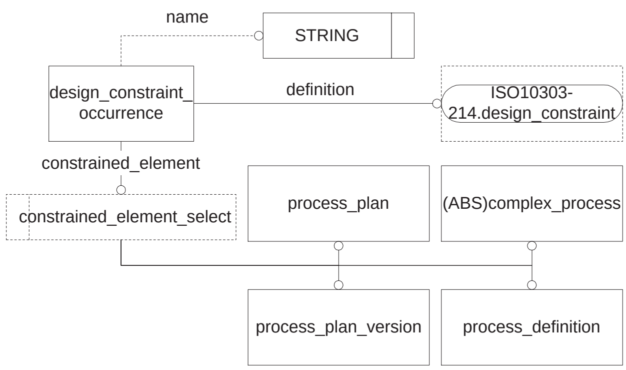

Figure 5.22. The representation of process constraint.

The *design constraint occurrence* is an occurrence of its definition, the *design constraint*. Process entities that have been considered important to constrain are the *process plan*, the *process plan version*, the *complex process*, and the *process definition*. For instance, a constrain of a *process plan* may be a maximum cost per manufactured unit or a minimum of tolerable faulty outputs.

As mentioned, the design constraint mechanism may also be used for product design solutions. This will be discussed briefly in Section 5.4.13.

5.4.8 Representation of Documentation

The reality today, and for a vast amount of time, is that companies store a lot of information in what, traditionally, is called a document, e.g. paper documents, and digital files of word processing applications, but may also be a digital file for CNC-program. It is important to keep track of these documents in terms of creator, creation date, and, naturally, what objects they document.

Figure 5.23 show the representation of the document mechanism for process entities. Naturally, other types of entities may also be documented, such as capability, and product and manufacturing resource entities.

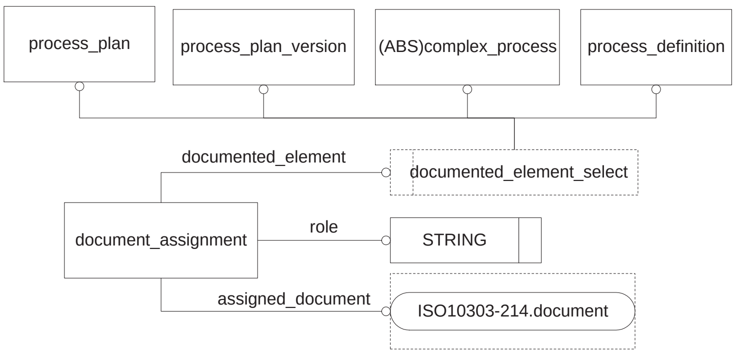

Figure 5.23. The representation of document.

A *document assignment* object assigns a *document* object to a *process* object. The *role* defines the semantical meaning of such an assignment, e.g. *mandatory* if the object must match the content of the document, and *behavior* if the objects behavior is described.

5.4.9 Representation of Organization

As with the documentation, the organizational information is also important to keep track of. The model must be able to represent organizations and persons, as well as their relationships to the information in terms of, e.g. owner and creator.

Figure 5.24 show the representation of organizational information and its association to process entities. Of course, as with documents, organizational information may be associated with other entities as well, e.g. the creator of a particular document, or the person who updated a particular part of a product.

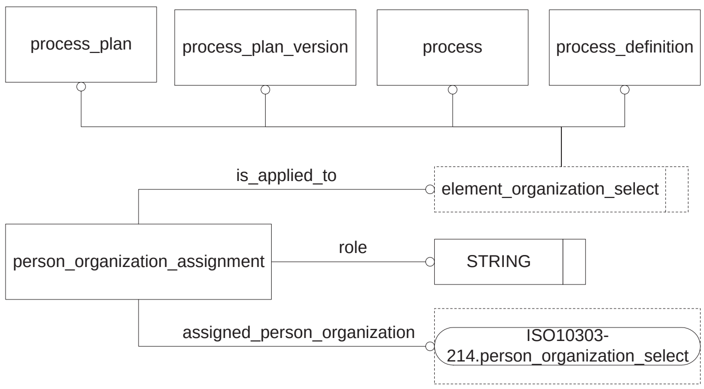

Figure 5.24. The representation of organizational information.

A *person organizational assignment* object assigns a person in an organization, or an organization, to a process object. The *role* defines the semantical meaning of the assignment, e.g. *creator* for the creator of the object, and *owner* for the owner of the object.

5.4.10 Representation of Effectivity

To control the validity of a particular object, the effectivity mechanism was included in the model, cf. Figure 5.25. For instance, the effectivity can be used to control what version of a particular process plan that is valid at the moment, and when it is due.

An *effectivity* is assigned to the effective element, e.g. *process plan version*, *process*, and all the relationships in the process plan core model,

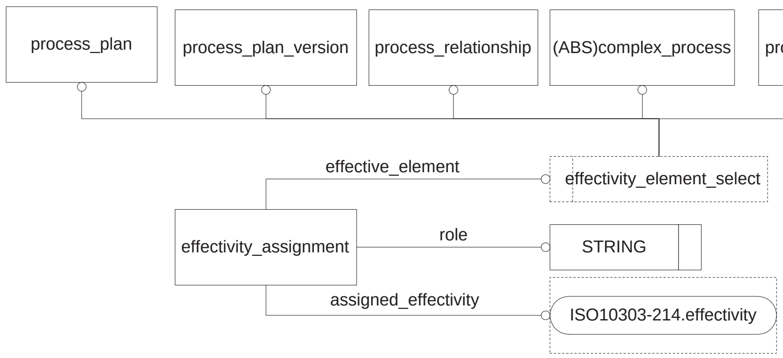

Figure 5.25. The representation of effectivity.

via the effectivity assignment. The semantical meaning of the assignment is defined by the *role* attribute, which can be assigned the following values: *actual* defining an actual period of the effectivity, *planned* defining a planned period of effectivity, and *required* defining a required period of effectivity.

Naturally, other elements may also have an effectivity assigned, e.g. documents, entities defining a product and a manufacturing resource. However, they will not be considered here since the mechanism is the same and the focus is on processes.

5.4.11 Representation of Coordinate Space

A reference coordinate space in which the process may be defined is an important information requirement. Such a coordinate space would provide a reference coordinate space in which the process is defined. That is, the coordinate space in which all manufacturing resources and products involved in the process are defined. This is represented using the Cartesian coordinate space mechanism in ISO10303-214, cf. Figure 5.26.

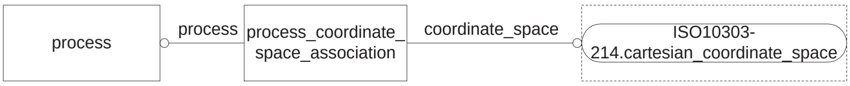

Figure 5.26. The representation of a reference coordinate space of a process.

5.4.12 Representation of Product

Even though the representation of product definition is important it is not the focus of this thesis. The information requirements in ISO10303-214 (ISO/TC184/SC4, 2001) have been found to be sufficient for the purpose of this thesis and, thus, those are used.

Some examples of information about the product that are necessary:

- intermediate states,
- product shape,
- tolerances,
- product volume, and
- documentation.

Figure 5.27 show the product definition mechanism of the ISO10303-214 model. The purpose is to give an overview of the product definition mechanism. Therefore, most of the attributes and some of the relationships have been left out in order to simplify the interpretation.

The *item* and *item version* is mechanisms to identify an item, which may be a finished product, raw material, or a manufacturing resource. Yes, the manufacturing resources is represented using the same mechanisms, cf. reasoning in Section 4.6.3.

The difference between, e.g., an assembly and a part, or a product and a manufacturing resource, is defined by the *specific item classification.* The *classification name* is assigned values that define the type of item,

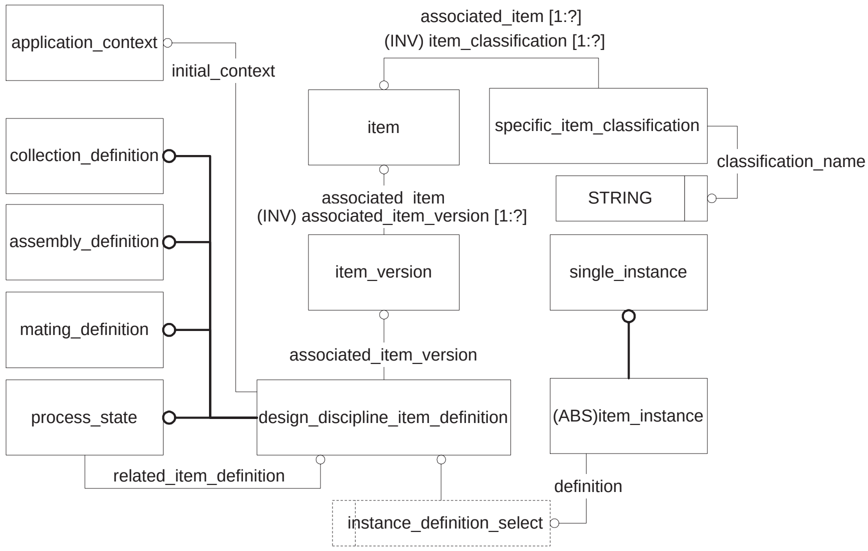

Figure 5.27. The representation of product and manufacturing resource.

e.g. *part* for parts, *tool* for manufacturing resources, and *assembly* for assemblies.

The *design discipline item definition* defines a view of an *item version*, which is used to collect information about an *item version* in a particular application context. This mechanism enables the separation of, e.g., information about the electrical design of a product from the mechanical design of the same product.

Of the other types of design discipline item definitions, the *assembly definition*, the *mating definition*, and the *process state* are the most important for this thesis. The *assembly definition* defines an assembly view of a product, cf. Figure 5.28, the *mating definition* defines a mating view of a product, cf. Section 5.4.18, and the *process state* defines an intermediate state of a product, e.g. in a sheet metal die process where several process steps must be made to accomplish the final shape of the metal sheet.

The *item instance* is a mechanism that is used when an instance of an *item version* is needed. For instance, if an occurrence of an *item* *version* is needed in an assembly.

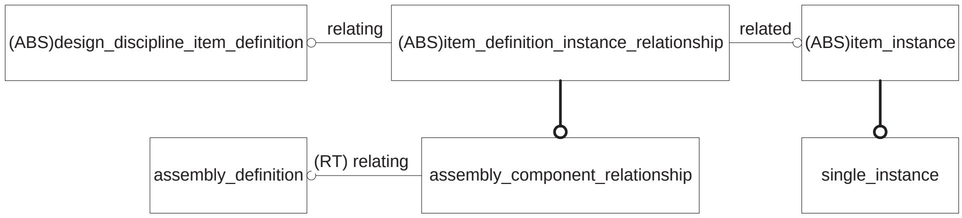

Figure 5.28. The representation of assembly.

Figure 5.28 show the assembly mechanism. The *assembly component relationship* is the center of this mechanism. It relates item instances, the children in an assembly, to an *assembly definition*, the view of an assembly. Here, the *single instance* will only be considered. The *single instance* represents an instance of an *item version* which will occur in an assembly at a particular location once. If the same *item version* is to appear more than once, then a *single instance* need to be created for each appearance.

Naturally, many of the entities in the product definition mechanism, e.g. *item*, and *item instance*, may be assigned, e.g., documents, effectivity, and organizational information in a similar way as the processes.

5.4.13 Representation of Product Concept

The purpose of the innovation process is to transform ideas into products that are ready for the market. In this process several requirements must be considered from different interest groups, e.g. customers (those who buy the product), owners, government, and so on, often called customers.

The requirements are then transformed to functional requirements describing the function structure that are needed to fulfill the requirements of the different interest groups. From the functional requirements concept solutions are created. The concepts with best potential of success is chosen and developed further by embodiment and detailed design.

It is important to document the development from identified requirements to detailed design in order to, e.g., keep track of decisions, reuse concepts, and reuse solutions. Figure 5.29 show the mechanism to represent requirements, functions, and concept solutions. The mechanism is mainly the same as the ISO10303-214 complex product mechanism with the difference of product requirement.

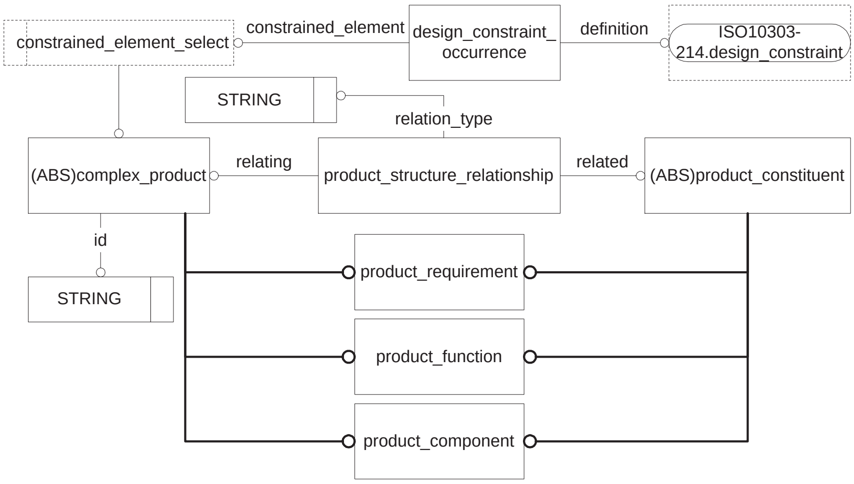

Figure 5.29. The representation of a mechanism to represent product requirements and concepts.

The main structuring mechanism consist of the *complex product*, the *product structure relationship*, and the *product constituent*. That is, a *complex product* may be related to a *product constituent* by the *product structure relationship*. The *complex product* and the *product constituent* must always be one of *product requirement*, *product function*, or *product component*.

The semantical meaning of a *product structure relationship* is defined by the *relation type*. The attribute may be assigned the following values:

- *decomposition* - define a hierarchy between two objects of the same type, e.g. two product functions,

- *dependency* - define a dependency between two objects of the same kind, e.g. two product requirements,
- *functionality* - define the functionality, product function, of a product component,
- *occurrence* - define an occurrence of a product component,
- *realization* - define the realization of a product function in terms of product component, and
- *specialization* - define that an object of the same kind fulfills the requirements in a more specific way.

The relationship should be interpreted as a relationship where the *relating complex product* is decomposed in, has function as, occur as, is realized by, or is specialized by the *related product constituent*. The only exception from this is the *dependency*, which should be interpreted as a relationship where the *related product constituent* is dependent on the *relating complex product*.

Naturally, a *complex product* may be assigned documentation, effectivity, properties, and organizational data in a similar way as the process entities.

5.4.14 Representation of Project Management Information

In a network of competences, especially where the competences belong to different organizations, the management of a project becomes crucial and difficult. One aspect of this problem is the ability to communicate work requests, work orders, responsibilities for resolving the requests, and much more. Here, the mechanism from ISO10303-214 is used, cf. Figure 5.30 for a stripped version of the mechanism.

The *work request* represents a request for some work to be done and the *scope* specify the design objects that are subject to the request.

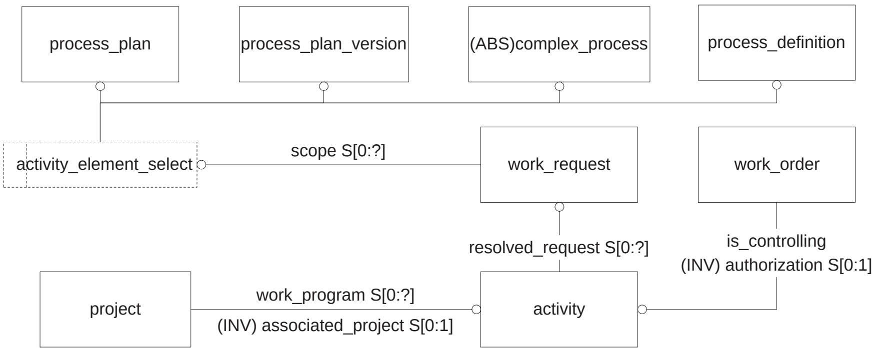

Figure 5.30. The representation of project related information.

Naturally, other objects may be subject for a request as well, e.g. item and document. A work request is solved by an *activity* that may be part of a project, and authorized by a *work order*.

Each of these entities may be associated with organizations, persons, and documents. This enables the representation of who made the request for a particular work to be done, who is responsible for a particular activity, and who authorized a particular activity. Effectivity and date are other types of information that may be associated with these entities in order to represent when a particular activity is planned to be carried out and what date a particular request was issued.

5.4.15 Representation of Produced Output

Each process plan that is created will have, at least, one main output, i.e. the finalized product or part. This is represented in Figure 5.31 by the produced output mechanism.

The produced output mechanism consists of two entities, the *plan produced output association* and the *produced output select*. The former is used to associate a *process plan version* with its produced output, which is one of the choices of the *produced output select*, the *item version* or the *product component*. An *item version* is the representation

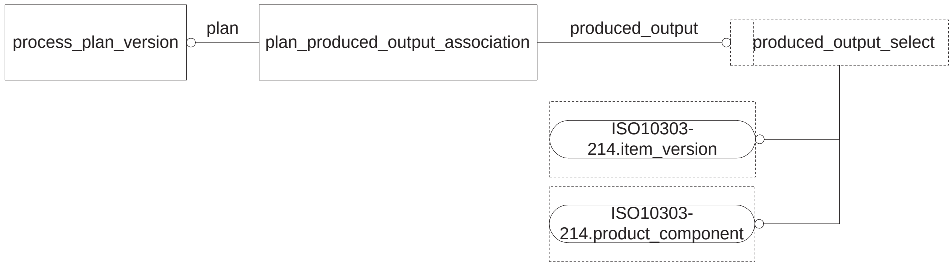

Figure 5.31. The representation of produced output.

of a version of a product whereas the *product component* represents a conceptual product design.

5.4.16 Representation of Input and Output to and from Processes

Obviously, to describe how to manufacture a product it is necessary to describe the state of the product before and after the process is performed. An input describe the state a product should have before a particular process is performed and an output describe the state the same product should have after the particular process. The representation of inputs and outputs are shown in Figure 5.32.

The *process input output* define an association of a process to its input or output, the choices of the *input output element select*. The semantical meaning of the *process input output* is defined by the *role*. If the *role* is assigned a value of *input* the relationship defines an input, whereas a value of *output* defines an output.

The elements that may be selected as input or output may be raw material, parts, semi-finished parts, sub-assemblies, and the final product. These elements are represented by the *item instance*, the *design discipline item definition*, and the *product component*.

An *item instance* is used when a particular instance of an *item version* is needed to define the input or output of a *process*, the *design disci-*

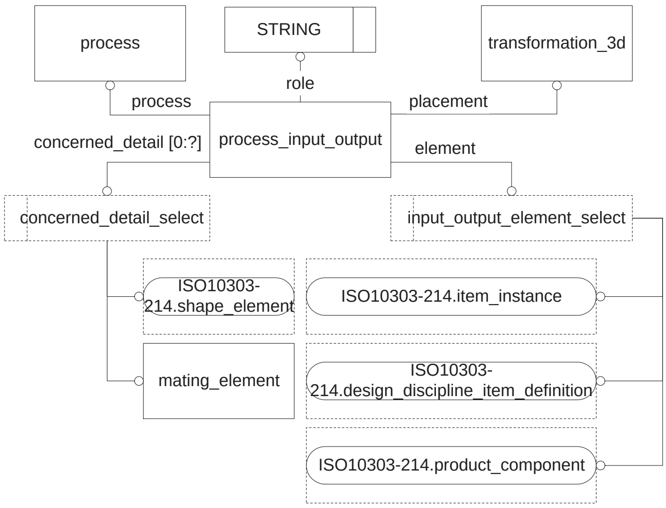

Figure 5.32. The representation of input and output of a process.

pline item definition is used if that particular collection of information about a product is needed, and the *product component* is used when the detailed product design is not yet determined, e.g. during concept design.

The *concerned detail* is used to specify the *shape element* or *mating element* that may hold detailed product information that are necessary to perform the process, e.g. a hole or a weld spot.

5.4.17 Representation of Location System

The location system is a system of master location points and location points that are used to determine the location of a part for manufacturing purposes. The master location and location points defines the contact points between products and manufacturing resources, e.g. product and fixture contact, or product and gripper contact.

The outcome of a process is highly affected on the design of a product's contact points with its, e.g., fixture. Depending on the location of contact points the variance of quality in the final product may be minimized. The work of minimizing the variance is often referred to as robust design, cf. work by Söderberg and Lindkvist (2000).

For further reading on location system, master location points, and location points cf. Appendix C.

Figure 5.33 show the location system mechanism, which consists of two main mechanisms. The two mechanisms are the location system mechanism and the location point mechanism.

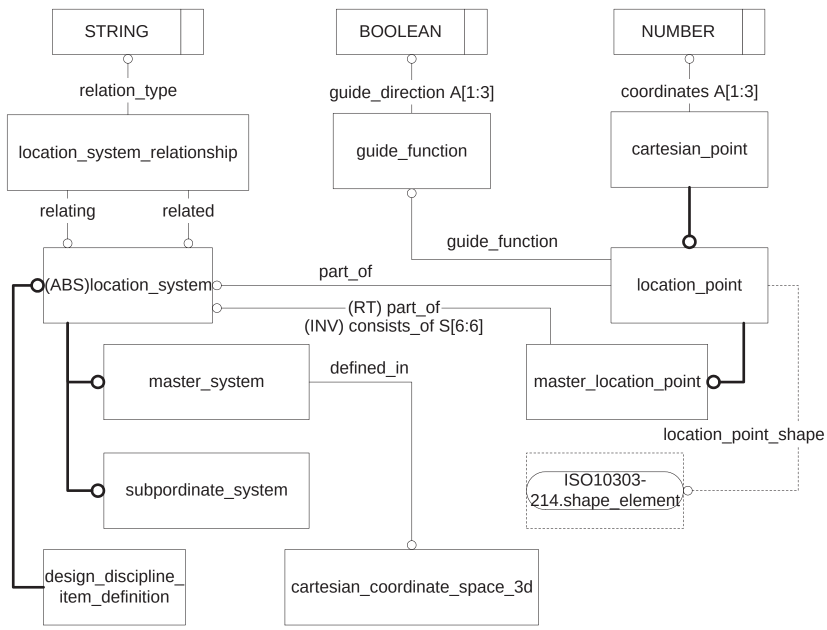

Figure 5.33. The representation of reference system.

The *location system* is a type of *design discipline item definition* that defines a collection of location points that are used to determine the position of an element, e.g. the product or the manufacturing resource. A *location system* consists of a fixed number of *master location point* objects, 3 + 2 + 1 points, and anything from zero to an infinite number of other *location point* objects.

The six master location points are used to determine, in an unambiguous way, the location of an element, such as a product or a manufacturing resource. The zero to infinite number of non-master location points are used to support the six master location points in the case of, e.g. slender bodies.

Two types of location systems exist, the *master system* and the *subordinate system*. A *master system* is used to determine the location of the element itself whereas the *subordinate system* is used to locate particular functions of an element, e.g. shape of openings or mountings.

The *location system relationship* is used to relate two location systems with each other. The semantical meaning of the relationship is defined by the *relation type*, which can be assigned the values *dependency* and *subordinate*.

A *dependency* relationship define that the *related location system* is dependent on the *relating location system*. This may, for instance, be used to define that a *master system* of a fixture depend on the *master system* of a product, or that a *subordinate system* of one part depend on a *subordinate system* of another part.

A *subordinate* relationship define that the *related subordinate system* is subordinated the *relating master system*. Consequently, in this type of relationship the *relating* will always specify a *master system* whereas the *related* will always specify a *subordinate system*.

The *location point* is a type of Cartesian point that are defined in a three dimensional Cartesian coordinate space, specified by the *defined in* of the *master system*. The coordinates in the Cartesian coordinate space is defined by the *coordinates*, which is an array that is indexed from one to three of *number* representing the X-, Y-, and Z-axis in the coordinate space.

In addition to the coordinates, a *location point* also have a *guide function*, and, may have, a shape associated. The *guide function* define the directions in which the *location point* guide the located element. This is represented by the *guide direction*, which is an array indexed from one to three of *Boolean* representing the X-, Y-, and Z-axis in the coordinate space. A value of true in the first array element would indicate that the *location point* guide in the direction of the X-axis, whereas a value of false would indicate that it does not.

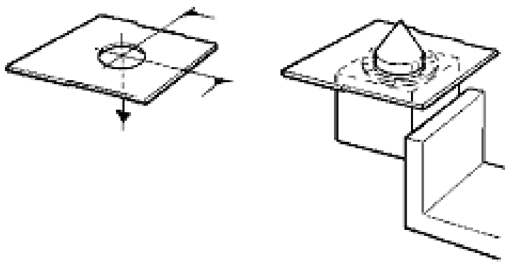

Figure 5.34. A location point, in the shape of a hole, that guide in three directions (from Volvo (1996)).

The *location point shape* does, naturally, specify the shape that are associated with the *location point*. This is the actual shape of the *location point* in the physical world, cf. Figure 5.34.

5.4.18 Representation of Mating

Most products consists of more than one part and, thus, it is, in addition to the topological structure of a product, important to represent how the parts are joined together. Usually the area where parts are joined together is referred to as a joint, which add information to the product that may be of concern for manufacturing.

However, here the terminology from ISO10303-214 (ISO/TC184/SC4, 2001) have been preserved. Hence, the area where parts are joined together will be referred to as a mating.

In the automotive industry the body-in-white operations are important, which include mating of metal sheets. An often used mating method is spot welding, even though other mating methods may be used, e.g. gluing, clinching, and press fit.

Figure 5.35 show the mechanism for representing matings. This mechanism may be used to represent any kind of matings including those mentioned above.

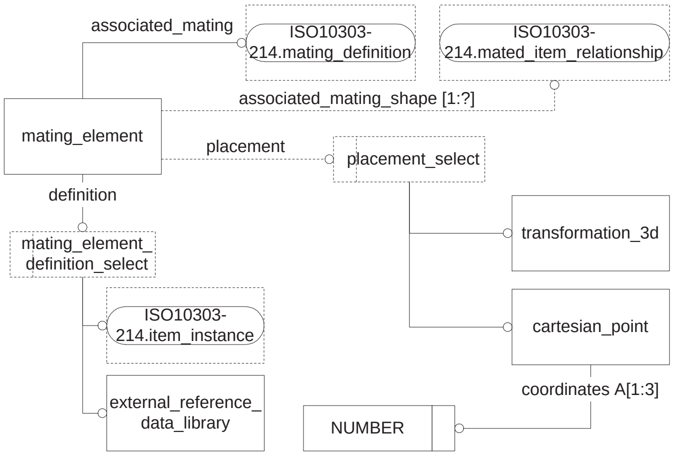

Figure 5.35. The representation of a mating definition.

The main entity in the mating mechanism is the *mating definition*. This is the mechanism in ISO10303-214 and define the mating itself. It has been extended here to enable the representation of mating elements in a mating, e.g. bolts, nuts, and weld spots. The aim has been to create a mechanism where the mating can be defined with all its requirements without the need to define the exact type of mating or detailed design of the mating. This may be done later when a particular manufacturing method has been chosen, e.g. to use spot welding or to use gluing.

Each *mating definition* may have two or more item instances associated, which define the parts that are mated together. Their respective placement in the mating is defined by the three dimensional transformation, cf. Section 5.4.20, and their surface of actual mating is specified by the mating surface.

The *mating element* is the representation of an element, physical or non physical, that is used to join the different parts in a mating; a bolt is an example of a physical element and a weld spot is an example of a non physical element. Its definition is specified by the *definition* that can be assigned to an *item instance* or an *external reference data library*. Typically a bolt would be represented by an *item instance* whereas a weld spot would be represented in an *external reference data library*.

The placement of a *mating element* is defined by either a *transformation 3D* or a *Cartesian point*. The *transformation 3D* is used when the *mating element* is already defined in its own coordinate space, e.g. for a bolt defined by an *item instance*. The *Cartesian point*, on the other hand, is used to define the placement of mating elements that are not defined in their own coordinate spaces, e.g. for a weld spot defined by an *external reference data library*.

Last, but not least, is the representation of properties to a *mating definition* and a *mating element*. This is shown in Figure 5.36.

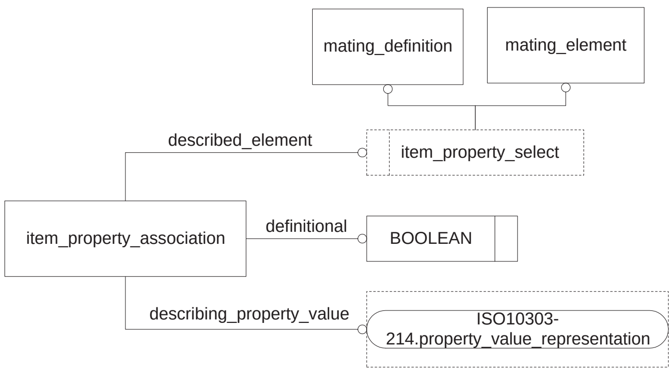

Figure 5.36. The representation and association of properties to matings.

The *item property association* associates a property to the representation of a product. In this case the product representation is the *mating definition* and the *mating element*. Each property may be definitional or non definitional, which indicate whether the property can be used to distinguish the element from elements of the same kind or not.

5.4.19 Representation of Material

Having access to the right material data is necessary for production engineers to make the right decision about the type of process and manufacturing resources that are needed. In addition, the material also determines the value of different process parameters, such as current and welding time, either explicitly by a weld robot programmer or implicitly by an adaptive robot controller.

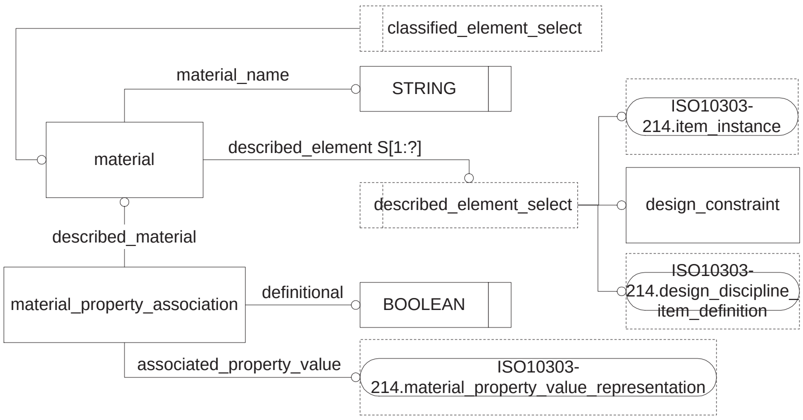

Figure 5.37. The representation of material.

Figure 5.37 show the representation of *material* and its association to described element, e.g. a product definition. The *material* itself have a name and is defined by the material properties that are associated with it. A property may be definitional, meaning that the particular value of the property can be used to distinguish a particular material from other materials of the same kind.

In addition, a *material* may also have a classification associated. The classification define the type of material. The classification mechanism also provide an external reference data library definition, which means that external definitions may be used to classify materials.

5.4.20 Representation of Manufacturing Resource

The ability to describe resources is another important information requirement for process planning. This is important in order to understand which resource that is executing a particular process.

As was discussed in Section 4.6.3, a resource is only a usage view of the product. During the development of a manufacturing resource it could be considered a product with the purpose to be used for manufacturing of other products. Hence, no additional requirements on the representation of information defining the manufacturing resources will be made; instead cf. Section 5.4.12.

The mechanism to represent the usage of a manufacturing resource is shown in Figure 5.38.

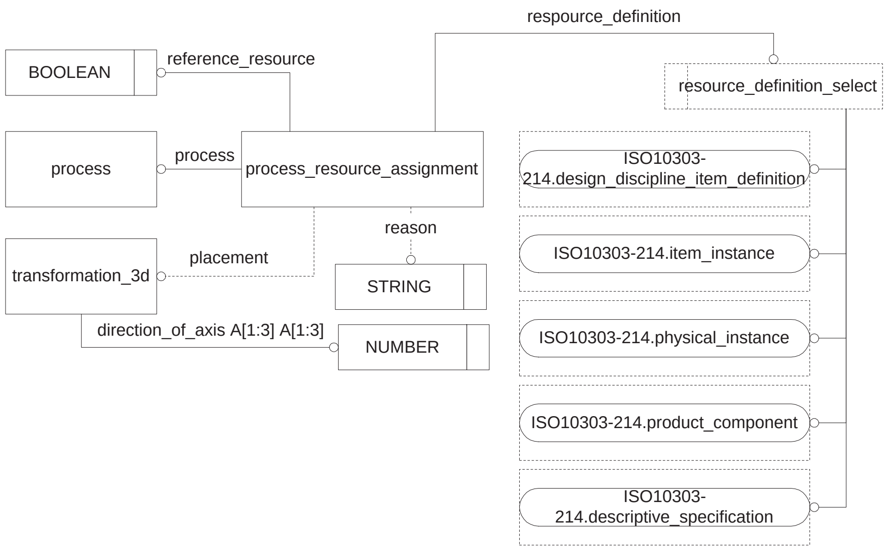

Figure 5.38. The representation of a resource and its association with a process.

A *process* may be assigned a manufacturing resource that is to execute that particular *process*. This is enabled by the *process resource assignment*. Whether the coordinate system in which the resource is defined is used as the reference coordinate system of the process is determined by the *reference resource* attribute. The *placement* is used to place the resource in relation to the reference coordinate system of process, in case the resource is not a reference resource.

The definition of the resource may then be represented by a *design discipline item definition*, an *item instance*, a *physical instance*, a *product component*, or a *descriptive specification*. The different entities will be used for different purposes. For instance, the *physical instance* will be used whenever the meaning is that an actual existing manufacturing resource is used for a particular *process*.

In addition, it is important to represent different structures of the resources. Beside the requirement-, functional-, and component-structures of resources, as discussed in Section 5.4.13, at least one additional type of structure can be identified, the mechanical structure. The mechanical structure describe how the resources are related, mechanically, to each other, e.g. a robot gripper is mounted at the end of a robot arm.

Usually manufacturing resources are grouped together according to the process areas of a factory. A process area is an area where a characteristic process is carried out, e.g. the line where an engine is assembled. Usually these groupings are named *line*, *zone*, *station* or *cell*.

Whether a grouping of manufacturing resources is a *line* or a *station* can be determined using the classification mechanism, cf. Section 5.4.3 and Figure 5.39.

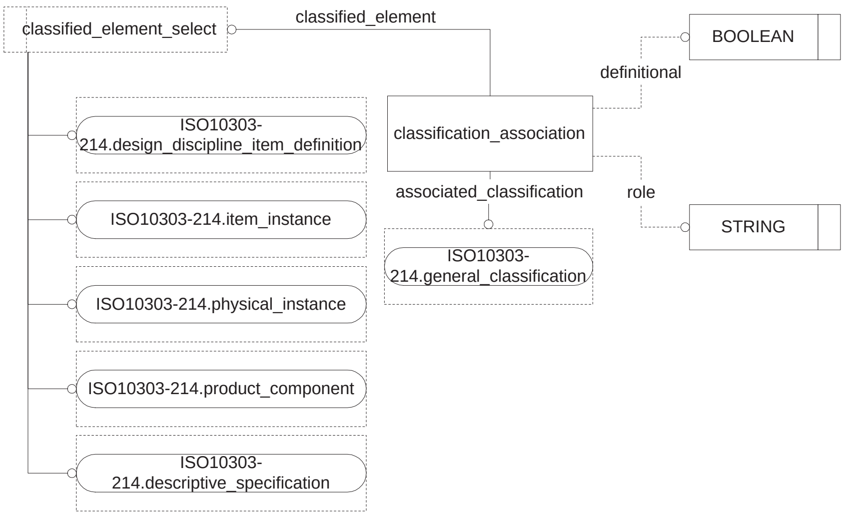

Figure 5.39. The representation of a resource and its classification.

5.4.21 Representation of Alternative Resources

In Section 5.3.7 the representation of alternative processes was discussed. A similar requirement is the requirement to represent alternative resources. In fact, the mechanism is the same.

Alternative manufacturing resources are assigned to their own *process* objects that are related to each other by an alternative relationship. It is considered to be alternative manufacturing resources when the same *process definition* object is used for all the involved *process* objects. If two different process definitions are used then it would be considered to be alternative processes running in different manufacturing resources.

Chapter 6

Validation of the Information Model and Test of the Hypotheses

The purpose of this chapter is to validate the PPR information model, and to test the hypotheses. The validation and test activity was based on a weld cell development project. This project was a collaborative project between Scania in Oskarshamn, customer role, and ABB BiW in Olofström, vendor role.

The validation and test activity was made by populating the PPR information model by the information that was communicated between Scania and ABB BiW in the project. Typically this information was communicated in documents, e-mails, and speech, e.g. in meetings and by telephone. The main flow of information is presented in Figure 6.1, where the information sent by Scania is presented above the time line, and information sent by ABB BiW is presented under the time line.

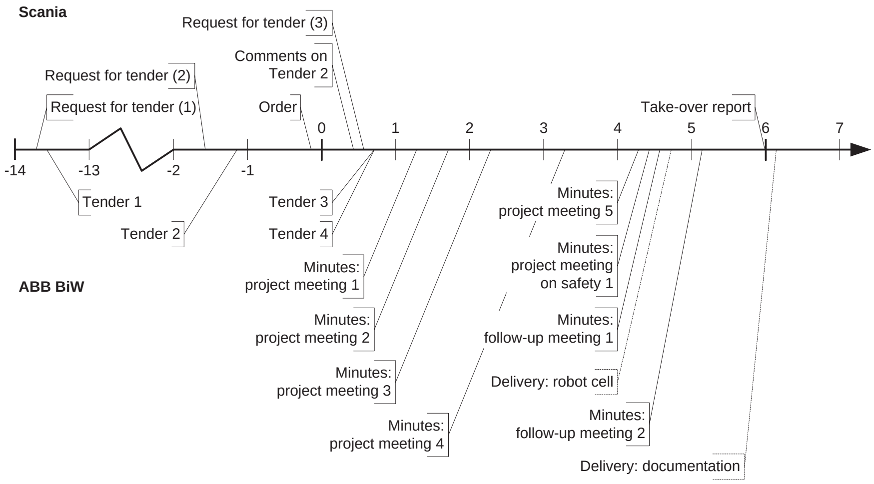

Figure 6.1. The main flow of information between Scania and ABB BiW.

6.1 Case: Development of Weld Cell at Scania Oskarshamn

The case was, as mentioned, based on a weld cell development project at Scania Oskarshamn, Sweden, in collaboration with ABB BiW Olofström, Sweden. Even though the development project considered four different subassemblies, the case was limited to consider the weld cell development for one subassembly only, the 10310025 carrier frame assembly. The carrier frame assembly was composed by the 10310325 door carrier reinforcement and 10310363 carrier cross member.

Further limitations were that only the mechanical aspect of the development project and no manual processes were considered. This is due to the limited time of the research project.

The Scania product model specified that the door carrier reinforcement and carrier cross member were to be joined by 33 weld spots. Three of these weld spots, decided by Scania, was welded manually outside the weld cell. These were the, so called, geometrical weld spots, i.e. weld spots that are welded first and located so that the geometrical shape of the assembly can be maintained without the use of a particular fixture.

Hence, the task for ABB BiW was to develop a solution that could, in terms of Hubka and Eder (1988), *transform* 10310325 door carrier reinforcement and 10310363 carrier cross member to the 10310025 carrier frame assembly by welding 30 weld spots at predefined locations.

In this case, however, only one geometrical spot and three weld spots will be considered. The purpose is to validate the information model by testing the principles and not to represent all information in the development project.

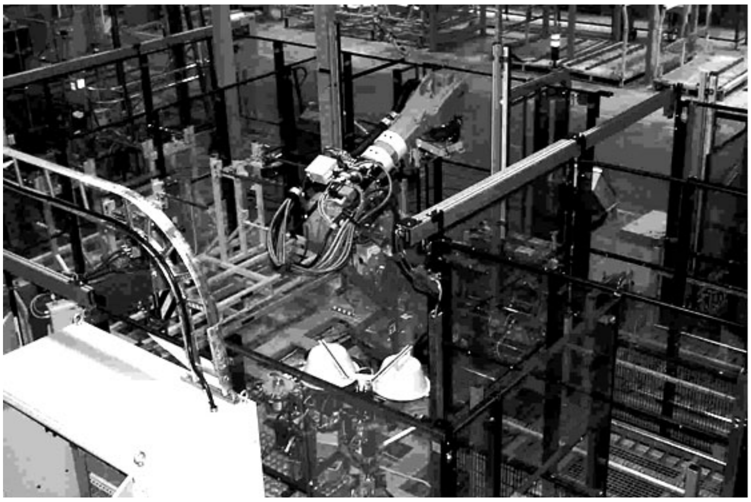

Figure 6.2. The weld cell as it was delivered to Scania.

The task was solved by ABB BiW by developing a weld cell that was powered by an ABB robot with a gripper, and a stationary weld gun, cf. Figure 6.2. Included in the solution was the manufacturing processes, in this case the welding of 30 weld spots. The robot used the gripper to move the carrier frame assembly and weld the 30 spots in the stationary weld gun.

6.2 Validation of the Information Model

In addition to the earlier limitations, the validation of the process information model mainly focused on three aspects of the model. These aspects were the weld spot aspect, the process aspect and the manufacturing resource aspect.

6.2.1 Product Specification

The product specification specify the 10310025 carrier frame assembly and its constituents. The carrier frame assembly is represented by the *item* and *item version* in the PPR information model, cf. Figure 6.3.

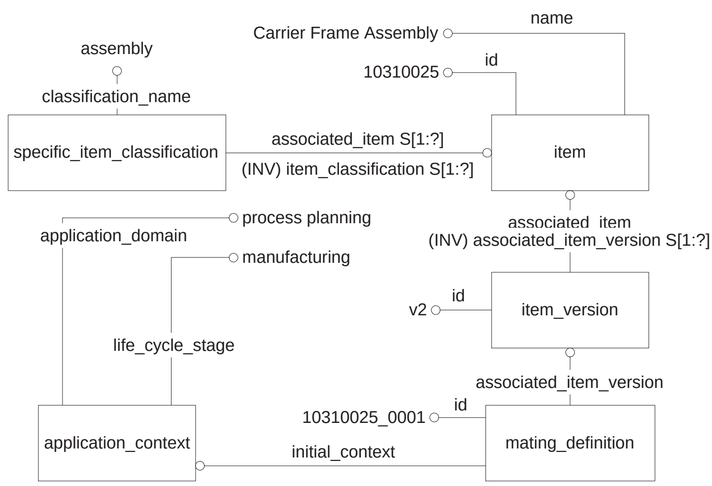

Figure 6.3. Representation of the mating of the carrier frame assembly.

The *mating definition* is a view of the carrier frame assembly in terms of how the constituents of the carrier frame assembly is joined to become the assembly. In other words, the *mating definition* is a collector of information about the carrier frame assembly that are necessary to define how its constituents are joined. The *application context* specify that the information define the assembly from a manufacturing and process planning perspective.

Figure 6.4 show the 10310325 door carrier reinforcement and 10310363 carrier cross member as they have been joined.

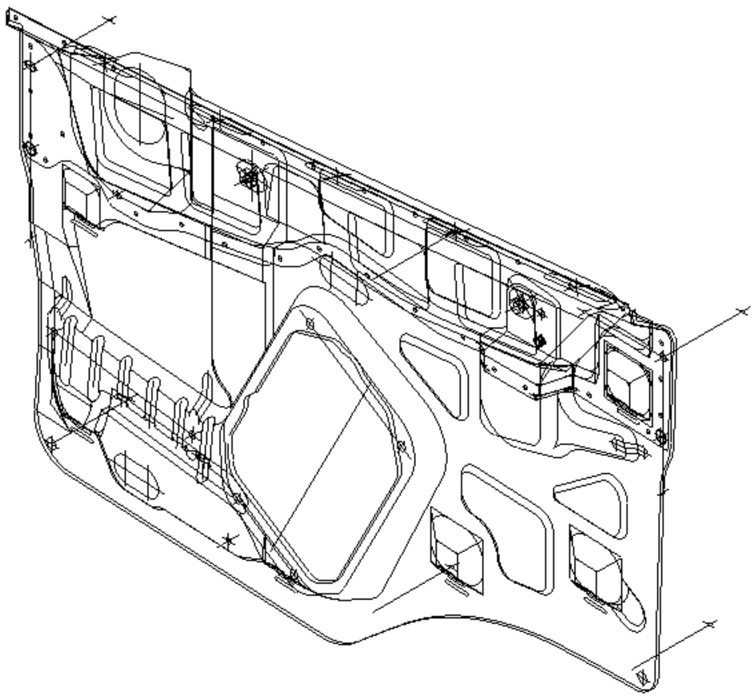

Figure 6.4. The 10310025 carrier frame assembly.

The constituents of the 10310025 carrier frame assembly, i.e. the 10310325 door carrier reinforcement and 10310363 carrier cross member, are represented analogously with two exceptions. The *classification name* have the value of *part* instead of *assembly* and the *mating definition* is replaced by a *design discipline item definition*.

The value of *part* for the *classification name* is used because neither of the constituents are assemblies. The *design discipline item definition* is used for the same reason, i.e. the constituents are not assemblies and can, thus, not be specified in terms of matings (joints).

In addition to the *item*, *item version*, and *design discipline item definition*, the constituents need to be represented by a *single instance*, cf. Figure 6.5.

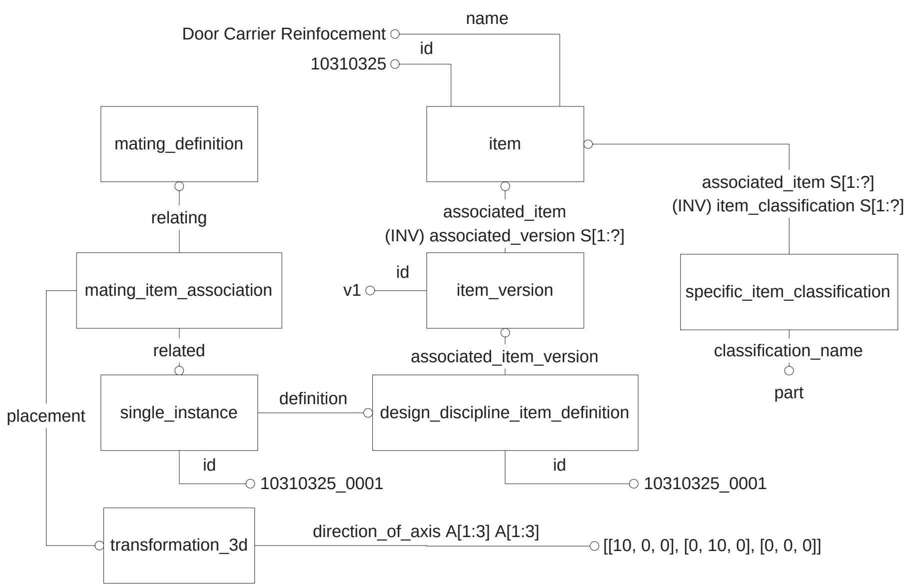

Figure 6.5. Representation of an instance of the 10310325 door carrier reinforcement and its association with a mating definition.

The *single instance* represents and instance of a *particular item version* in the *mating definition*. This mechanism enables the reuse of the same item definition in several different product structures, or if the same item occurs several time in the same product structure. For instance, a wheel, which may occur four times in a car, front left, front right, rear left, and rear right.

The *transformation 3D* is used to place the particular instance in the coordinate space of the item defining the assembly, i.e. 10310025 carrier frame assembly. The principle is shown in Figure 6.6, where the door carrier reinforcement is placed in the coordinate system of the carrier frame assembly.

Note that the door carrier reinforcement is a part and not an assembly as the carrier frame assembly. Note also that the *design discipline item*

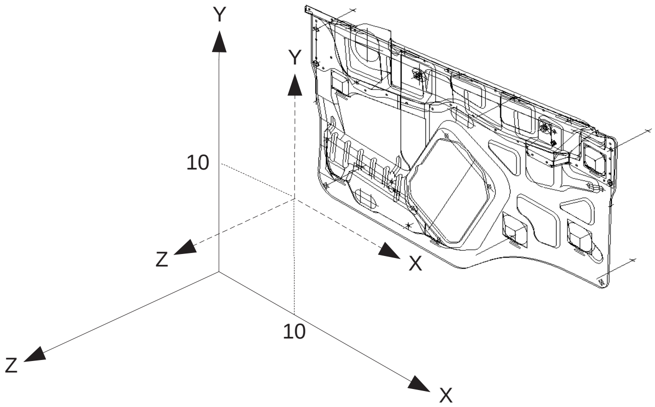

Figure 6.6. The transformation of the door carrier reinforcement in the coordinate space of the carrier frame assembly.

definition of the door carrier reinforcement should be assigned to the same application context as the *mating definition* of the carrier frame assembly.

The instances of the door carrier reinforcement and the carrier cross member is related to the *mating definition*, cf. Figure 6.7. This indicate that they are parts that are joined together in the mating.

The *mated item relationship* specify a relationship between the door carrier reinforcement and the carrier cross member. The relationship specifies the actual point of contact between the two instances. In this case the contact is where a weld spot is located. Hence, there could be a *mated item relationship* for each weld spot. The word could is used because the relationship is only necessary when the shape[1] and/or material of the mating is needed.

The identification of a weld spot is represented by the *mating element*. In Figure 6.8 a weld spot in the carrier frame assembly is represented. It is associated with a *mated item relationship* specifying the shape of it, cf. Figure 6.7, a *Cartesian point* defining its placement, and an *external reference data library* that defines the weld spot.

[1]Note that the shape in Figure 6.7 is a simplification to save space.

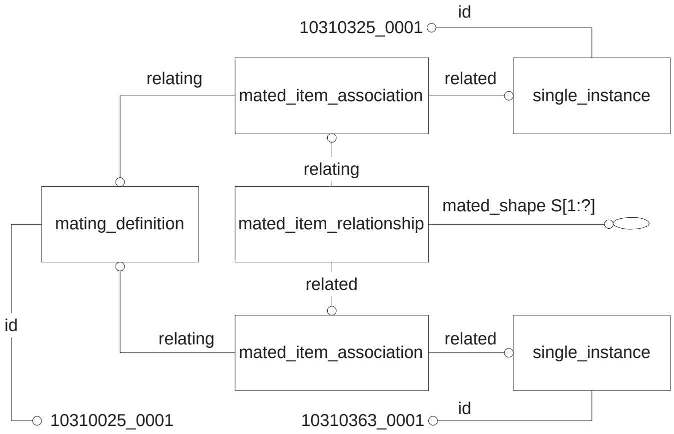

Figure 6.7. The representation of the instances of door carrier reinforcement and the carrier cross member in a mating.

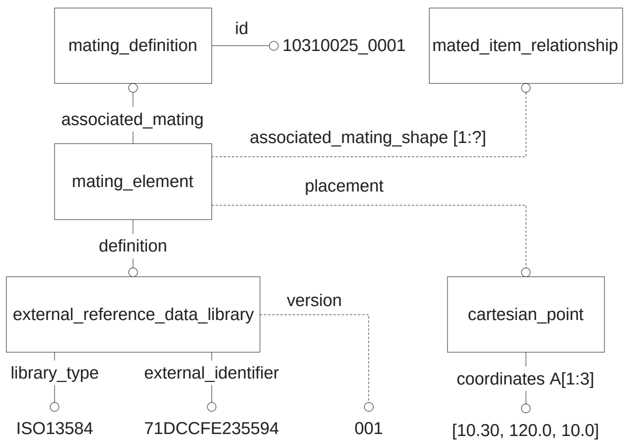

Figure 6.8. The representation of a weld spot.

Without the external reference data library the *mating definition* would not be a weld spot. In addition to defining the type of welding element, the definition of a weld element in an external reference data library can also be used to define data types that must be associated with a weld spot.

Two data types have been identified, the diameter of the weld spot, and an attribute to define whether the weld spot is a geometrical weld spot or not. In addition, the definition was also used to define that a weld spot must always be associated with a *Cartesian point* and not with a *transformation 3D*. The definition was made using the ISO13584-25 (Parts Library), cf. Figure 6.9.

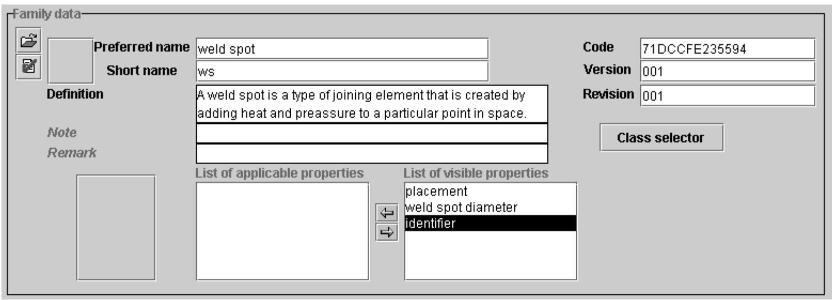

Figure 6.9. The presentation of the definition of a weld spot in the PLibEditor application.

The definition of the *mating element* defines that the mating element is a weld spot and should have an *identifier* (short name is *id*), a *placement*, and a *weld spot diameter* associated.

The *identifier*, or *id*, is a string that uniquely identifies a mating element. The presentation of the *id* in PLibEditor is shown in Figure 6.10.

Consequently, the *mating element* must have a unique identifier associated. This is provided by using the property mechanism in ISO10303-214. The *id* is represented by a string property called *id*.

The *placement* is a reference to the Cartesian point class in the dictionary. It defines that a weld spot must have a placement specifying a Cartesian point as its placement. Hence, the attribute *placement* of a

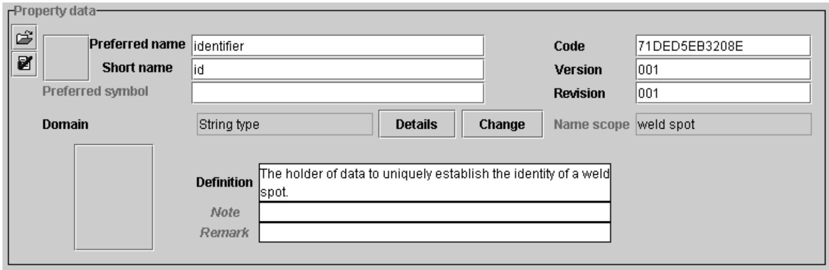

Figure 6.10. The presentation of the definition of the *identifier* in the PLibEditor application.

mating element must, if the *mating element* is a weld spot, specify a *Cartesian point* and not a *transformation 3D*. The presentation of the *placement* in PLibEditor is shown in Figure 6.11.

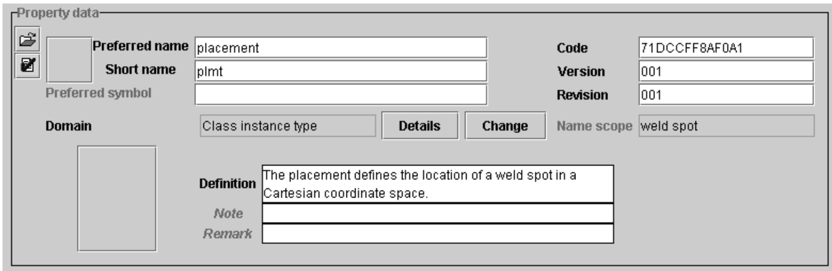

Figure 6.11. The presentation of the definition of the *placement* in the PLibEditor application.

Similarly, the *weld spot diameter* define the diameter of a weld spot. The value of the diameter is represented by a length property in the metric system. The presentation of the *weld spot diameter* in PLibEditor is shown in Figure 6.12.

It is clear that the use of external reference data libraries for definition of concepts is a strength. The strength is, among other things, that information model structures can be maintained even though the library of concepts is changed. For instance, if the concepts for some particular mating elements have been defined and a new type of mating element is developed, then the dictionary needs to be updated but not the information model.

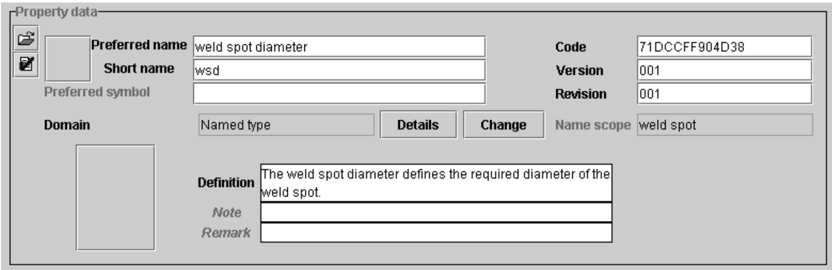

Figure 6.12. The presentation of the definition of the *weld spot diameter* in the PLibEditor application.

6.2.2 Process Plan Specification

Along with the product specification was a process plan sent to ABB BiW. The process plan specified a restriction in sequence of manufacturing processes on a macro level.

The mating of the carrier frame assembly was made in two processes. First, the process plan specified that three geometrical spots were to be made manually. Second, the rest of the weld spots were to be made in an automated solution. The representation of the process plan is presented in Figure 6.13.

The *process plan* and *process plan version* together represent a particular process plan. Each *process* in the *process plan* is assigned to the particular version of the *process plan*, in this case version *001*.

The sequence of the processes is not given by the *process identifier*, but with the *process relationship*, indicated by the value *sequence* assigned to the *relation type*. The *process* specified with the *relating* is preceding the *process* indicated by the *related*.

The *process definition* objects define each *process*. The definition is done by adding properties, documents, and classification to the *process definition*. In Figure 6.14 the classification of the process definition *002* is presented.

The *general classification* assigned to the *process definition* in Figure 6.14 is definitional. This means that the classification defines the

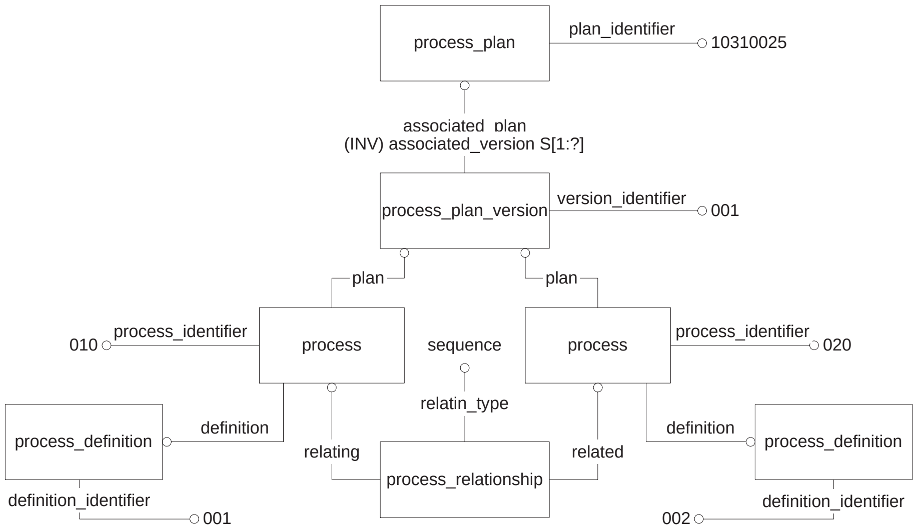

Figure 6.13. The representation of a process plan and its two processes.

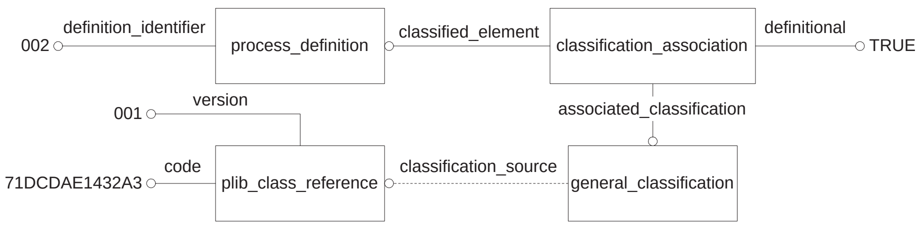

Figure 6.14. The representation of a process definition and its classification.

process definition.

The general classification also uses a ISO13584 (Parts Library) reference. This is the source of classification, i.e. the concept in the dictionary, to which the general classification refers, contain the specification of the *general classification*, cf. Figure 6.15.

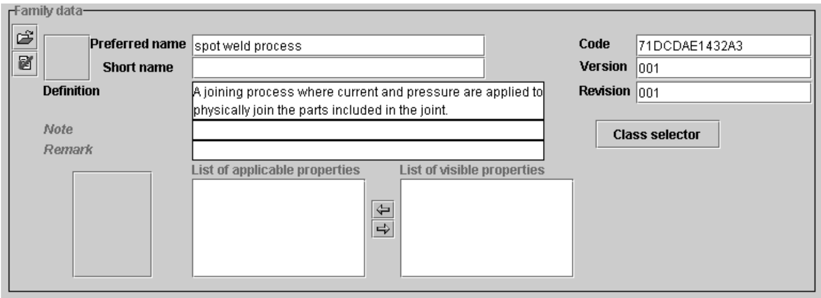

Figure 6.15. The representation of the definition of spot welding in the PLibEditor application.

In this case it was already decided by Scania that it was a solution for a spot weld process. However, in a concurrent engineering process the process may at first only have a definition defining that it is a joining process and not what type of joining process. Then the supplier of the equipment have less constraints to deal with and can, perhaps, develop a, better solution.

6.2.3 Work Request

In addition to the information defining the product to be manufactured and the process plan, Scania also communicated a request for ABB BiW to develop a solution for the process *020*. This information is represented to the left in Figure 6.16. The *work request* is a request for a development activity that is required from a manufacturing point of view, indicated by the *work request type*.

Together Scania and ABB BiW set up a project to develop a solution for the concerned process, the *Robot Cell - 0020* project. To the *project*

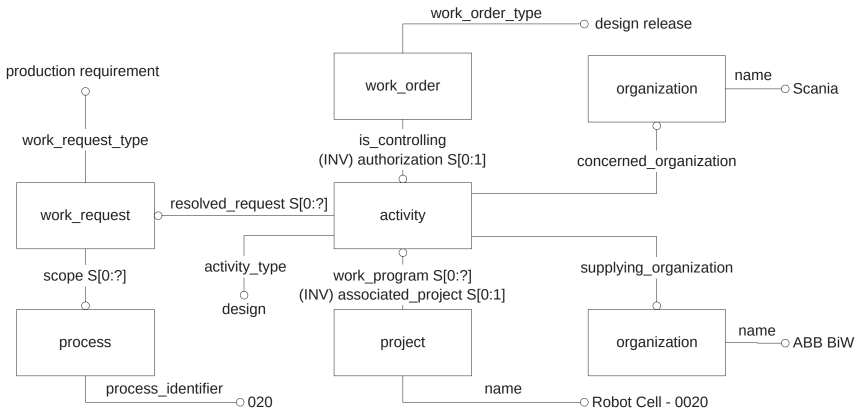

Figure 6.16. The representation of a work order and related information.

is also a design *activity* assigned to resolve the work request initiated by Scania. The design *activity* is mainly carried out by ABB BiW, indicated by the *supplying organization*, whereas Scania is the organization that is affected by the result of the *activity*, indicated by the *concerned organization*.

Then Scania creates a *work order* for a *design release*. The *work order* authorize and initiate the *activity* which was assigned to the *project* in order to resolve the *work request*.

6.2.4 Process and Manufacturing System Solution

When the work is authorized by Scania, ABB BiW can start developing a solution for process *020*. This is done by further developing and detailing the *process*, and developing a manufacturing solution that realizes a set of functions that are required by the *process*. A function required by a *process* is represented by a related *product function*, cf. Figure 6.17.

Moreover, the *product function* realizes some capability that is required by the *process* in order to fulfill some product property. In Figure 6.18

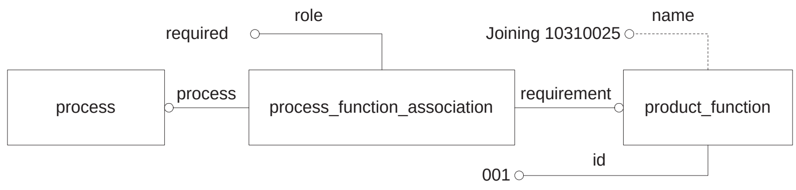

Figure 6.17. The representation of a functional requirement on a manufacturing resource.

the delivered capability is represented by the capability mechanism.

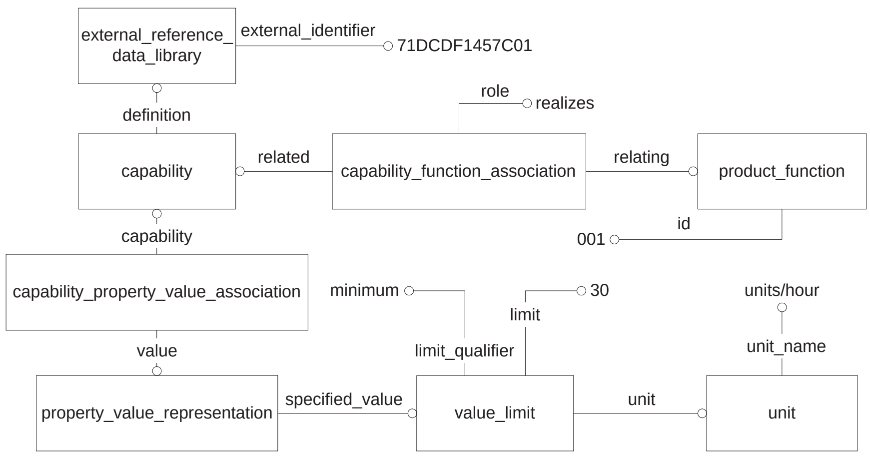

Figure 6.18. The representation of a functional requirement and the capability the function is required to realize.

In this case the joining capability is represented as the definition of the product requirement in Figure 6.18. The capability is defined as the ability to join two or more parts together. The property associated with the *capability* specify that the function realizes a capability of joining a minimum of 30 units per hour. The definition of the capability itself is represented by an entry in an ISO13584-25 (Parts Library) dictionary, cf. Figure 6.19.

For each functional requirements, such as the *assembling 10310025* function, were then a conceptual manufacturing solution developed.

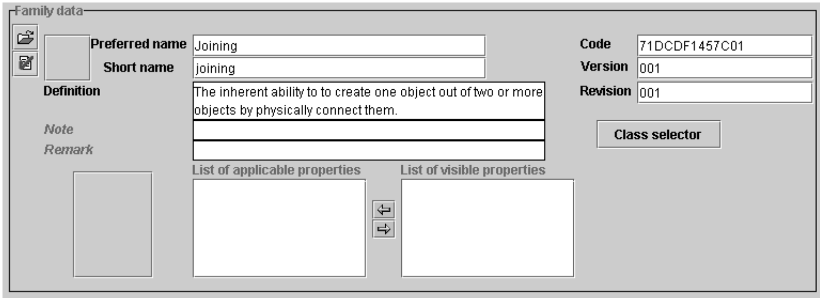

Figure 6.19. The representation of the definition of the joining capability in the PLibEditor application.

The conceptual manufacturing solution for the *assembling 10310025* function is presented in Figure 6.20.

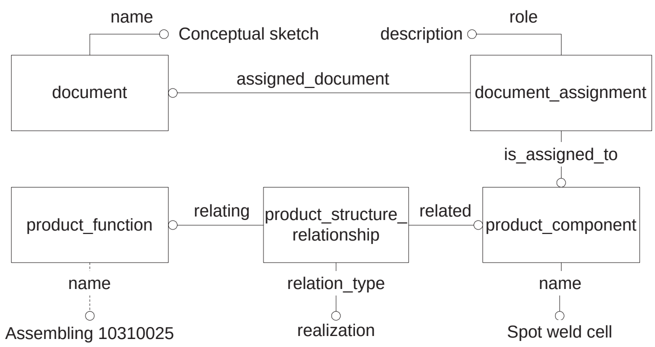

Figure 6.20. The representation of functional requirement and conceptual solution.

The *product component* called *spot weld cell* represent the concept of the solution that ABB BiW are developing for Scania. Different types of information may be associated with it to describe the concept, e.g. documents, as in Figure 6.20, and properties. Naturally, documents and properties may also be used to describe a *product function*.

Another useful mechanism is the constraint mechanism. It enables the assignment of a *design constraint* to, e.g., a *product component*. A *design constraint* constrain the possible realizations to a concept represented by a *product component*. This may be used to constrain, for instance, the maximum cost of a concept, as in Figure 6.21.

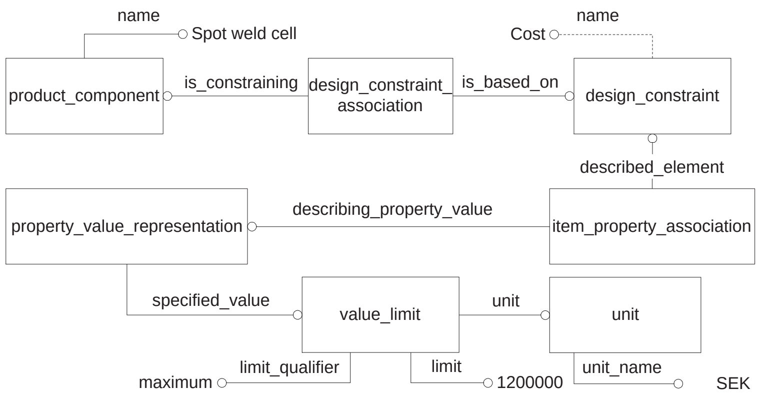

Figure 6.21. The representation of the constraints on a product component.

The constraint should be interpreted as an upper limit of the cost of the *product component*. That is, the *product component*, i.e. the concept, must not cost more that 1.2 million SEK to realize. Naturally, such a limitation decreases the number of solutions that can be considered.

As the development process continues the description of the desired function of the solution becomes more and more detailed by decomposition, cf. Figure 6.22. This is, of course, succeeded by a decomposition of the concepts too to match each functional requirement. Analogously, a *design constraint*, such as the maximum cost, may also be decomposed and related to each, e.g., sub-component.

In Figure 6.22 the assembling function is decomposed in a spot welding function, a transporting function, and a storing function. These functions can then be related to their conceptual solution respectively, as in Figure 6.20. In this case the *spot welding* function was related to a stationary spot welding component, the *transporting* function was related to a robot with a gripper component, and the *storing* function was related to a buffer component.

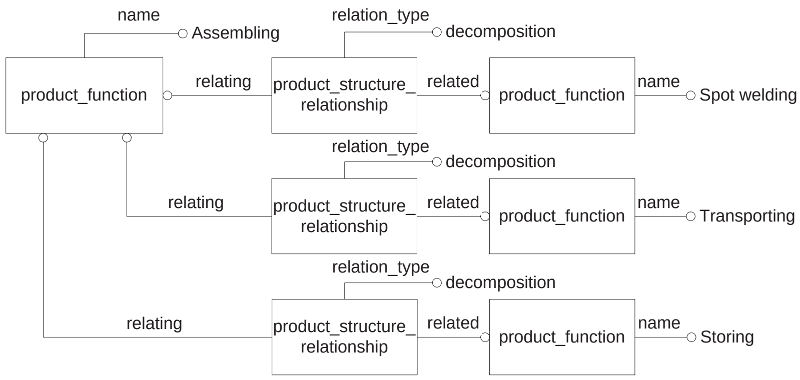

Figure 6.22. The representation of a decomposed function.

In parallel with the development of the manufacturing equipment, ABB BiW also started to develop the process plan. This is mainly done by adding information to the already existing process plan for a more detailed description of how to manufacture the carrier frame assembly.

Hence, in a similar way as with the functions and the concepts, the manufacturing process *020* was also decomposed. Two of the decomposed processes are shown in Figure 6.23. Analogous with process *020*, each of its subprocesses were associated with a *process definition*.

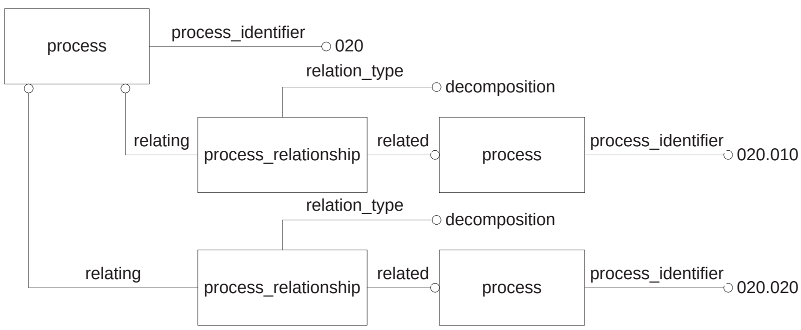

Figure 6.23. The representation of a decomposed process.

The same type of processes are, naturally, associated with the same *process definition*, e.g. the weld processes for each weld spot. Consequently, the processes in Figure 6.23 that represent the welding of two different weld spots are both related to the same *process definition*.

As the process *020* is being detailed, information about the product needed to describe what to do in a particular *process* is also associated with that particular *process*. In Figure 6.24 a *process state* of the carrier frame assembly is the input to the process*020.020* and another *process state* is the output.

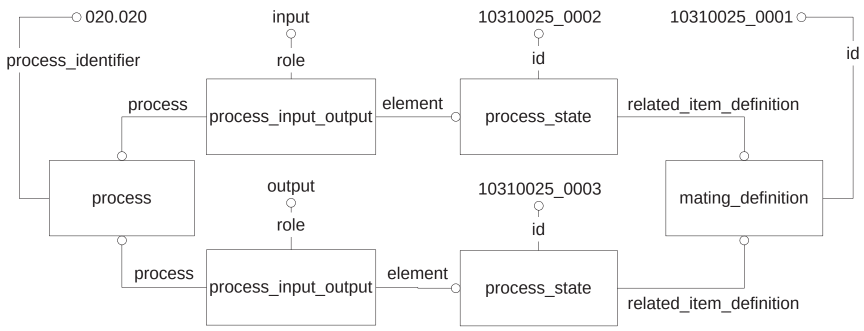

Figure 6.24. The representation of input and output of a process.

The input describe the product as it is before the process and the output as it is after the process. The *process state* is used because the 10310025 carrier frame assembly is in an intermediate state, i.e. neither is this the first process nor the last process that are needed in order to manufacture the carrier frame assembly.

If instead it would have been the first process of the process plan, i.e. where the first geometrical weld spot was welded, the input would have been the two *single instance* objects representing instances of the constituents and the output would have been a *process state*. Similar, if it would have been the last process the input would have been a *process state* and the output would have been the *mating definition*, which would represent the finished carrier frame assembly.

Note also that each *process state* is related to this *mating definition* by the *related item definition*. This is to specify the final product of which they are intermediate states.

For each input a concerned detail may also be associated. The *concerned detail* specify the detailed information about the product that is necessary to carry out the process. In this case, a weld spot, *mating element*, is a concerned detail, cf. Figure 6.25.

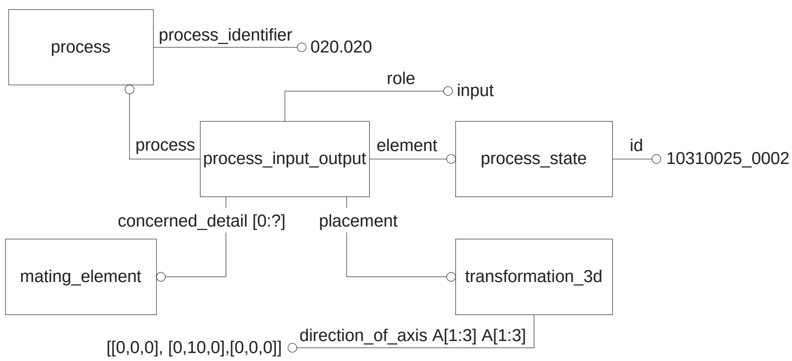

Figure 6.25. The representation of concerned detail and transformation of a process input.

In addition, a transformation of the input may be associated. The *placement* specify the transformation of coordinate space of the input to the reference coordinate space of the process. The reference coordinate space of the process is the coordinate space in which the process is defined or the coordinate space in which the reference resource is defined, cf. Figure 5.26 and Figure 6.26 respectively.

Later in the development process, when a decision to use a particular manufacturing concept have been made, the particular manufacturing concept is associated with the concerned manufacturing process. This provide an ability to document, already in the conceptual phases, what resources that are to carry out what processes.

In Figure 6.26 the weld process *020.020* is associated with the concept of using a stationary spot welding unit, represented by the *product component*, as a manufacturing resource. In addition to the stationary spot welding unit, other resources may also be associated with the same process, e.g. the manufacturing resource that will hold and position the product in order for the weld spots to be welded.

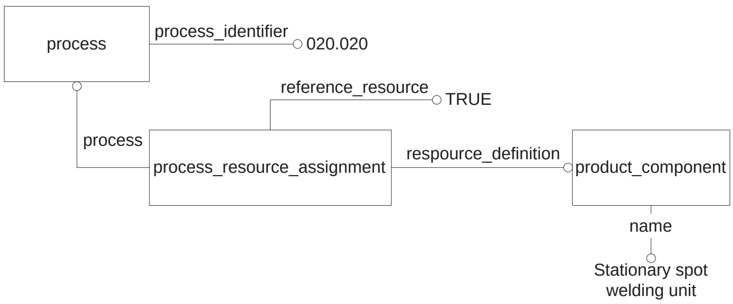

Figure 6.26. The representation of a process and its manufacturing resource concept.

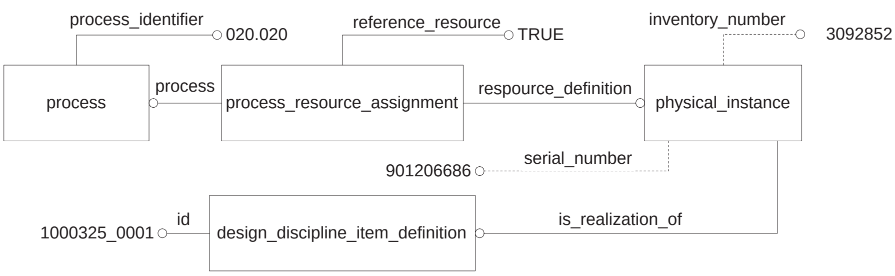

Figure 6.27. The representation of a process and its physical manufacturing resource.

Naturally, as the design of the manufacturing system solution evolves more and more detailed information is created and stored in the model. Finally, when the development project is finished, and all the serial numbers and inventory numbers of the physical manufacturing equipment is known, it is possible to represent exactly what physical resource that are to carry out a particular process. In Figure 6.27 the stationary weld gun is presented. Its serial number is *901206686*, which is different from the Scania inventory identification *3092852*.

6.3 Test of the Hypotheses

In Section 6.2 the PPR information model was validated. That is, it was instantiated to test that it could represent the information it was intended to represent. This was done by using information from a real case at Scania involving spot welding processes. Since the model is a reflection of Hypothesis 5.1 and Hypothesis 5.2, the hypotheses were tested as well.

The first hypothesis deal with the effects of the separation between the generic and specific information concepts. The information concepts behind the process plan and its processes have been considered generic information concepts and has, thus, been represented within the PPR information model. The definitions of specific types of processes have been considered specific information concepts and has, thus, been represented by instantiation of the PPR information model; in this case with the general classification mechanism.

It was shown in the Scania case that the PPR information model could represent a spot welding process. The definition of the process is represented by the *process definition*. The definition of the type of process, i.e. the spot welding process, is represented by the *general classification* and a reference to an external reference data library, in this case based on ISO13584-25. It is clear from Figure 6.28 that adding instances of *general classification* to represent any process type will not affect the representation of a process.

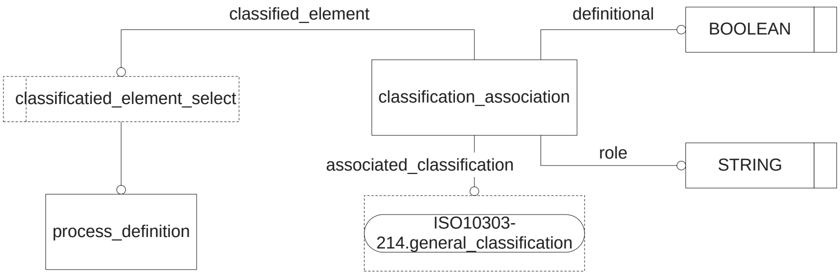

Figure 6.28. The separation between the process mechanism and the classification mechanism makes it possible to represent any type of process with the same process mechanism.

The infrastructure of the PPR information model can remain and, still, process types that were not thought of when the PPR information model was developed can be represented. This has been achieved by separating the generic information concept, the process represented by the *process definition*, from the specific information concept, the type of process represented by the *general classification*. The model can, thus, represent any type of process with the same process mechanism. Consequently, the test of the model has not been able to falsify Hypothesis 5.1 and, thus, the hypothesis has been corroborated.

The second hypothesis deal with the effect of modularization of information models. One affect is that of updating parts of the information model without affecting other parts of the model, i.e. functional separation. This has not been tested by the Scania case. However, it can be tested by logical reasoning. The information in the process plan core model is separated from non core information by interface mechanisms, such as the plan produced output mechanism in Figure 5.31.

This mechanism is presented again in Figure 6.29 in two variants. The upper variant is the same as the one that is used in the PPR information model. The lower variant is modified to use another representation of product information. It is clear that the part of the information model representing the product is changed while the representation of the *process plan version* remain unaffected. The change only affect one side of the interface mechanism, the *plan produced output association*.

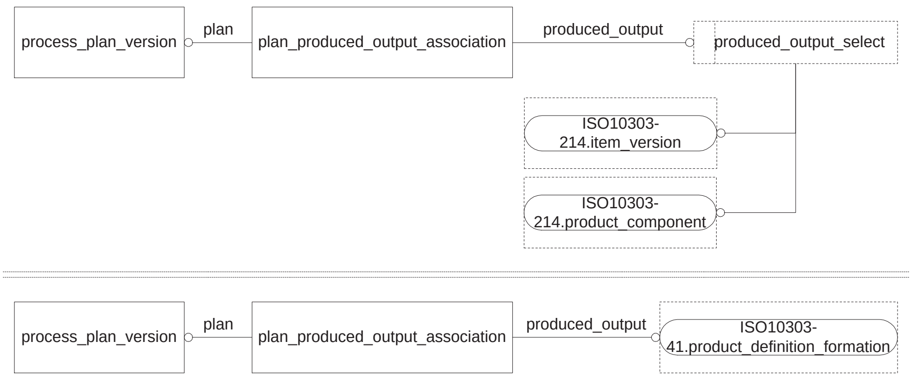

Figure 6.29. The interface plan produced output mechanism makes it possible to update or change the model representing a produced output without affecting the representation of a process plan version.

Consequently, the hypothesis has been tested and was not falsified. This leads to the conclusion that non of the hypotheses were falsified by the tests. Hence, both Hypothesis 5.1 and Hypothesis 5.2 were corroborated.

Chapter 7

Discussion and Conclusions

The purpose of this chapter is threefold. First, to interpret and explain the result by indicating its strengths and points of improvement. Second, to relate the result to previous work in the area. Third, and finally, to indicate neglected areas where further research is necessary and conclude the thesis.

7.1 Discussion

In this thesis information requirements for process planning in the context of concurrent engineering have been identified. The identified information requirements have been formalized and represented in an information model using the EXPRESS-language. The information model was then used to represent information from a Scania-ABB BiW project, the *Robot Cell - 0020* project, where a robot cell for spot welding of the *10310025 Carrier Frame Assembly* was developed.

7.1.1 Strengths and Implications of the Results

The use of information from the *Robot Cell - 0020* project to populate the PPR information model corroborated its practical use. It was shown that the PPR information model could represent information about such things as the carrier frame assembly in terms of, e.g. its identification and weld spots, the project in terms of, e.g. work requests and activities, and the processes in terms of, e.g. process plans and processes. In addition, its ability to represent information about capability, documents, functional requirements, and concepts was also shown.

Furthermore, important connections between products, manufacturing processes, and manufacturing resources were identified. These were the obvious connections such as input and output of a process, and executing manufacturing resource, but also connections such as the connection between a process and a functional requirement on a manufacturing resource. This connection provided a mechanism that can document the source of a functional requirement, i.e. its reason to be.

An implication of this is that the PPR information model enables conceptual process planning. The PPR information model can represent information about products, manufacturing processes, and manufacturing resources at the early stages when the detailed design is not yet established. In addition, the PPR information model can represent information about detailed design, as well as its evolution from conceptual design. Consequently, manufacturing related decisions taken in the early product realization process can be documented in terms of process and resource design objects. This enables traceability of the evolution of the product, process, and manufacturing resource designs and their interrelationship.

The rationale behind a particular decision may also be documented, e.g. in a text-document, and related to a particular design object. Hence, the rationale behind the decision taken to choose a particular design solution can be traced as well.

Traceability of the result of a made decisions and its rationale, in turn, enables an efficient project follow-up for quality improvement of design solutions, and improvement of the development process as a whole. For instance, a malfunction in a final product may be traced back to where the source for the malfunction was introduced. In some cases this may lead back as far as to a bad decisions to use a particular function to fulfill a customer requirement, or to use a particular concept to realize a functional requirement. Documenting the decisions enables an organization to trace this, identify the source of the problem, and avoid it in future development projects.

Consequently, the PPR information model provides a base for implementing an information system for concurrent engineering in an organization. This is independent of if the information system is human, digital, or a mix thereof.

Furthermore, the two hypotheses that were developed and corroborated have a positive affect on the longevity of information models. Modularization, in turn, enables information modules to be updated without affecting other information modules of an information model. In addition, an information model may, by modularization, be common for a whole company; some modules will be common for all departments of the company while other modules will differ. This would enable an efficient information sharing between departments through the common information modules.

The lessons learned from the research have also been used in the PDTnet[1] project. The contributions have mainly been on the use of ISO10303-214 for communication of manufacturing system development data, including process plans; on the content of the PDTnet-schema[2]; and on the development of an export interface from Tecnomatix *e*M-Planner to PDTnet-schema.

[1]The PDTnet project is a joint European project involving companies within the automotive industry, such as BMW, Bosch, DaimlerChrysler, Delphi, Scania, and Volkswagen.

[2]The PDTnet-schema is an XML-schema based on part of the ISO10303-214. The schema was configured and developed in the PDTnet project.

Finally, a detail in the process plan mechanism of the PPR information model, the process definition. The concept of a process definition is a powerful mechanism that enables the reuse of process definitional information in one or multiple process plans. This idea was, in collaboration with Mattias Johansson[3], also introduced in ISO10303-214, and accepted as part of the international standard.

7.1.2 Points of Improvement

A model can never be complete because it is a simplification of the things in the real world. If it would be complete it would be the real world. Consequently, the PPR information model has a limit universe of discourse and does not cover all aspects of the real world.

Its universe of discourse is a reflection of how the researcher, i.e. the author of this thesis, have interpreted the real world, and how the researcher have decided to express this interpretation in the EXPRESS-language. Hence, all aspects of the information model is colored by how the researcher understand and interpret the real world and the researchers ability to express this interpretation.

Other researchers may understand and interpret the real world differently, all colored by their own pre-understanding of, in this case, the innovation process in general and the process planning activity in particular. They may identify requirements that they find important and that have not been identified here. This will be more frequent in areas where little, or no, research and modeling have been done, and the arguments and criticism in these areas will probably be more aggressive. Typically these areas are: (i) capability, (ii) location system, and (iii) mating.

As these three areas are quite new in the information-modeling society they are also, most likely, the parts of the PPR information model

[3] Mattias Johansson is a former researcher in the research group at the Computer Systems for Design and Manufacturing at Kungliga Tekniska Högskolan, Sweden.

where most improvements can be made. Especially, more consideration could have been put on how the feature concept is related to the concepts of capabilities, location systems, and matings.

In addition to questions that may be raised about capability, location system, and mating, questions related to terminology, definitions, relationships, level of detail of the model, level of abstraction of the model, modeling technique, and modeling philosophy may also be raised. For instance, can matings be represented in another and better way? Probably, or rather, most certainly, depending also on who you ask and this persons interpretation of the intention and purpose of the model.

Misinterpretation is also minimized by using a consistency throughout the information model. This concern both the terminology and the information concepts. It is important to decide, beforehand, on a naming convention so that the same concept have the same name throughout the model. This count for the information concepts as well, i.e. that similar information concepts in the model will be represented by similar modeling mechanisms.

This may be difficult, especially since there is a lack of established and formally documented methodological approaches to information modeling. It may even be difficult to keep the consistency when only one person is involved in the modeling activity. In the PPR information model this can be noted in, e.g., the use of reference data libraries for classification of process definitions, and for definition of capability. Naturally, a process definition could have been classified with the same mechanism as a capability.

Furthermore, the use of ISO10303-214 also complicated the consistency in naming convention and how similar concepts were represented. A typical example is that the attribute used to identify a particular object, e.g. a product, is called *identifier* in the PPR information model, whereas ISO10303-214 usually call this *id*. The definition and meaning is the same, but the references to the definition differ.

The naming and representation of some concepts in ISO10303-214 also led to compromises in naming and representation of some concepts in the PPR information model. In particular this is true for the mating definition and the mating element. Terminology wise the preferable terms would have been joint and joining element. Representation wise the mating definition mechanism in ISO10303-214 need further development. An example of a limitation is that the mating definition is not actually a joint, it is a view of the product from a mating perspective. In this view the equivalence to joints and joining elements cannot be identified.

The attempt in the PPR information model has been to use the *mating definition* not only as a view but as a joint. Then the *mating element* was added to uniquely identify a single joining element within a particular joint. A better solution would have been to develop and add a joint definition mechanism, which could have included joints, joining elements, and new relations to the *design discipline item definition* and the *item instance* entities.

Modularization of information models seem to have the same affect on information models as on products, e.g. carry over and technology development. However, modularization could have been used in a more structured way and more consistent throughout the PPR information model. For instance, could the Modular Function Deployment[4] (MFD) method have been applied? A more systematic and consistent way could also have been used when developing the interfaces between the different modules.

Finally, some thoughts on the choice of research subject. During the course of the research project it has been identified, as already mentioned, that no real methodology for information modeling exist. This would have been an interesting research subject with a high quality of novelty. The subject was touched upon during the discussion and testing of the hypotheses but need further investigation and development. For instance, what modularization methods exists that can be applied on information modeling, and how can they be applied?

[4]For further reading on Modular Function Deployment see (Erixon, 1998)

7.1.3 Fulfillment of Research Objectives

In the beginning of the research project two research objectives were set, cf. Section 1.2. The two objectives were then used as a base to formulate the three research questions that was used to guide the research project. Have the effort made in the research project resulted in answering these questions?

Research question 1. What information is needed for process planning?

Research question 2. What information is needed to describe the relationships between products, manufacturing processes, and manufacturing resources?

Research question 3. How can the information be structured in an information model?

From the discussion in Section 7.1.1 and Section 7.1.2 it is clear that the first and second questions have been answered by the information model. That is, the PPR information model represent the information requirements for process planning in the context of concurrent engineering.

The third question is also answered by the information model, i.e. the information model describe *how* in terms of the relationships between different information concepts. However, the third question could also be interpreted so that the expected result would be an information modeling methodology. The two corroborated hypotheses clearly is a result that would apply within the methodology domain. They indicate how information can be structured, and what the expected effects are.

7.1.4 Related Research

The findings of this thesis have similarities and differences to findings made by other researchers. In this section, some of the similarities and differences will be pointed out and discussed. Five aspects of the findings will be discussed: (i) the overall structure of the information model, (ii) representation of manufacturing processes, (iii) conceptual process planning, (iv) capability, and (v) weld joints.

Structure of the Information Model

The PPR information model is structured according to the idea of having a process plan core model, which is separated from other types of information by an interface. In literature, when process planning is discussed, different types of information is often clearly separated. For instance, Eversheim et al. (1991); Eversheim and Westekemper (2001); Feng and Song (2000); and Kimura (1993) clearly separate what is manufactured, the manufacturing process itself, and the manufacturing resources that carry out the manufacturing process.

However, Eversheim et al. (1991) and Kimura (1993) do not define information models. Their focus is to discuss the relationships between the different models and how the engineering task can benefit from using information from different domains.

Eversheim and Westekemper (2001); and Feng and Song (2000), on the other hand, define information models that have a similar content as the PPR information model. However, the structural differences are that both Eversheim and Westekemper (2001) and Feng and Song (2000) do not clearly separate the representation of different types of information with an interface. Consequently, a change to part of the models may have considerable effects on other parts.

The separation between different types of information is more clear in the work that Johansson (2001) has done on ISO10303-214. It is, however, no indication that there is a formalized method behind this separation, neither is the separation consistent throughout ISO10303-214.

In general, the structure, and intention of separating different types of information, are similar with what other have done. In more detail, though, other researchers do not seem to share the same philosophy of how this separation should be modeled.

A clear disadvantage here is that no well defined information modeling methodology exists today. Not in general and not when modularization is considered. Within the ISO10303 there is a work focusing on modularization of several of the different parts of the standard. Their work have, however, not yet been documented, methodology wise.

Representation of Processes

When representing manufacturing processes two fundamentally different approaches can be identified. These two approaches are here called the specific and the generic approach. The difference between these approaches is that whereas the specific approach specifically define different types of processes, e.g. the model developed by Feng and Song (2000), the generic approach does not, e.g. the model developed by Eversheim and Westekemper (2001) and the process plan core model.

Obviously, a specific approach will be obsolete whenever a new process type is developed. This will also be the case if not all process types were considered when the model was developed. A problem that does not occur in the general approach as the process representation is general and no specific process type is indicated in the model. On the other hand, the generic approach has its limitations in that the semantics of the type of process may be lost.

This problem can, however, be solved by using an external dictionary, e.g. a reference data library like ISO13584. The process plan core model make use of an external dictionary for representing classification of processes. This is not the case in the model developed by Eversheim and Westekemper (2001), but it has another advantage in terms of generality. It is not limited to manufacturing processes. It can, in fact, represent any types of processes, including product development processes, which is also the case with the *Process Specification Language* (ISO/TC184/SC4, 2000).

An important aspect of process representation that separates these models from the process plan core model is that of the ability to reuse different processes without redefining them. Lutters et al. (1999) indicate that implemented methods, i.e. process definitions, may be used as a set of capabilities that are available, which may be used as an information base to constrain a product design. A process definition mechanism is available in the process plan core model. Hence, the process plan core model enables the reuse of process definitions, which in turn may be used as an information base for product design constraints.

The concept of a process definition mechanism is also available in the ISO10303-214. The reason is, which was mentioned earlier, that the author of this thesis and Mattias Johansson have, in collaboration, introduced this concept and mechanism in the standard.

Conceptual Process Planning

In Section 6.2 it was shown that the PPR information model can be used to create a development process where process planning is an active part of the development of a manufacturing system. This is clearly different from traditional process planning, cf. Curtis (1988) and Ham and Lu (1988), where manufacturing resources are selected rather than developed.

Feng and Song (2000) use the term concept process planning for an activity where manufacturability is assessed and cost is estimated. They continue to describe this as determining the processes and selecting the manufacturing resources. Hence, it is a traditional way of planning, only earlier. This is clearly different from being an active part of manufacturing system development.

Capability

Capability is usually represented in mathematical and numerical models (Kulvatunyou and Wysk, 2000), such as the 6 σ or six standard deviations (Juran, 1988), or the loss function (Taguchi et al., 1989).

The focus of these models are usually on the probability of a manufacturing resource to achieve something within the tolerances, e.g. the finish of a surface or the fitting of parts in an assembly. Naturally this is an important aspect of manufacturing, but the mathematical and numerical models that Bergman and Klefsjö (1998); Curtis (1988); Juran and Gryna (1988); and Taguchi et al. (1989) use does not say anything about the ability of a manufacturing resource to make, e.g., a particular shape or a particular joint, nor its ability to operate on a particular material. The intention of the capability mechanism in the information model of this thesis is to enable the definition of any type of capability.

Weld Joints

A lot of research have been conducted in the area of weld joints. Mainly the research have been related to how the material is affected, the weld process itself, or how to design a weld joint, e.g. Ceglarek and Shi (1998); Zhang et al. (2000); and Zhang et al. (2002). However, in the area of information representation of weld joints the research work is sparse.

Though a few exceptions exists. For instance, in Germany the GACI project (German Automotive CATIA Initiative) have been working on how to represent connections, including weld joints, in CATIA (Vielhaber, 2003). Similarly, Porsche have started to work on how to represent fasteners, including weld joints, in ISO10303-214 (Rosenthal, 2002). Some initial approaches on joint representation have also been made by Holmer et al. (1990); and Kjellberg (1984, 1987, 1988).

7.1.5 Identification of Further Studies

Most of the areas where further studies are necessary have already been indicated in the previous text. Thus, this section will merely summarize and make a list of these studies.

Further studies could take two directions, studies on principles of information modeling, and information requirements on process planning:

- Principles of information modeling:
  - Activity modeling - investigate and formalize the use of activity modeling to support information modeling.
    - Multiple activity models - investigate how different activity models can be used together. Develop prototype software that make use of different activity models, but with the same information base.
    - Support for information modeling - formalize the use of activity modeling to support information modeling.
  - Modularization - investigate how modularization can be used in information modeling. How should modules be created and what are the criteria? How should interfaces be created?
  - Reference data libraries, such as ISO13584 - investigate how reference data libraries can best be used to benefit from both having a generic and specific model. What reference data libraries exist? How should the reference mechanism be modeled? What should be part of the information model and what should be part of the reference data library?
  - Methods, such as axiomatic design (Suh, 1990) - structured approaches for information modeling and criteria for information models are needed. What constructs are better in particular situations? What level of detail is suitable? What level of abstraction is suitable?
- Information requirements on process planning:
  - Capability - investigate further how capability should be represented. What is capability? What characterizes different types of capabilities?

– Joints[5] - investigate further how joints should be represented. What are the different types of joints? What characterizes the different types of joints? How should these characteristics be represented? How can ISO13548-511 be used for classification/definition of joining elements, or fasteners?

– Location system - investigate further how location systems should be represented. How should the relation between location systems be represented, e.g. location point on product and clamp on a fixture?

7.2 Conclusions

As already mentioned, the research project presented in this thesis have identified information requirements for process planning in the context of concurrent engineering. These requirements have been in an information model using the EXPRESS-language. From the project and the work with the PPR information model the following conclusions have been made:

- The PPR information model represent identified information requirements for process planning.
- Important connections between the product, process, and manufacturing resource has been identified by the PPR information model, e.g. input, output, and functional connections.
- The PPR information model provides a base for an information platform in a concurrent engineering environment.
- Documentation of decisions made in the early stages of a product realization project is important for traceability and continuous improvements.

[5]In the PPR information model joints have been called a matings. However, there is a need to clearly separate these two concepts in an information model.

- Separation of generic and specific information concepts, as described in this thesis, affect the longevity of information models positively.
- Mating and joint are both important concepts and should be clearly separated in an information model.
- Modularization of information models enables an efficient maintenance of information models and information systems.
- Modularization of information models enables the reuse of the representation of information concepts.
- Modularization affect the longevity of information models positively.
- Modeling and representation of concepts must be further developed, e.g. the use of dictionaries and ontology.
- Better methods to support information modeling need to be developed.
- Modularization of information models need further investigation.
- Representation of joints, capability, and location systems need further development.
- The ISO10303-214 need further development in terms of representing joints.

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Appendix A

Definitions

Definition 2.1. A singular statement is a statement that accounts of results from observations or experiments.

(Popper, 2003)

Definition 2.2. A universal statement is a statement in terms of a theory or a hypotheses.

(Popper, 2003)

Definition 2.3. A hypotheses is a tentatively anticipated universal statement that is the subject of testing.

From (Popper, 2003)

Definition 3.1. M is a model of a system S if M can answer questions about S with an accuracy of A.

(Marca and McGowan, 1988)

Definition 3.2. An event is an instantaneous happening that have an effect on the universe.

Definition 3.3. An action is the state of acting or doing.

(American Heritage, 2000)

Definition 3.4. An activity is a set of actions that consumes time while it makes a change to the universe.

Adapted from ISO/TC184/SC4 (1999)
and ISO/IEC/JTC1/SC7 (2001)

Definition 3.5. Data are symbols which represent information for processing purposes, based on implicit or explicit interpretation rules.

Adapted from Schenck and Wilson (1994)

Definition 3.6. Information is data interpreted in its original meaning.

Definition 3.7. Knowledge form the sum of experiences and information a person have collected and more or less consciously structured for its needs.

(Holmer et al., 1990)

Definition 3.8. Competence is the ability to use the acquired knowledge to make appropriate decisions and actions.

Definition 3.9. An information model is a formal description of data and its interpretation rules.

Definition 4.1. Innovation is the transformation of customer needs into new products on the market, from idea until a stable manufacturing process is established.

Definition 4.2. A transformation process transforms an input to an output by adding values to satisfy previously declared needs.

Adapted from Hubka and Eder (1988)

Definition 4.3. The sum of all elements and influences (and their relationships among them and to their environment) that participate in a transformation is collectively termed a transformation system.

(Hubka and Eder, 1988)

Definition 4.4. Concurrent engineering is the simultaneous consideration of more than one aspect of a system during its design phase.

Definition 4.5. A feature is a perceived geometric element, functional element, or property of an object useful in understanding the function, behavior, performance, or manufacture of that object.

Adapted from Brown et al. (1992)

Definition 4.6. A manufacturing process is a process that transforms a physical object from one state to another.

Definition 4.7. A process is a set of interrelated activities.

(ISO/IEC/JTC1/SC7, 2001)

Definition 4.8. A product is an object intended to be sold to, or leased by, a customer.

Definition 4.9. A resource is an object that is used, or consumed, to fulfill some need of the user.

Definition 4.10. Capability is the inherent ability to deliver performance.

Adapted from Juran (1988)

Definition 4.11. Machine capability refers to the reproducibility under one set of process conditions.

(Juran and Gryna, 1988)

Definition 4.12. Process capability refers to the reproducibility over a long period of time with normal changes in workers, material, and other process conditions.

(Juran and Gryna, 1988)

Appendix B

List of Publications

1. Nielsen, J. and Kjellberg, T. The ISO 10303-214 Process Model as a Core for a Process-Planning Tool. In *International CIRP Design Seminar*, 2000.

2. Nielsen, J. and Bernard, B. Modeling and Discrete Event Simulation Supporting Conceptual Design of Manufacturing Systems. In *The 33:rd CIRP International Seminar on Manufacturing Systems*, 2000.

3. Nielsen, J. Inte bara frid och fröjd i den digitala fabriken. *Verkstadsforum*, 5, 2000.

4. Nyqvist, O. and Nielsen, J. Features as Part of the Functional Interface Between Product and Resource: An Approach Based on Standards. In *International CIRP Design Seminar*, 2001.

5. Kjellberg, T. and Nielsen, J. Digital Information System for World Class Manufacturing. In *The Fourth Workshop on Current CAx Problems*, 2001.

6. Aganovic, D. and Nielsen, J. Current Trends and Emerging Technologies in Digital Manufacturing. In *CIRP Design Seminar*, 2002.

7. Aganovic, D., Nielsen, J., Fagerström, J., Clausson, L., and Falkman P. A Concurrent Engineering Information Model based on the STEP Standard and the Theory of Domains. In *International Design Conference - Design 2002*, 2002.

8. Aganovic, D., Nielsen, J., Fagerström, J., and Falkman P. Multi-Viewpoint Modeling of the Innovation System - Using a Hermeneutic Method. In *ICAD 2002*, 2002.

9. Falkman P., Nielsen, J., and Lennartsson, B. A Formal Mapping of Static Information Models into Dynamic Models for Process Planning and Control Purposes. In *Workshop on Discrete Event Simulation (WODES) 2002*, 2002.

10. Nielsen, J. Standards for the Digital Plant: An Overview. In *International Symposium on Robotics (ISR) 2002*, 2002.

Appendix C

Volvo Car Corporation - A Case Study Report 2000

Authors:	Johan Nielsen, KTH/DKT, and Petter Falkman, CTH/CAL.
Participants:	Johan Nielsen, KTH/DKT. Petter Falkman, CTH/CAL. Jonas Rosén, KTH/DKT.
Supervisor:	Niklas Andersson, VMC.
Interviewed persons:	Anders Carlsson, VMC/PAS. Andreas Westholm, team leader CADCAM. Björn Söderberg, geometry assurance P2. Carl Angervall, C-plant. Christer Pettersson, FKB-process. Fredrik Forsman, weld spot database. Lars Johansson, DMU-project. Negar Ghassemi, Corporate standards. Niklas Andersson, VMC. Olle Hansing, VMC/PAS. Torbjörn Wissö, VMC/PAS. Ulf Malmberg, Corporate standards. Ulla Franke, VMC/PAS.

C.1 Introduction

Assar Gabrielsson and Gustaf Larson founded Volvo Car Corporation (VCC) in 1927, since then the guiding principle has been safety. Today VCC is part of Ford Motor Company within the Premium Automotive Group (PAG). VCC has a total number of employees of 25 400 and production cites all over the world, e.g. Sweden, Belgium, Malaysia and South Africa. In 1999 the total number of produced cars was 408 150.

A vision at VCC is to provide engineers with the capability of Virtual Manufacturing, i.e. a computer-based environment to model, test and validate the manufacturing of any product. Ultimately, such an environment will provide a solid base for all decisions without any physical prototypes, but also a way to directly control the manufacturing without any manually generation of control code. However, to be able to compare different test runs, both input (data/information) and the working methods need to be unified. In other words, there is a need for common representation of data/information as well as common definitions of how data/information is created and changed and what data/information is needed for a particular test run.

Two crucial processes within the Body-in-White operations are the development and management of process points, e.g., development and management of reference points, or master location points as they are named in the Volvo corporate standard STD 5026,2 (Volvo, 1996). Process points are used, e.g., during the design of a car, development of manufacturing and assembly processes, analysis of gaps and inspection of the final results. Of course, process points are one of the inputs in virtual manufacturing and thus falls under the same requirements of unified input and working methods as stated in the paragraph above.

To accomplish unified inputs and working methods in the scope of master location points, location points (or body handling points) and weld spots within the VCC Body-in-White operations, a project (Digital Plant - VCC) was initiated. The project was subordinate the Process and Assembly Structures (PAS) project, which deals with Product

Data Management (PDM) issues such as information requirements for the PDM-system Enovia from IBM. See Figure C.1 for an overview of the project organization.

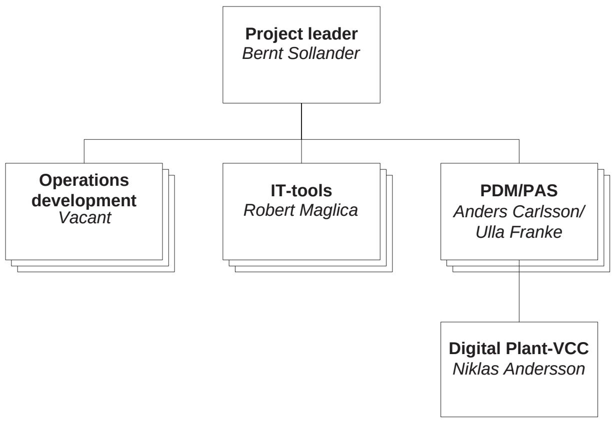

Figure C.1. Project organization at Volvo Car Corporation.

Although the Digital Plant - VCC (DPV) project was subordinated the PAS project it worked as an interface between PDM and operations development (OD), cf. Figure C.2.

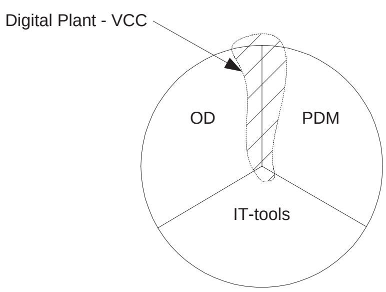

Figure C.2. Organizational scope of the Digital Plant - VCC project.

The scope of the state-of-the-art study at Volvo Car Corporation was, therefore, limited to find in what extent virtual manufacturing has been implemented within Body-in-White operations. The issues that are highlighted are related to the development and management of master location points, location points and weld spots. For instance, how these process points are influencing the decisions made from analysis of Digital Mock-Up´s (DMU´s), simulation of assembly processes or Off-Line Programming (OLP) of weld robots.

C.2 Process Points

Process points are created for the purpose of handling, positioning, inspecting, assembling, etcetera, product parts. These points are used to specify the product and are essential for the outcome of the manufacturing process. Often different types of process points are exchanged between the manufacturing system vendor and their customers. Following is an incomplete list of different process point types:

- master location point (reference point),
- location point,
- weld spot, and
- inspection point.

C.3 Master Location Point

The purpose of using a master location system is to determine the interposition of parts included in the vehicle and to ensure the right quality of the final car (Volvo, 1996). By using a master location system, initial points for requirement specification, manufacturing and inspection can be established consistently. It also simplifies analysis, e.g. finding errors in the production.

A reference point, or master location point, is a point on a part, fixed in a Cartesian coordinate system by the intersection of three coordinate planes, i.e. X-, Y- and Z-plane (Volvo, 1996). It is intended for theoretical determination of position of a part in a coordinate system and is represented in the physical world by a master location surface. A master location surface is intended for practical use to determine the location of a part, and the surface position is represented by a locating feature, e.g. guide lugs, guide pins, holes. Locating features are not only part of the product but also represented in the manufacturing system by a corresponding feature on the fixture. A locating feature is used as a position indicator for part location, cf. Figure C.3.

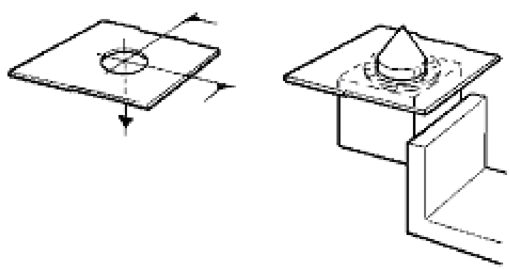

Figure C.3. A locating feature for three guide functions (from Volvo (1996)).

To determine the location of a part the 3-2-1-rule is used, i.e. at least three points in the Z-plane, two points in the Y-plane and one point in the X-plane are needed to fully determine the location of a part, cf. Figure C.4.

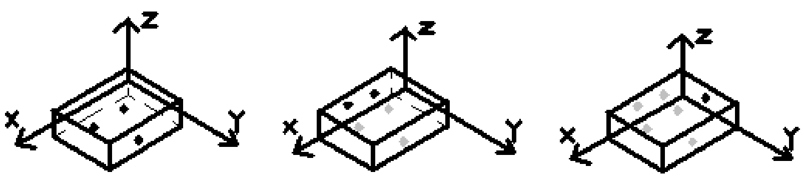

Figure C.4. The 3-2-1 rule is used to determine the location of a part.

At Volvo Car Corporation (VCC) Master Location points are defined by the following data;

- 3D-location - defines the location of the reference point in a Cartesian coordinate space,

- guiding orientation - defines the direction in which the reference point should locate the part,
- locating feature - defines the representation of a reference point in the physical world, and
- project - the project in which the reference point is used.

C.4 Location Point

A location point, is a point on a part, fixed in a Cartesian coordinate system by the intersection of three coordinate planes, i.e. X-, Y- and Z-plane (Volvo, 1996). It is intended to supplement master location points for theoretically determination of position of slender parts in a coordinate system. Location points are represented in the physical world by a location surface, which is intended for practical use to determine the location of a part and its position. A locating surface is represented by a locating feature, e.g. guide lugs, guide pins, holes etcetera. A locating feature is used as a position indicator for part location, cf. Figure C.3.

C.5 Weld Spots

A weld spot is a discrete point where two or more metal sheets are joined in a weld joint. Weld spots are defined by the following data:

- spot identification - uniquely identifies the spot,
- 3D-location - defines the location of the spot in a Cartesian coordinate space,
- geometrical point - defines if the spot is welded early in the production process to keep the body together, and
- description - additional free text description of the spot,

- weld model - identifies the weld spots created within a certain project of a certain module team,
- weld joint - identifies a set of one or more weld spots, and
- weld process - defines the properties that are needed to weld a certain spot.

Several corporate standards are related to the development and management of weld spots, e.g.:

- Spot Welding - Symbolic representation and requirements
- Spot welding - Symbolic representation and definitions in 3D-models
- Quality assurance spot welding - It gives references to the requirements for spot welding, test methods and routines for checking and re-working operations.
- Welding date for spot welding of two-sheet combinations - The standard specifies base values for welding data of various thickness.

C.6 Master Location and Location Point Preparation

The activity model in Figure C.5, is a result of interviews and review of existing process documentation at VCC from a production point of view. The results or the output of the *master location and location point preparation* activity are *change orders*, *existing product solution*, *new product solution*, *identified consequences*, and *frozen master location and location points*. The inputs to the activity are *existing product* and *miscellaneous*. Existing and new product solution and frozen master location and location points are represented in the NUFO[1]. *Product requirements* and *existing industrial system* constrain whereas *engineers* support the master location and location point preparation activity.

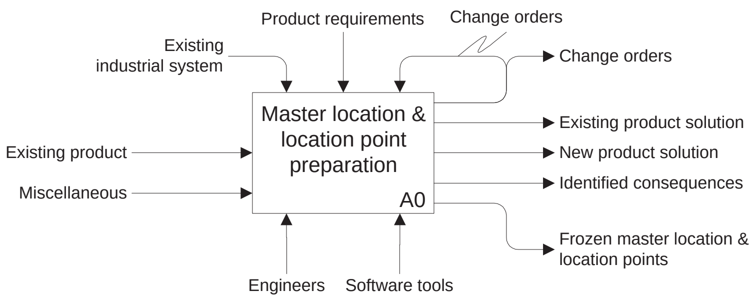

Figure C.5. IDEF0-diagram of the master location and location point preparation activity.

The master location and location point preparation activity can be decomposed into *product design*, *consequence identification*, , and *master location and location point change*, cf. Figure C.6.

During the product design activity, cross-functional module teams create a *proposed new product*, represented by the NUFO. The proposal is based on an *existing product* and constrained by *product requirements*, *existing industrial system* and sometimes *change orders*. During the activity, tolerance chain analysis takes place to identify and correct system solutions that are not fault tolerant. For some system solutions, tolerance chain analysis takes place before any geometry exists. The location of master location and location points are verified by the manufacturing engineers and documented by the product engineers.

The main purpose of the consequence identification is to result in a basis for the decision activity. Consequence identification is divided into three steps. The main objective of the first step is to identify areas in the existing industrial system that are affected by the changes of the master location and location points in the proposed new product. The second step involves comparison of changed product prerequisites with

[1]NUFO is the abbreviation for NUmerisk FOrmgivning, which is Swedish for numerical shaping.

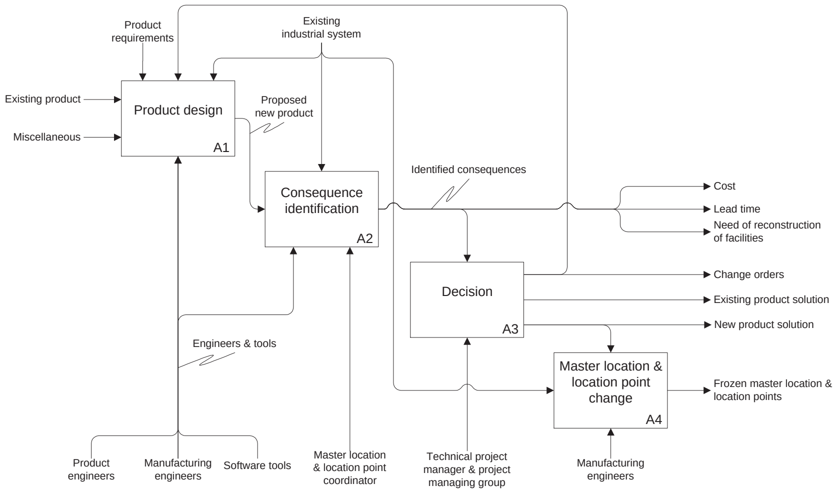

Figure C.6. IDEF0-diagram of the decomposed master location and location point preparation activity.

existing master location and location points for the identified areas in the existing industrial system. The purpose of the second step is to identify deviations in the proposed new product compared to the existing industrial system. In the final step the identified deviations is used as a base to identify and analyze the consequences of the proposed new product. The result is *identified consequences* in terms of *cost*, *lead-time* and *need for reconstruction of facilities.*

The identified consequences, i.e. cost, lead-time and need for reconstruction of facilities, are used as a basis for decision. The result of the decision is to use the *existing product solution*, in terms of master location and location points, or to use the *new product solution.* When a new product solution is rejected the master location and location points of the existing product solution are used and thus a *change order* to use the existing product solution is sent to product design. The *technical project manager & project-managing group* (usually the module team managers) participate in the decision-making activity.

When a new product solution is accepted the activity flow continues with *master location and location point change.* The main objectives with this activity are to change master location and location points in the existing industrial system to fit the new product solution and to assure the topicality of these points. The result is *frozen master location and location points* of a modified industrial system.

C.7 Weld Spot Preparation

In 1998 a study of the weld spot management was conducted and documented in the Weld Spot Management-report (Maglica, 1998). The purpose of the study was to identify and document the activities for the development and management of weld spots. According to the author, Robert Maglica, the proposed activities from 1998 is still valid and has been the base for the development of a weld spot database where weld spot data is stored. This section will briefly present and discuss the activities for weld spot preparation.

In Figure C.7 an overview of the weld spot preparation activity is presented. The result or the output of the activity consists of *change orders*, *verified weld process specifications (WPS)*, *verified process inspection and instructions (PII)* and *verified robot programs.* The input to the activity consist of the *NUFO*, describing the geometric properties of the metal sheets that make up the car body, and *sheet data* (Excel-document), describing the material characteristics of the metal sheets. The NUFO also include master location points as well as location points. *Engineers* from various disciplines using a set of *software tools* perform the activity, which is constrained by the product and process requirements.

The weld spot preparation activity can be decomposed into *weld joint design*, *weld process planning* and *process instruction creation*, cf. Figure C.8. The three activities are executed concurrently and have no sequential priority.

During the weld joint design activity the *designers* create a set of weld spots that are assigned to the car so that the *product requirements* and *change orders* are fulfilled. Based on joint requirements the designer

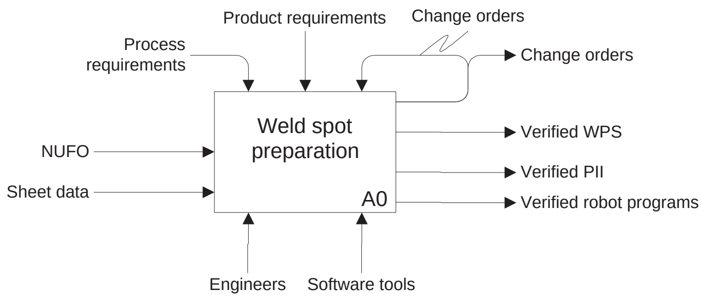

Figure C.7. IDEF0-diagram of the weld spot preparation activity.

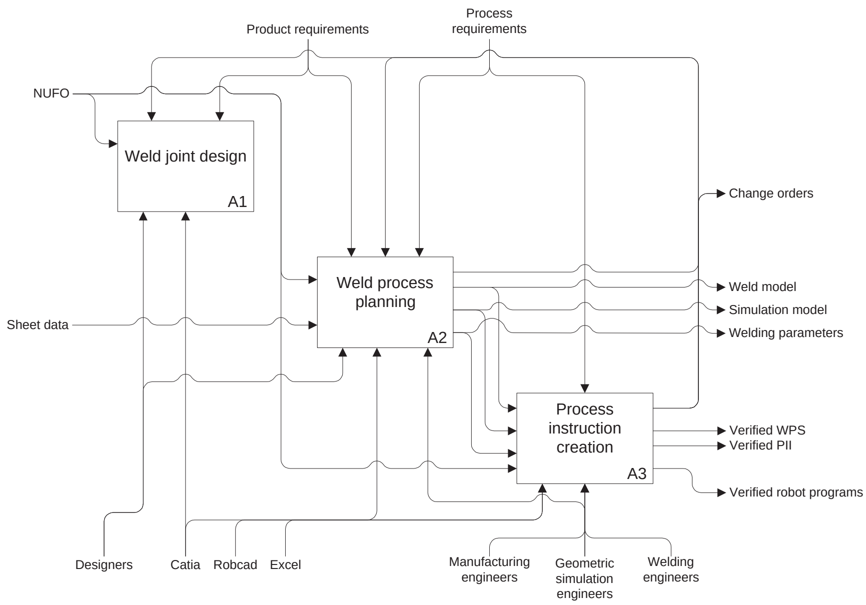

Figure C.8. IDEF0-diagram of the decomposed weld spot preparation activity.

adds a number of weld spots to the NUFO using Catia. However, the weld spots are stored separate from the sheet data in a *weld model* within the NUFO.

The main purpose of the weld process planning activity is to assure that it is possible to manufacture the car body in the proposed manufacturing unit, which is either an existing unit or a unit under development. The activity is very complex and therefore several different disciplines collaborate resulting in:

- *change orders* - issued back to weld joint design when weld spots need to be relocated (paper format),
- *simulation model* - geometric properties and dynamic behavior of the manufacturing system including the product to be manufactured (RobCAD-format),
- *welding parameters* - set of data defining the weld process (Access database), and
- *weld model 2* - same as weld model with the difference that some weld spots may have been relocated and some weld spots may have been designated as geometry points (Catia-format).

Inputs to the process planning activity are NUFO, weld model and *sheet data*. The sheet data is an Excel-document describing the material characteristics of the metal sheets of the car body. The content of the Excel-document originates from the KDP[2]-system.

During the product instruction creation activity the *designers*, *manufacturing engineers*, *geometric simulation engineers* and *welding engineers* create and verify the *weld process specification (WPS)*, *process instruction and inspection (PII)* documents and *robot programs*. Some times weld spots need to be relocated and thus *change orders* are created. The weld process specifications are created manually and are

[2]KDP is an information system that represents the product structure.

downloaded to the welding controllers. The process instruction and inspections are created in Catia and shows the location of the weld spots. Finally, the RobCAD-tool called VOLP (Volvo Off-Line Programming tool) is used to create the robot programs that are to be downloaded to the robot controllers.

Weld spot preparation is a complex activity and several *engineers* are involved during the development and management of weld spots. A large part of the weld spot definition is carried out by sub-contractors outside of VCC and thus makes the matter even more complicated.

C.8 The Use of Master Location Point and Weld Spot Data in Virtual Manufacturing

Today, assembly of product parts is validated in digital mock-ups (DMU's) in VMAP, Dassault Systemes/Deneb (now Dassault Systemes/Delmia Corporation) and 4D-Navigator, Dassault Systemes/CATIA and has reduced the need for physical test objects significantly. In VMAP the part trajectory is analyzed to detect collisions, assembly time estimation etcetera. 4D-Navigator is mainly used for assembly method analysis to validate part sequence, dynamic fitting of parts, and simple tool analysis. Master location points are, however, not used during the DMU-analysis. The reason is that all product parts should defined in the vehicle's main coordinate system (Volvo, 1994), cf. Figure C.9. Thus translations between local coordinate systems do not need to be taken into consideration during the DMU validation.

The DMU-tools, VMAP and 4D-Navigator are fed product data from VPM, PDM-system from Enovia, cf. Figure C.10. The product data origins from the four in-house-built systems PM (main document for 3D-geometry), KDP (product structure), POS (position of geometry) and PKI (process structure).

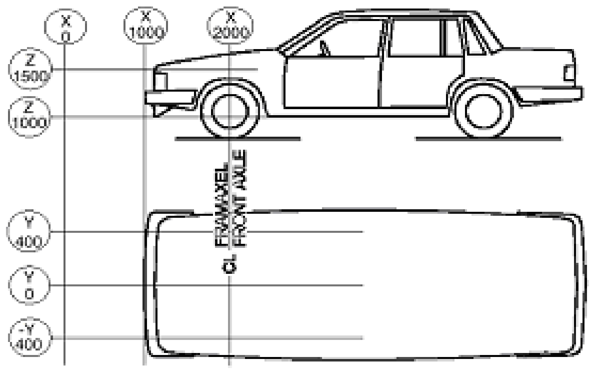

Figure C.9. Main coordinate system of vehicle (from Volvo (1994)).

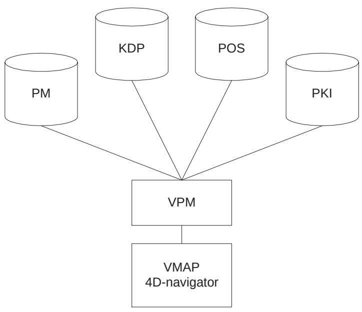

Figure C.10. Overview of systems for DMU-analysis.

Master location and location points are used in product design activity as input to the RDT-tool (Robust Design and Tolerancing) (Söderberg and Lindkvist, 2000) for analysis of the robustness of the design in terms of placement of master location points. Depending on variance in material and spring back etcetera, the placement of master location points can either damp or amplify the variance.

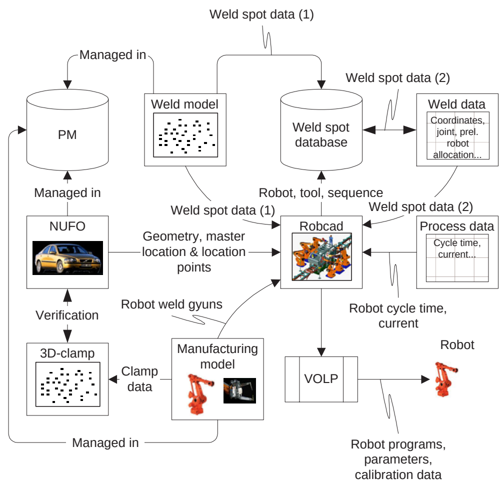

Figure C.11. Overview of input data to Robcad for weld spot validation and OLP.

In Figure C.11 an overview of necessary input data and systems for validation and OLP of weld processes is presented. In the center is Robcad, a robot simulation software from Tecnomatix. In Robcad the sequence of weld spots, that weld spots are within reach of weld robots and weld guns, that weld spots are not positioned to close to master location points and collision detection are tested. Robcad is also used to feed VOLP (Volvo OLP) with robot movements. VOLP then creates robot programs that can be uploaded to all on-line robots. VOLP manage calibration of the robots extremely well and thus on-line touch-up can be reduced to a minimum. The information used in Robcad originates from different sources, cf. Table B.1.

One of the largest problems related to the exchange of information in Figure C.11 is to update the manufacturing model in the same pace as

Source	**Format**	**Content**
Weld model	Catia	Spot id, location, joint belonging, and lens diameter.
Weld data & process data	Excel	Part id, sheet thickness, material, surface quality, welding time, welding current, electrode force, electrode diameter, welding gun, and weld spot sequence.
NUFO	Catia	Geometry of the car, master location and location points.
Manufacturing model	Different CAD-formats	Robots, tools (weld guns, grippers, etcetera), palettes, fixtures, and peripheral equipment.

Table C.1. Information sources for Robcad-simulation.

changes are introduced in the product model, e.g. changes of master location points. For this reason the clamp data of the manufacturing system design is continuously compared to the master location points of the product model to verify that each clamp of the manufacturing equipment have its corresponding master location point on the product.

C.9 Discussion and Conclusion

The case study at VCC has focused on the development, management and use of master location points, location points, and weld spots in virtual manufacturing within body-in-white. A key issue for virtual manufacturing to take affect, which is well understood at VCC, is that virtual manufacturing should not be an end in itself but a tool to support decisions. What decisions that are to be made must be understood before modeling of a product or a manufacturing system takes place. The modeling activity must provide the right information for the test.

The quality and the content of the information must be uniform for different test series. Otherwise the result of the different test series cannot be compared on a fair base.

Working methods and management of information is crucial for the outcome of virtual manufacturing. By using uniform working methods with a uniform information input it can be ensured that models of different test series have the same quality and thus they can be compared on a fair base. VCC has started this work by initiating the VMC-project, which have three main areas operations development, IT-tools, and PDM. Where the PDM efforts include product, process and resource data management.

It is, of course, important that all information that is used during design and testing is up to date. Today, information is often stored redundantly and thus it is difficult to keep it updated. For instance, weld spot data is stored in CATIA-files, Robcad-files and in the weld spot database. A particular program has been implemented to verify that weld spot data in the different storage medias is the same in terms of position, joint belonging etcetera. This is not a special case but a common problem that information is stored in files and thus the use and management of the information is limited, e.g. engineers working with DMU's have estimated that 50-85% of their time is spent on finding the right and updated information. One purpose of the PDM-efforts in the VMC-project is to provide a logical place to store and retrieve data to and from, and thus makes data easier to manage and update.

An increasing problem is how to share information with sub-contractors and vendors. An important part of the product data that is shared is master location and location points. For instance, master location and location points are often the first and only data that is received by ABB Body-in-White with a request for an offer of a robot cell.

Another problem for VCC is the recent merge with the Ford Motor Company. Forthcoming products will be developed together and perhaps manufactured in common plants. This means that representation and presentation of information about master location points, location points, and weld spots need to be unified between the two companies.

Of the two companies, VCC has reach much further with the ideas, strategies and implementation of virtual manufacturing.

Although VCC uses virtual manufacturing to a great extent, there are still areas that can be improved. Within the area of master location point analysis and tolerance chain analysis, for instance, the simulation of dynamic behavior needs to be improved. Today it does not exist any means for this type of simulation and thus all product parts is approximated with rigid bodies. This results in that the engineers cannot simulate the behavior in material when two parts are welded together. Another improvement area is that of visual aids that can scan parts and by that locate their master location points, location points and estimate the quality of the parts that are to be assembled. Then by calculating the difference between the parts they could be positioned in a better way or some parts may be scrap even before they are included in an assembly.

From this case study it can be concluded that:

- Virtual manufacturing is a tool to support decision-making.
- Unified working methods for virtual manufacturing are needed.
- Unified information input to virtual manufacturing tools is needed.
- The implementation of virtual manufacturing at VCC has reduced the need for physical test objects significantly.
- Information is often stored in files.
- Information is often store redundantly.
- It is difficult to manage and update redundant information.
- Virtual manufacturing at VCC can be improved.
- The VMC-project is an effort to develop and implement virtual manufacturing at VCC.
- The merge with Ford Motor Company has made the situation even more complicated.

Appendix D

ABB Body-in-White - A Case Study Report 2000

Authors:	Petter Falkman, CTH/CAL, and Johan Nielsen, KTH/DKT.
Participants:	Johan Nielsen, KTH/DKT. Petter Falkman, CTH/CAL.
Supervisor:	Gordon Sjöqvist, simulation.
Interviewed persons:	Rune Svensson, process preparation. Gordon Sjöqvist, simulation.

D.1 Introduction

The Swedish company ABB Body-in-White[1] (ABB BiW) is part of the global organization of ABB Flexible Automation. ABB BiW is a full service supplier with complete solutions for the vehicle industry. Their total function systems include everything from pre-studies (simultaneous engineering), simulation, process and design, installation

[1]Since the report was written ABB Body-in-White have changed name to ABB Automation Technologies (ABB ATRM/AM).

and commissioning to education, training, service and financing. The head office is located in Olofström in southern Sweden. ABB BiW also has regional offices throughout Sweden in Gothenburg, Malmö, and Umeå. ABB BiW also has sister offices and/or representatives in France, Spain, USA and Canada.

ABB BiW offer complete assembly lines as turn-key installations. Their assembly systems are based on standardized and/or requirement-tailored solutions, and they are designed to meet all production volumes for cars and trucks. ABB BiW also offer separate, individual equipment units for installation in existing assembly lines, for example hemming units. Full service competence together with extensive, genuine process knowledge and a project management organization that is a true team will be working to find the best, most efficient solutions.

The scope of this state-of-the-art study is how tender preparations are conducted at ABB BiW. The results are based on interviews with two people at ABB BiW. The main contact at ABB BiW has been Gordon Sjöqvist and interviews have also been conducted with Rune Svensson. The main focus has been on:

- Which activities that are involved.
- What computer tools that is used.
- What information that is handled by the different activities and how it is extracted to the specific activities.
- How and in what extent created information is reused.
- How ABB BiW would like to work in the future.
- How changes in the input to the tender preparation can be handled and consequences can be analyzed quick and easy.

Another aspect that has been dealt with is weather there exist formal methods that are followed during the tender preparation activity and in which amount hands-on solutions are created.

D.2 Tender Preparation

The customer decides which company that gets an order based on the tender, e.g. cost calculations, manufacturing solutions, cyclic times. The costumer also to some extend decides which supplier gets the order based on how the tender is presented and in what format the results are presented in. It is becoming more important what tools that are used and to if simulation models are delivered together with the manufacturing system.

It is becoming more important that the supplier creates simulation models early in a project and that these models are continuously updated. It is demanded that these simulation models are in the specified format so that the costumer can use these models when testing the product solution or changes in the product design. This is a development towards the main objective that a virtual manufacturing system is concurrently with the design of the product and the process in order to make simulations early in the projects.

This makes it important that the tender is prepared in a formalized manner and that every solution is carefully analyzed in respect to cost, efficiency, implementation etcetera. There must also be a balance between how much effort there is put in to a tender preparation and how likely it is that the supplier gets the order.

In Figure D.1, an overview of the tender preparation activity is presented. The result of this activity is an evaluated tender that is sent to the presumed customer. It is also created manufacturing solutions and simulation models during this activity. A calculator delivers a cost analysis that describes the cost for the total solution together with cost calculations of the parts of the manufacturing solution. The input to this activity is a product description, estimated product lifetime, yearly production, reference to similar solutions, desired cyclic-time and a description of the facility layout. The product description can be presented in different format and in different detail depending on how detailed the customer wants the tender to be. The tender preparation activity is constrained by the facility layout, regulations and

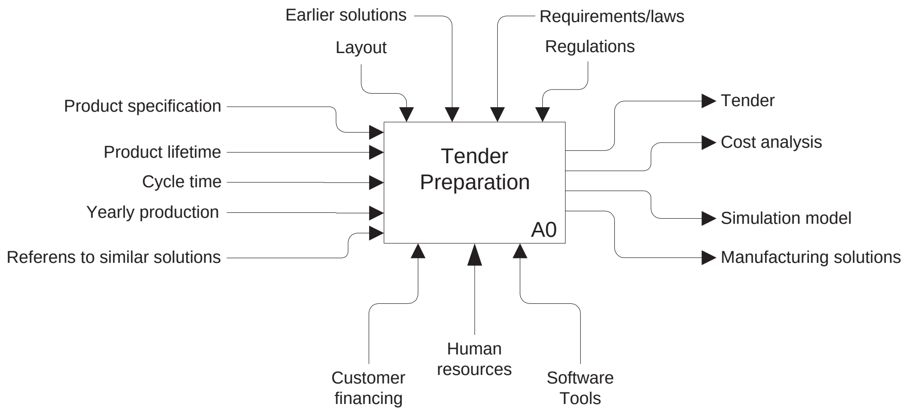

Figure D.1. IDEF0-diagram of the tender preparation activity.

several different requirements that will be described in the decomposition of the tender preparation activity, see Figure D.2. Engineers from various disciplines perform the activity using different software tools and in some cases earlier solutions.

The tender preparation activity is decomposed into risk analysis, start-up meeting, preparation and evaluation. In Figure D.2 this decomposition is presented as an IDEF0-diagram. A process planner conducts the Risk analysis activity together with a salesman and the tender preparation project leader. The process planner and the tender preparation project leader is usually the same person. The risk analysis activity investigates whether or not they should prepare a tender, this analysis is based on the product description, the facility layout, estimated yearly production and maximum cycle time. The product description can be delivered in different formats, the most common formats are 3D/2D-drawing, assembly structures and Excel sheets defining weld point and process point locations.

The purpose of the risk analysis activity is to investigate if they can build the manufacturing system for the specified product and if they think they have a chance at getting the order of building the system. Costumer relationships are one factor that lies as a constraint and can influence the choice of supplier e.g. a customer has a close cooperation with a specific supplier. If a decision is made that they are going to prepare a tender then the project leader split up the input information and prepare information folders for the participants involved.

If the Risk Analysis activity results in that a tender should be prepared in the specific case a start-up meeting is conducted. This start-up meeting is the second activity in Figure D.2 and is performed by the tender preparation project leader and members from several different disciplines, e.g. process planner, calculator, salesman, named participants in Figure D.2. In the Start-up meeting activity the project leader presents the tender and a time plan for the tender preparation. Different tasks and the information folders are handed out to the different participants and a time-plan is presented.

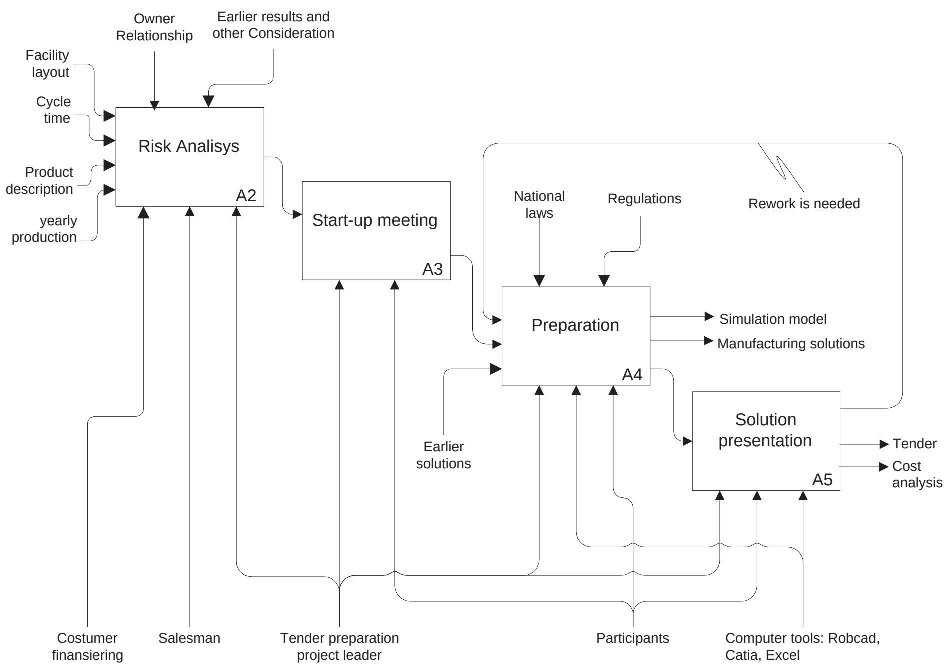

Figure D.2. IDEF0-diagram of the decomposition of tender preparation activity.

The preparation is activity is conducted by represents from all the different disciplines and to their help they use different computer tools e.g. Catia, Robcad, Excel. The activity is divided into sub-activities that represent different disciplines e.g. process-planning, simulation, cost calculation. The information folders serve as input to the sub-activities. There are constraints that depend on who the costumer is for example national laws and different local and global regulations. Since this activity is performed concurrently by several different disciplines there are meetings during the preparation activity in order to get early feedback about different manufacturing solutions. The result of this activity is manufacturing solutions and robcad-simulation models and also to some extent cost calculations from the different disciplines.

The last activity in the tender preparation is the solution presentation. The solutions from the preparation activity are used in the solution preparation activity in order to present the results and decide however the tender is satisfactory or if rework is needed. A total cost analysis is presented together with cost analysis of the different sub-activity solutions.

D.3 Pilot Study of *e*MPlanner from Tecnomatix

ABB BiW has begun an evaluation of Tecnomatix *e*MPlanner. A pilot study has been conducted at ABB BiW together with represents from Tecnomatix. The purpose of this pilot study was to examine how it would change the way ABB BiW is working today concerning information handling between different activities and the reuse of earlier solutions. Another important affect is weather or not it would simplify working concurrently in a tender preparation and process preparation in order to get early feedback on process solutions. One focus was also to evaluate how the use of *e*MPlanner would support the version handling of all kinds of documents in order to secure that it always is the right version that is dealt with.

D.3.1 Background

ABB BiW and in particular the department of Process Planning wants to reach a better information flow in the internal process and that it is beneficial to reuse the information created in the tender preparation activity. There is also a wish to use the solutions created in the tender preparation later in the project and in that way avoid unnecessary rework.

D.3.2 Goals with the Pilot Study

The project goals are to find the advantages and disadvantages using Tecnomatix *e*MPlanner and in what way the introduction of this new software is going to affect their way of working today. The main objective ABB BiW is to be able to use the same computer tools as today but make it easier to extract the right information without making a lot of translations. All the computer tools should use the same information. Another important feature is to be able to reuse complete solutions with all its documentation. Today solutions are reused but these are just the ideas not the formal complete solutions.

The main focus was to evaluate how *e*MPlanner could improve and simplify the their way of handling a number of activities that are specially important.

- Handling of product data, how to get, view and organize the data coming from ABB customers to ABB BiW. How to handle changes during quotation.
- Handling of product structures.
- Layout, 2D to 3D.
- Operation- and resource descriptions, ABB wants to have a good way of presenting the included operations in their design.

- Manufacturing management, Weld point distribution in the process, rivets, and glue strings.

- Sequence diagram.

- Cost estimate.

The result of this first study was according to the participants good and therefore a new study is planned in order to enlarge the scope.

It is becoming more and more important to have an information structure that makes it fast and easy to extract useful information to certain application in order to reuse earlier solutions. If it demands a lot of time and work to gather information, e.g. earlier solutions, new solutions are created instead.

This state-of-the-art report has focused on how tender preparation is conducted and who is involved and what information that is required and also in what extent the created information is used later in the project. One of the purposes of introducing *e*MPlanner is to support the wish to reuse the information created during the tender preparation in the process planning activity later in the project. Today, the created information is to a high degree re-created and the efforts in the tender preparation are to some extent unnecessary. Another goal with the introduction of *e*MPlanner is to create an information structure that supports all the computer tools that are used during a project in order to connect information together in a way so different data refers to each other e.g. a product operation refers to the resource that is used for this particular operation.

Today, the input to the supplier normally is a product description and site layout and some constraints but a trend is that the supplier is involved early in the design of the product and working in close cooperation with the costumer. This is advantageous both for the supplier and the costumer because the supplier with their knowledge is able to have influence on the design of the product and comment on solutions that make the manufacturing system more complex and therefore more expensive. The activity model described in Figure D.3 is therefore expanded with an extra activity that describes this cooperation with the costumer called a pre-study.

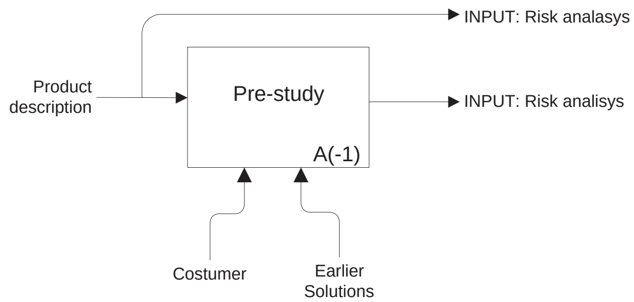

Figure D.3. IDEF0-diagram of the pre-study activity.

The first activity in the new decomposed tender preparation activity is then the pre-study. The input to this activity is early product descriptions and is delivered in co-operation with the customer. Process planners from ABB BiW participate early in the product design together with the customer in order to influence them in the design of the product.