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A CONCURRENT ENGINEERING INFORMATION MODEL BASED ON THE STEP STANDARD AND THE THEORY OF DOMAINS

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1. Introduction

Manufacturing companies are developing their products by capturing the product requirements from the customer along with the strategies of the company, including external and internal constraints, and turning theses requirements into realizable product and manufacturing system solutions. In addition to the product requirements, the manufacturing company needs to consider business requirements, which are mirroring quality and productivity demands of the customer on the manufacturing system. In order to deliver the product according to all the demands, the manufacturing company needs to coordinate the development of the product and its manufacturing system.

One way to coordinate and structure the development process is to use a supporting method based on an engineering design theory. By doing so, the design intent, the design history, and the design decisions made by the developers, can be captured and represented in a product model. Engineering design theories describe, among other things, how a product model can be structured [Hubka and Eder 1988], [Andreasen 1992]. In addition, engineering design theories are exploring some possibilities of representing the relationship between the product and its manufacturing system, but a detailed understanding of that coupling has not yet been achieved.

Naturally, the product and manufacturing system models are developed in an organization consisting of niche professionals. These professionals are responsible for execution of different development tasks, which are often distributed throughout different organizational entities. In order to increase productivity and quality of the product and manufacturing system development process, the product and the manufacturing system need to be developed by executing product-specific and manufacturing system-specific development tasks concurrently. This way of working, called concurrent engineering, is characterized by an extremely intensive information exchange between the different tasks [Fagerström et al. 2002].

Consequently, this information needs to be managed, and as the development process is increasingly computerized the information is managed by using systems for product data management (PDM). In order to maximize traceability of the design decisions and their impact, configureability of the products and manufacturing systems, and controllability of the development process across the organizational borders - the engineering design theory could be utilized for development of a generic and conceptual PDM core information model. Some initiatives in expressing the conceptual PDM core information model using the engineering design theory have been proposed [Malmqvist and Schachinger 1997] [Sivard 2001].

However, none of these approaches, nor the theories of engineering design, is explicitly addressing the concurrent development of products and manufacturing systems. Thus they have not been able to identify the important relationships between the product and manufacturing design objects.

The objective of this paper is to address the concurrent development of products and manufacturing systems by identifying the relationship between the product and manufacturing system design objects, as well as the relevant information entities in the ISO 10303-214 (STEP AP214) standard [ISO10303-1 1994]. Accordingly, the following two research questions are addressed:

- How are products and manufacturing systems, as well as the relationship between them, captured in a design object decomposition created according to an engineering design theory, the Theory of Domains (ToD), that is developed by [Andreasen 1992]?
- How is the general information model for development of products and manufacturing systems, according to the ToD, represented according to the STEP-standard?

2. Methodology

The study consists of three main activities: a case study based on ToD, the creation of an UML information model and an information model according to the STEP AP214 standard. To structure the research process, the model of research presented in Figure 1 was used.

The case study is performed to explore how the development of product and manufacturing systems is captured in design object decomposition. The objects for the study were a telecommunications product, Bias-T, and its manufacturing system. They were selected both due to the simplicity in the product and the fact that it was possible to gain access to documentation describing the product and its manufacturing system. The observations were conducted, on both documentation and the physical product, in the context of the ToD. The observation followed an approach where a hypothesis was put up, analyzed and reconstructed, according to the hermeneutic method, until a sufficient model was found [Fagerström et al. 2002]. The presentation was performed using the terminology of ToD.

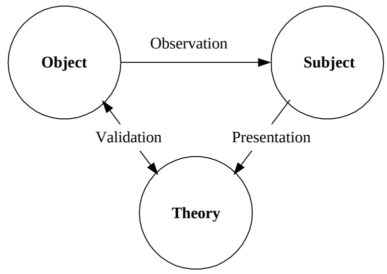

Figure 1. Model of research [Fagerström and Moestam Ahlström 2001]

The Unified Modeling Language (UML) [Booch et al. 1998] was used to create a generalized information model of the decomposition made in the case study. The purpose for this was to identify the generic couplings between a product and a manufacturing system. The object for this modeling was the ToD-model from the case study. The observation followed the same pattern as the case study observation. The presentation was done using the terminology of UML.

STEP-standard was used to represent the generic decomposition made in the case study. The object for this modeling was the model from the case study and the UML model. The observation followed the same pattern as the case study observation. The presentation was done using the terminology of STEP.

The validation of the models is, naturally, best performed if the models prove themselves to be useful in many innovation processes. Unfortunately, this type of validation is a far to extensive operation to cope with within this project, but it could be a good object for further research. However, the use of a recognized research method and a detailed method section provides the means for other researchers to evaluate the results of this paper.

3. Engineering Design: The Theory of Domains

The Theory of Domains, presented by [Andreasen 1992] is a theoretical foundation for mechanical design based on four perspectives on technical system, namely the process system, the function system, the organ system and the constructional (components) system. This multi-perspective view appears also in the Theory of Technical Systems (TTS), introduced by [Hubka and Eder 1988].

The purpose of a technical system is to transform its operands (materials, energy or information) from original state into desired state. This transformation is carried out in a process where individual sub-processes alter one or several properties of the operand. The technical system must produce effects that are necessary for carrying out the appropriate transformation of the operand. These effects are mirroring the functions of the technical system. The function system is producing a set of effects needed to carry out processes of the process system. The active units, which produce the effects within

a technical system, are called organs. Organs are also referred to as function carriers or technical concepts. The organ system is concretized in the constructional system. Here, the organs are distributed among the physical components with specified spatial relationships.
The concept of domains is in the ToD extended by specifying the causal relationships between the structures in the domains. The ToD can be utilized as the basic structure for computer aided product modeling. This structure contains, due to the introduction of the causal relationships, the information about origins of the design characteristics that can be regarded as *genetic* information about a product (the product chromosome).
The ToD is generally applicable on modeling of technical systems. [Andreasen 1992] is taking a total life cycle aspect on product modeling by introducing the notion of product life phase systems. A product is during its life interacting with life phase systems, for example, manufacturing system, distribution system or destruction systems. These systems are developed and/or configured concurrently with the product. One of the major aims with this paper is to elucidate the relationship between products and manufacturing systems in context of the ToD.

4. ISO 10303-STEP

ISO 10303, or STEP (STandard for Exchange of Product model data), is an international standard that "provides a representation of product information along with the necessary mechanisms and definitions to enable product data to be exchanged" [ISO10303-1 1994]. The term exchange should be interpreted as the exchange of data between computer systems in environments associated with the complete lifecycle of a product, including manufacturing.
Four important requirements on information systems of an extended enterprise are addressed by the standard: portability, interoperability, longevity, and extensibility [Fagerström et al. 2002]. The means for implementation of information systems that can meet these requirements is divided into six groups: description methods, integrated resources (IRs), application protocols (APs), conformance testing, abstract test suites, and implementation methods [ISO10303-1 1994]. The most relevant of these means, for this paper, are described below.
The *description methods* are used to define the information content of an application in a formal way. This is implemented through EXPRESS, a data definition language, which provides a mechanism for the definitions to be processed by computers. In addition, a subset of EXPRESS, called EXPRESS-G, enables the definitions to be visualized in graphical context, and thus simplifies human interpretation and understanding.
The *application protocols* are formal specifications of the information requirements for a particular industrial application, for instance AP214 for automotive mechanical design processes, which is also considered to be applicable on mechanical products in general. These information requirements are represented in the *Application Interpreted Model* (AIM) by using the integrated resources. In addition, an application protocol also includes conformance requirements to be satisfied by any product claming to support the application protocol.

5. Case Study: Bias-T

5.1 Decomposition according to the ToD

In this section a telecommunications product, Bias-T, and a part of its manufacturing system, the final assembly system, is decomposed according to the ToD.

5.1.1 Bias-T

Bias-T (Figure 2) provides direct current power (DC) to the antenna low noise amplifier (LNA) in the mobile communications networks. Bias-T receives the DC and the radio frequency signal (RF), injects the DC on the low-potential RF, and provides the high-potential RF to the LNA. Both Bias-T and LNA are mounted

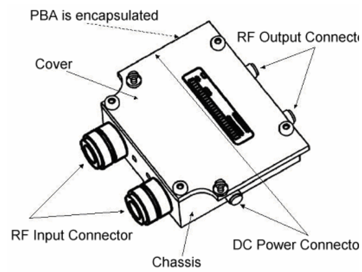

Figure 2. Bias-T

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

5.1.2 The Decomposition of the Product

The product, Bias-T, has only one service, that is to receive the DC and the RF-signal, combine them, and provide the result to the tower mounted LNA. The desired functionality of the product is expressed in the process sequence (PPx-PPy) that is shown in Figure 3.

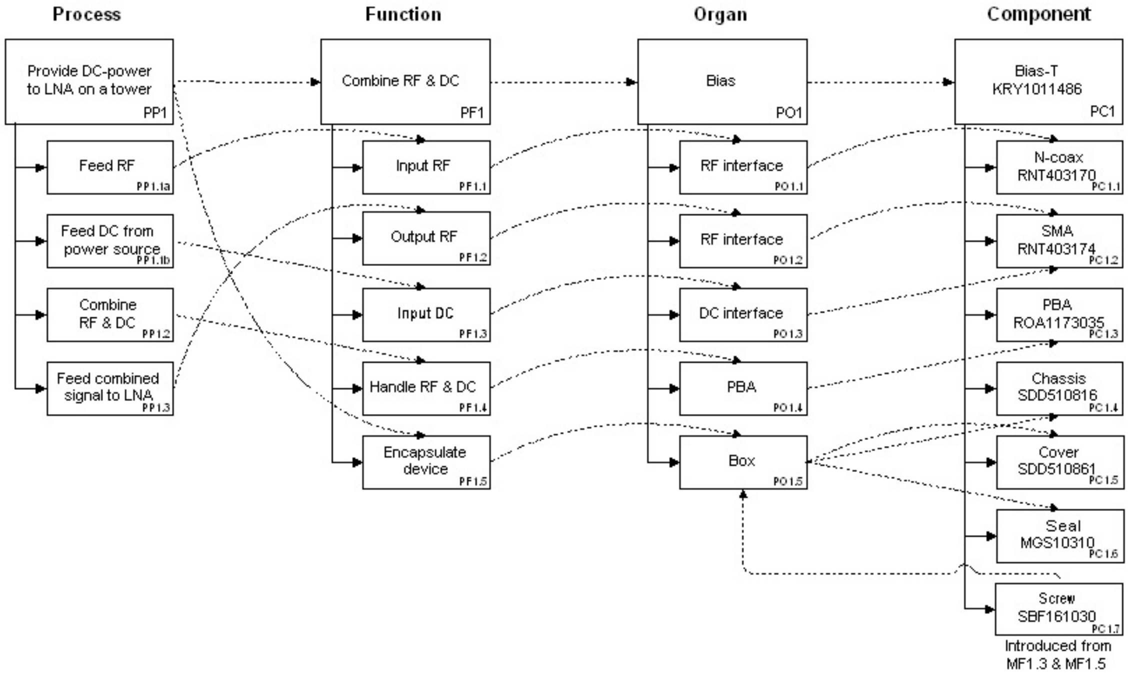

Figure 3. Bias-T decomposition

In order to be able to provide the service the product must contain a set of basic functions that can be combined into the desired process. These basic functions depicted in the function tree (PFx-PFy) are resulting from the desire to handle the DC and the RF-signal as well as from the environmental constraints. These constraints are specifying that the product have to be mounted in the antenna tower. The environmental constraints here are for example, mounting surfaces, temperature variation, and NOx in the atmosphere. These constraints are together with the natural desire to spatially contain physical functionality carriers determining the requirement on the encapsulation function.
The functions are realized by the organs depicted in the organ tree (POx-POy). These organs are technical solutions to the functional requirements and can be represented in for example, the circuit diagrams or printed board schemas.
The organs are realized by the components in the component tree (PCx-PCy). These components are either standard components or components tailored in order to materialize a specific organ that realizes a special functionality. In this work the printed board assembly is considered to be a “black box” that is materializing the organ responsible to realize the main functionality of the product, namely DC-RF combination.

5.1.3 The Decomposition of the Manufacturing System

Bias-T is produced in a manufacturing system that is executing a manufacturing process specified in a process structure (MPx-MPy) in the Figure 4. This process is a product centric description of the sequence of subprocesses that must be executed in order to successfully assemble the Bias-T product. Since the process description is product centric, the subprocesses that are connected with fixturing and

transport of the product between the assembly subprocesses are not included in this study.
In order to be able to provide the service, the manufacturing system must contain a set of basic functions that can be combined into the desired manufacturing process. These basic functions are depicted in the function tree (MFx-MFy).
The choice of the functions is affecting the product design. Since the product is chosen to be assembled by screwing a new component, the screw, is introduced in the component tree. Naturally, the other components in the product are also affected by, for example, the introduction of needs for screw-holes in the printed board, the chassis and the cover.

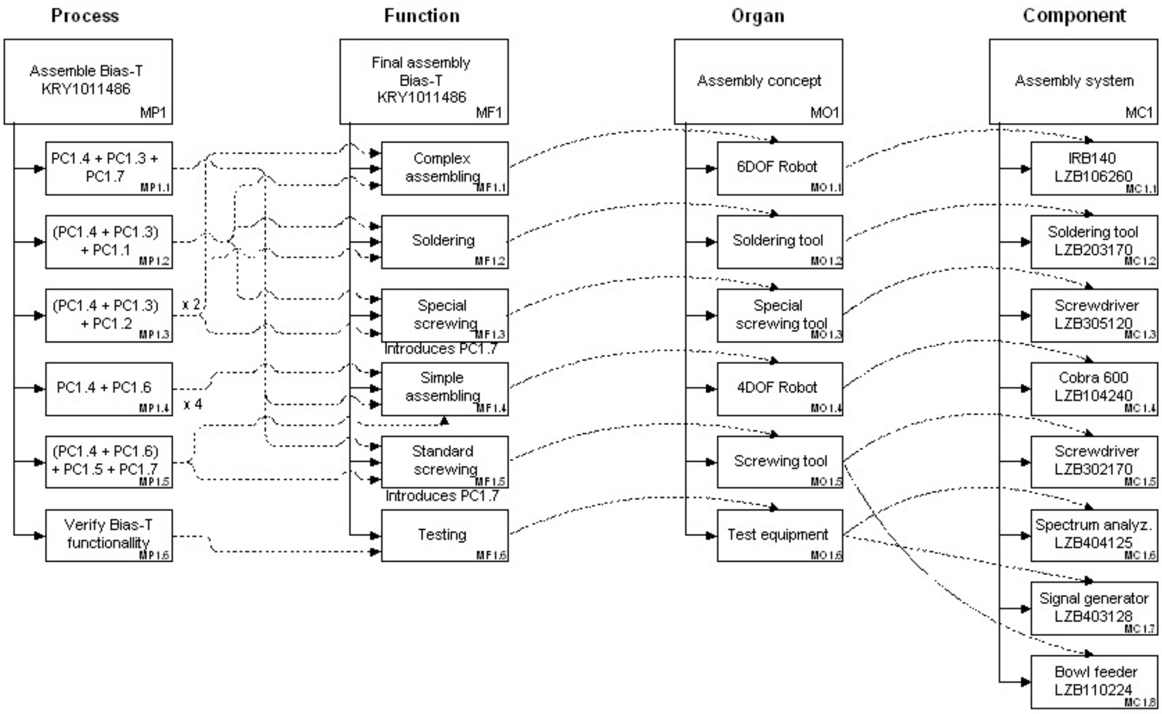

Figure 4. Decomposition of the Bias-T Manufacturing System

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

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

In this section some general conclusions are drawn from the decomposition of Bias-T and its manufacturing system and presented as an information model expressed in UML. This UML-model is a conceptual model that is not containing software classes, attributes, methods and association multiplicity. The model consists only of the information entities and the associations between them.
Most of the information entities are specializations of an abstract entity called *Chromosome*. This entity has some general characteristics that are inherited by its child-entities. These characteristics are associations with the entities *Constraints* and *Design Specification* as well as the capability to get decomposed into a hierarchy of its own. This decomposition capability is represented as a self-aggregation association. The entities *Constraints* and *Design Specification* as well as their associations with *Chromosome* is described by [Andersson 2001] and [Malmqvist and Schachinger 1997].
The entities derived from the chromosome entity are:

- Group 1: Product Process, Product Function, Product Organ, and Product Component

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

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

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

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

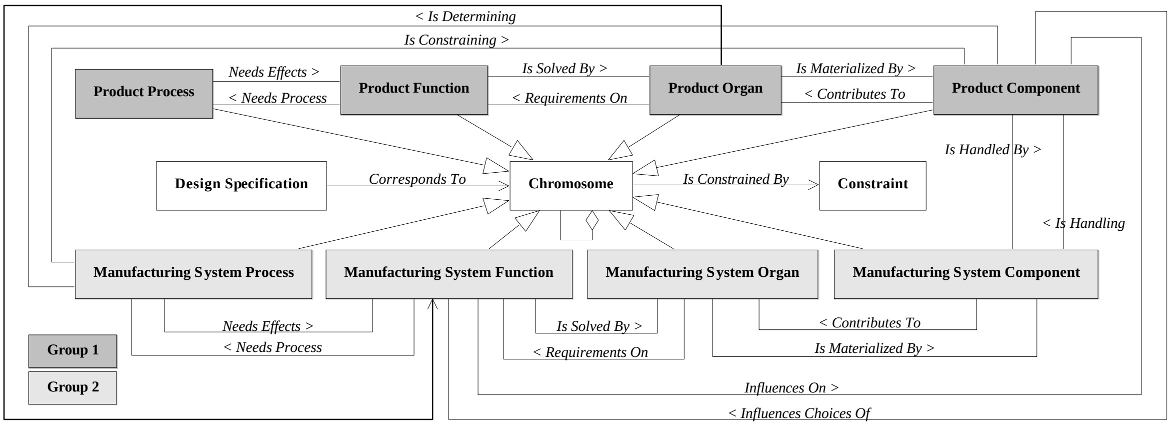

Figure 5. General Information Model for Products and Manufacturing Systems

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

5.3 Harmonization of the ToD-based Information Model with STEP

In this section, the AP214 standard is analysed and mapped to the ToD UML model with the purpose to present the relationship between the ToD and AP214. That is, to present what parts of AP214 that will be populated when zigzagging through the domains of the ToD, see Figure 6. The reader should have in mind, though, that Figure 6 is simplified and some entities of AP214 and all attributes have been left out.

The model in Figure 6 will be explained starting from the right with a component domain, ending in the process domain to the left, which is the main interface between the customer and the system regardless if the system is a product or a manufacturing system.

The component domain consists of the *item* entity, which always has a version, the *item_version*. All information that defines an item is related to a view of the *item*, the *design_discipline_item_definition*, such as a mechanical view or an electrical view. An *item* can occur in several different structures and is then represented by an *item_instance* for each occurrence. In the role of a *product_constituent*, the *item_instance* is the connection point between the component domain and the organ domain.

The organ domain consists of the *design_constraint* mechanism and the *product_component* entity. A *product_component* inherits from both *complex_product* and *product_constituent*, and, thus, organ structures are constructed by using the *product_structure_relationship*. This relationship entity is also used to connect the organ domain with the function domain.

The function domain consists of the *product_function*, which have the same inheritance as the *product_component*, and, thus, function structures are constructed in analogy with organ structures.

The process domain consists of the process plan mechanism. This mechanism provides the means to describe how a product should be manufactured in terms of process steps, in this case represented by the *process_operation_occurrence* and the *process_operation_definition*. What is left out in the model is the mechanism to represent different relationships between processes, for instance a sequence relationship.

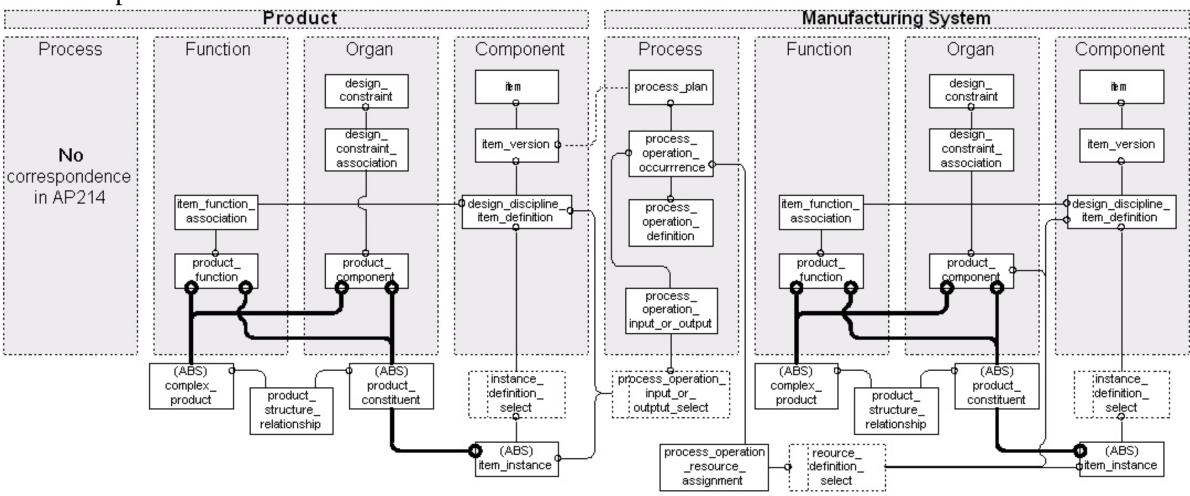

Figure 6. Simplified AP214 model mapped to the domains of the UML model

The relationship between product component and manufacturing system processes are represented in AP214 by the *produced_output*, that is the dotted line between *process_plan* and *item_version* in Figure 6 and the *produced_input_or_output* on the *process_operation_occurrence* level. These relationships are not explicitly defining a determinative/constraining relationship between a product and its manufacturing processes, but rather an implicit determinative/constraining relationship.

Although similarities exist, some differences between the ToD UML model and AP214 can be recognized; the missing product process domain representation in AP214 is the first and most noticeable. The process representation of the manufacturing system cannot be used here because it is constructed with a view on how the product is manufactured and not on what is executed in the manufacturing system. This imposes that the AP214 process plan has no justification without a product related to it, and can, therefore, not be used to represent the product process.

A second difference is that the constraints only are related to the organ domain, the *product_component*, in AP214, as opposed to all product and manufacturing system domains in the ToD model.

A third difference is that there is no direct connection between the process domain and the function domain of the manufacturing system in AP214. Instead this relation is realized via the organ domain of AP214. In other words, a process, *process_operation_occurrence*, is related to an organ, *product_component*, that is related to a function, *product_function*. The reason for this mechanism in AP214 is that it probably captures the way designers and production planners work today; first a manufacturing process is decided, then a technical solution is assigned to the process and finally his technical solution is specified in terms of its functions.

A fourth difference is that there is no direct connection between an organ and a component in AP214. This connection is, instead, realized by the *product_structure_relationship*, which is a relationship between a *product_component* and an *item_instance*. The *item_instance* is then related to the component structure, to finally end in the *item*. The relation between the *item* and the *item_instance* is that the instance represents an occurrence of an item in a product structure. For example, there are four instances of the same type of wheel in an ordinary car structure.

A fifth, and last difference highlighted here, is the design specification found by [Malmqvist and Schachinger 1997], which have no direct correspondence in AP214. However, a design specification can be represented as a document in AP214 and then be related to the main AP214 entities in the different domains. Thus, a design specification can, in practice, be represented in AP214 as information about the document (meta-data) and an external reference to a digital file or a physical document as the container of the actual specification.

6. Discussion

A ToD-based information model that is capturing product and manufacturing system design, as well as the idea of concurrent engineering, is emphasized in this paper. First, a case product is decomposed along with its manufacturing system, according to the ToD. Here, the manufacturing system is regarded as a technical system that is equivalent to a product. Thereafter, the generalization of the case study is conducted by creation of an UML-model. The UML-model is containing some general couplings between products and manufacturing systems. This formalized map of the area of product and manufacturing systems development is also harmonized with the international ISO 10303-214 standard.

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

One limitation with this work is that it is based on a single case study. In order to gain better understanding of the problem domain and increase validity of the results further case studies should be performed.

It is important to mention that the ToD has been subjected to some modifications. A *new* approach, where the function domain has vanished as a structure of its own and the function has come to be seen as a behavior of its organ (function-carrier) has emerged [Andersson 2001], [Andreasen 1998]. In this paper, the mapping from process domain into organ domain has been carried out through function domain. It is a natural way of working since functions are carrying out processes and thus are appropriate *interface* between processes and organs. Since functions and organs have one-to-one relationship it is possible to assume that the function structure in this paper is just a perspective on the organ structure and thus in conformance with the *new* view on the ToD.

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

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

The presentation of findings through an UML-model and an AP214-conformant EXPRESS-G schema is supporting the implementation of a PDM-system for dynamic extended enterprises that is based on engineering design theory and an accepted international standard. By using the ToD as a foundation for design process control it is possible to assure that the relevant aspects and decisions about the product and the manufacturing system design are captured and at all times can be traced. Some product-focused steps in this direction were also made in earlier work [Andersson 2001], [Malmqvist and Schachinger 1997], [Sivard 2001].

7. Conclusions

The following conclusions are made:

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

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References

Andersson, F., "Functional Representation for Design Support: a design theory perspective", Licentiate Thesis, Machine and Vehicle Design, Chalmers University of Technology, Göteborg, Sweden, 2001.

Andreasen, M.M., "Designing on a "Designer's Workbench" (DWB)", Proceedings of the 9th WDK Workshop, Rigi, Switzerland, 1992.

Andreasen, M.M, "Reduction of the Complexity o Product Modelling by Modularization", Proceedings of Produktmodeller-98, Linköping, Sweden, 1998.

Booch, G., Rumbaugh, J, and Jacobson, I., "The Unified Modeling Language User Guide", Addison Wesley Longman Inc., Reading, MA, USA, 1998.

Fagerström, J., Aganovic, D., Nielsen, J.,and Falkman, P., "Multi-viewpoint Modeling of the Innovation System – Using a Hermeneutic Method", Proceedings of ICAD 2002, Cambridge, MA, USA, 2002.

Fagerström, J., and Moestam Ahlström, L., "Demands and Methods on Developing Work Focused on Concurrent Engineering", Proceedings of ICPR-16, Prague, Czech Republic, 2001.

Hubka, V. and Eder, W.E.,"Theory of Technical Systems: A Total Concept Theory for Engineering Design", Springer Verlag,Berlin, Germany, 1988.

ISO10303-1:1994, "Industrial automation systems and integration – Product data representation and exchange – Part 1: Overview and fundamental principles", ISO, 1994.

Malmqvist, J. and Schachinger, P., "Towards an Implementation of the Chromosome Model – Focusing the Design Specification", Proceedings of ICED 97, Tampere, Finland, 1997.

Sivard, G., "A Generic Information Platform for Product Families", Doctoral Thesis, Computer Systems for Design and Manufacturing, Dept. of Production Engineering, Royal Institute of Technology,Stockholm, Sweden, 2001.

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