Modelling Manufacturing Systems Capability

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Licentiate Thesis
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Kungliga Tekniska Högskolan
Stockholm, 2006

TRITA-IIP-06-04
ISSN 1650-1888

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CONTENTS

ABSTRACT

Any way of making the manufacturing industry more efficient is always of great interest due to the contribution of manufacturing to the society. A major asset within manufacturing is information about manufacturing systems, as a base when making decisions. The most essential information within manufacturing industry would be the manufacturing systems capability information. That information would include information about the resource, used process and produced product. Although important, manufacturing systems capability models are rare, and the information seems to be challenging to model.

The purpose of this thesis is to model manufacturing systems capability with focus on the machining industry.

In order to model manufacturing system capability, existing information standards has been used as a frame of reference. Some information standards have been evaluated on industrial cases and sometimes modified to serve a specific purpose. The information standards have been evaluated to first separately represent product, process and resource. Thereafter have the information standards been evaluated to represent all three domains together.

ISO10303-214 (AP214) has been modified and evaluated to represent any process within manufacturing. The state of the product and the state of used manufacturing system are described and connected to every relevant process step.

AP214 with ISO10303-224 (AP224) has been used together with a developed method, to describe manufacturing system capability within machining. Within the limitations of AP224 geometrical feature description, the capability of a manufacturing system can be defined and connected to a product description. Using similar feature based description for the capability and the product description, products manufacturability can be evaluated.

Also ISO14649 and ISO10303-238, both also known as STEP-NC, are treated in this thesis as enablers to describe manufacturing system capability. STEP-NC is shown to describe manufacturing systems within machining where the product, process and resource are collectively described. In order to describe capability and evaluate products manufacturability, STEP-NC has to be extended from describing/modelling one configuration of a manufacturing system to describe a set of configurations.

THESIS STRUCTURE

This thesis is an aggregation of the appended three papers and the appended field study. This thesis can be read independently from the appendices. This thesis comprises three chapters as described below:

The first chapter, the introduction, presents the research area, the frame of reference and the problem description. The first chapter also adds complementary background to the appended papers, where the introduction to the research area partly is brief.

The second chapter, the result section, present the papers that each one tackle parts of the problem description. This chapter is deliberately made concise in order to get a better overview and not degrade the original papers.

The third chapter, the discussion and conclusion, treats issues that are directly or indirectly connected to the problem description. Relevant issues to focus on in future research are also pointed out. The contributions are finally summarized in the conclusion.

LIST OF PAPERS

This thesis is a summary based on the following papers, referred to by their Roman numerals. Also a not previously published field study is appended and referred to as Field Study A.

Paper I Modelling Manufacturing Resource Capability - a discussion of the industrial benefits
P. Holmström, T. Kjellberg
Proceedings of the 37th CIRP International Seminar of Manufacturing Systems, p.79-82, Budapest, Hungary (2004)

Paper II A Neutral Representation of Process and Resource Information of an Assembly Cell – Supporting Control Code Development, Process Planning and Resource Life Cycle Management
A. von Euler-Chelpin, P. Holmström, and J. Richardsson
2nd International Seminar on Digital Enterprise Technology, Seattle, USA (2004)

Paper III Manufacturing system capability representation with run-time information for reliable prediction of produced output
P. Holmström, A. von Euler-Chelpin
Proceedings of Product Data Technology Europe 2004 13th Symposium, p. 199-206, Stockholm, Sweden (2004)

Field Study A Data exchange during the realisation process of machining manufacturing equipment – A field study
P. Holmström (2003)

Distribution of Work

Paper I

T. Kjellberg contributed as a reviewer.

Paper II

Paper II is a result of collaboration where it is not possible to distinguish the contribution of the different authors due to close teamwork. However, section 5 is divided and individually written by the three authors where I have written section 5.3.

Paper III

Paper III is a result of collaboration where it is not possible to distinguish the contribution of the different authors in detail due to close teamwork. However, I have mainly contributed to the theoretical foundation and methodology for modelling manufacturing system capability. My co-author has mainly contributed to connecting runtime data to the manufacturing system capability model.

ACKNOWLEDGMENTS

First of all I would like to acknowledge my supervisor Professor Torsten Kjellberg for supporting me during this work.

I would like to thank Jonas Rosén for opening my eyes for this area of research from the beginning, also Astrid von Euler-Chelpin and Johan Richardsson being my co-authors to the papers.

I would like to acknowledge the research environment of KTH Industrial Engineering and Management and the Division of Computer Systems for Design and Manufacturing, who are also acknowledge for reviewing this thesis, as well as the external industrial and academic network I have been privileged to be part of.

I would like to acknowledge the financial support that made this possible. Programme for Production Engineering Education and Research (PROPER), Woxéncentrum. I also would like to acknowledge those companies that have supporting my research with open doors and time spent. Among others I would like to mention Eurostep, Scania, Volvo Car Corporation.

Stockholm, April 2006

Patrik Holmström

ACRONYMS

AI	Artificial Intelligence
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CE	Concurrent Engineering
CNC	Computerized Numerical Control
GUI	Graphical User Interface
NC	Numerically Controlled
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
SADT	Structured Analysis and Design Technique
IDEF0	Integration DEFinition language 0
STEP	Standard for the Exchange of Product Model Data
UML	The Unified Modelling Language

1 INTRODUCTION

The purpose of this chapter is to introduce the context of performed research. It gives a background from, and an introduction to, the field of manufacturing and information management. This chapter also treats information as an asset and the information model as a mean to preserve that asset. The problem, objective and delimitations of this research are established. The outline is to start with manufacturing in general and get more specific further on in the section.

1.1 Manufacturing

Manufacturing and the manufacturing industry is the foundation of the welfare state. The manufacturing industry provides the society with goods with less effort than others. Provided goods fulfil certain requirements, for example vehicles for transportation or heating systems for housing environment. A capable manufacturing industry can meet a wide range of different requirements. An efficient manufacturing produce goods with a minimum of effort, utilizing available resources with a minimum of waste.

The question of what goods that should be manufactured is rather political and will not be treated further in this thesis. Neither will the usage of our common resources, economical growth or suchlike issues be treated. Even though these are issues that often are discussed in connection with manufacturing, there is always potential for improvements in how we are using our common resources such as raw materials or human resources. It is always valuable to improve manufacturing in terms of minimizing efforts, maximizing output and eliminating waste. In other words to be efficient or – doing things right.

Considering the impact of manufacturing from a closer, real or daily perspective, we may look at some figures from the country of Sweden. In 1996 half of the working labour in Sweden was employed in the manufacturing industry [NAT04]. The same year the value added by the manufacturing industry was almost 47% of the total added value of the industry and 50% of the Swedish export was from the manufacturing industry [NAT04]. The economical impact of the manufacturing industry is massive. Improvements that can be implemented by this sector, or parts of it, has a huge economical impact on the society.

1.2 Manufacturing systems

The use of tools might be one of the most significant characteristics of the human race. Tools such as knife, axe and plough have for generations simplified the life for mankind. Tools have opened the opportunity for higher material standard with given resources. Tools can be used by hand or used in a manufacturing system as a component. A manufacturing system is a resource that supports and simplifies the way to make a physical thing or set of things.

In order to clarify manufacturing, also production is scrutinized.

Production means *lead forward* etymologically [HOL04]. Production embraces physical products (goods) and non-physical products (services). A production system is defined as “A group of technical production facilities which are linked with each other for a certain type of production including the existing relations between them” [CIR04]. This can be used to describe the product creation process from supplier to customer, including logistics, services, etc.

The origin of the word *manufacturing* comes from the Latin *manus factus*, in other words *the hand makes* [MÅR05] which indicate the production of physical objects. Out of this, the following definition of the manufacturing system is used in this thesis, stating the production system as superior to the manufacturing system:

A manufacturing system has the ability to change the properties of material in order to produce physical products.

A *product* is intended to meet customer needs [SOH05]. A product can certainly be a component in a system, for example a crankshaft where the engine is the final product. It is worth to keep in mind that a product often is a manufacturing system or a production system. A machine tool for example can be considered as a product or as a manufacturing system. A truck is another example that can be considered as a product or as a part of a production system performing transportation of goods. The distinction between a product and a resource will be treated further in this thesis.

A *system* is defined as “objects and events connected and controlled in time and space in order to obtain intended functions” [SOH05]. This definition is applicable to the use of “system” in “manufacturing system”. The objects of the manufacturing system are treated in their role to obtain the intended function. If an object directly or indirectly has a role to obtain the intended function then it is part of the manufacturing system. Many objects can be declared to be part of a manufacturing system although not considered as manufacturing systems themselves. For example, a drill tool does not fulfil the definition to be considered as a manufacturing system since it cannot drill a hole (change properties of material) without being part of a drilling machine.

Although not in focus of this thesis, an assembly system is a manufacturing system due to the manufacturing system definition. The association of an object to another object is considered as a property of that object. Even though two objects assembled together often are considered to be another (new) object it can still be described as the original object associated with the other original object.

1.3 Manufacturing processes

It is stated above that a manufacturing system has the ability to produce products. In order to produce a tangible product the manufacturing system acts on a material, for example a work piece. The state, event and activity of a manufacturing system are treated in this section. A manufacturing process is defined in this section which is later used as a fundamental part to describe the capability of a manufacturing system.

State

Describing a state of an object involves its properties and is fundamental in this section. A change is described out of the difference in the state of something. The following definition of state, taken from The Unified Modelling Language (UML) [UML99], is used in this thesis:

"A state is a condition or situation during the life of an object during which it satisfies some condition, performs some activity or waits for some event."

The state of an object is accordingly defined out of its properties.

Events

An event is fundamental for an activity and thereby also for a process. In this thesis, an event is defined as:

An event is a happening where the state of an object is changed.

The object that is changed can be a manufacturing system or a product. For a manufacturing system it could be the position of a tool that is changed. For a product it could be the shape that is changed. Also the state of non-material objects can be changed, for instance the part of a process control program that is active and that is being in command of the manufacturing system.

Activities

An activity is an event involving an active or causing object, which acts on another object, a passive or receptive object. Out of this, activity is defined for this thesis:

An activity is an event where an object acts in order to change the state of another object.

Note that the object in this definition can be a material object as well as a non-material object. This means that also the change of state of a non-material objects can be considered as an activity. For example, a verification activity of a manufacturing system verifies that a start button is activated and the state of the manufacturing system control program changes state from idle to working.

The difference between an event and an activity is consequently in the number of involved objects that are chosen to be considered and their relation with respect to the change. When an event is referring to one object, an activity is referring to two objects.

Processes

In order to represent several events or activities, and the relations between them, a process description is used where the process is defined in this thesis as:

A process is a set of interrelated events and activities.

Different types of processes are used in this thesis, for example the manufacturing system realization process, a specific mechanical process such as the cutting process or the manufacturing process control for control purposes such as a robot program. From the process definition a manufacturing process is defined:

A manufacturing process is a process where a manufacturing system acts, in order to produce tangible products.

Since a process involves activities and events, a manufacturing process also involves activities and events. As defined for an activity, there is an object acting on another object, for example a drill act (drill) on a raw material. Where the activity is an obvious part of the manufacturing process, an event might not be that obvious. As defined an event is a happening where the state of an object is changed. An event of a manufacturing process can for example be that a painted product is drying for a period of time. Certainly an event is seldom happening without anything activating the event and certainly the exemplified drying activity can be described. However, the use of event allows the manufacturing process description to be simplified when desired.

From the definition, a process description involves relations between the activities and events the process consists of. Examples of relation types for a manufacturing process can be sequence, substitution, alternative, etc. Figure 1 illustrates a manufacturing process with different relation types connecting included events and activities.

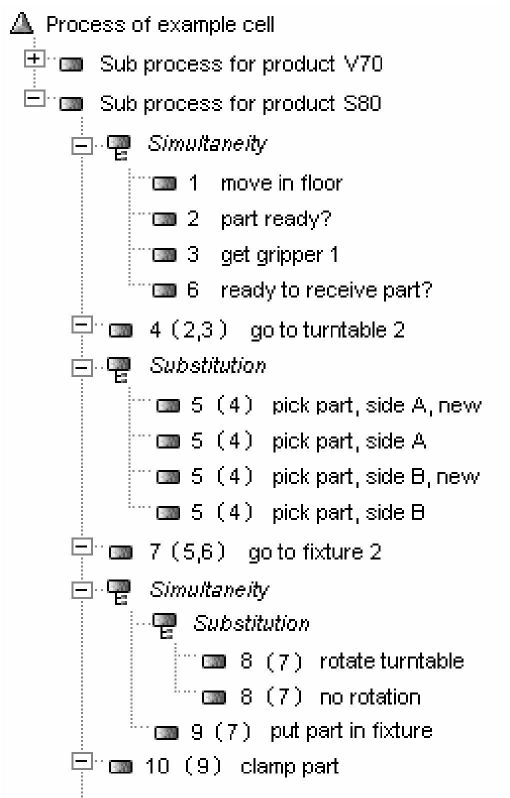

Figure 1: Example of a manufacturing process description

Manufacturing process control

A manufacturing process is closely connected to, and sometimes hard to separate from, the manufacturing system. In order to represent what the manufacturing system can perform, that is essential to model manufacturing

facturing system can perform, that is essential to model manufacturing systems capability, it is essential to describe how it is done.

A manufacturing process description can be used to describe how a manufacturing system can act but also as control and supervision of how a specified manufacturing system should act.

Practically, the manufacturing process control needs to communicate with various manufacturing system hardware in order to involve the changes in state of the manufacturing system. It also needs to handle the relation between activities, e.g. sequence, substitution, etc. There are a number of different control languages, often unique languages connected to the control hardware vendor, for example Programmable Logic Controllers (PLC) and industrial robots.

1.4 Models

A model serves as a container of information for communication between a sender and a receiver.

1.4.1 Models in general

This thesis is very much based on models and modelling. Before defining a model, let us start to consider some other definitions of a model found in a number of dictionaries. The purpose is to get a better understanding of the concept of a model.

- A model is internal relations and functions of a reproduced and idealized object [DUD96].
- A model is a description or analogy used to help visualize something (as an atom) that cannot be directly observed [MER04].
- A model is a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs [MER04].
- Models represent a part of the (real) world for a specific purpose from a specific viewpoint [NIE03].

So, a model is an interpretation of something for some purpose and it can be used quit widely. Furthermore there is a communication aspect of the model usage which will be examined further.

Perception and model definition

Communication is a phenomenon that involves a sending part and a receiving part. The preservation of meaning is essential and that requires considering the sender and the receiver. When humans are involved, control of the perception is the foundation for control of the interpretation. Marvin Minsky, active within the area of Artificial Intelligence (AI), have described the model from the viewpoint of perception and mental models [MIN88]. He states that a person creates his own mental model when observing reality or a model of reality. This mental model is then stated as knowledge. It is likely to believe that two persons observing the same object will create different mental objects of the observed object. Figure 2 illustrates how person $\mathbf{B_1}$ and $\mathbf{B_2}$ are both observing the same object and are both making up their own mental model of **A**, $\mathbf{M_1}$ and $\mathbf{M_2}$. **A** can be an object, system or a model itself.

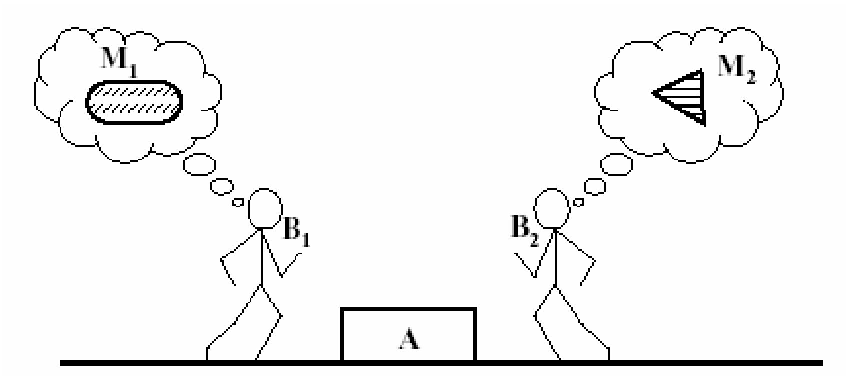

Figure 2: Perception requires a mental model. Interpretation of Minsky by Schnieder [SCH03]

There is then a perceptive part of the model usage that is of importance to consider. The quality of a model can be evaluated out of its ability to answer questions about the object that it is a model of. To further develop this statement, a model should be able to capture the accuracy, which is important in industrial applications. The following definition is found to be the most accurate and suitable definition of a model and hence is the one used in this thesis.

*"**M** is a model of a system **A**, if **M** can be used to answer questions about **A** with an accuracy of **a**"* [MAR88]

A model serves as a container of information for communication between a sender and a receiver. A model can also clarify selected part of the world by intentionally amplifying selected important data and filter noise away.

Linguistics and modelling

With this definition of a model in mind, it is worth reflecting over the extensive amount of models that are encountered in daily life. Some examples are mathematical models or maps. Languages, written or spoken, are models where words and sentences are representing different meanings depending on the context. The relation between any model and our mother tongue is worth reflecting upon. Even though not directly used, research in linguistics has influenced this work. The following terms are found especially interesting for a model, where the examples are adapted from The Swedish National Encyclopedia [NAT06]:

- *Predicate*. What is expressed by one word? How solid is the meaning of a word in different contexts? As an example the word *kill* is used. *Kill* can be defined as “to deprive life”. An example of a phrase would be “Young Morris killed the wasp”. Besides the definition of the word *kill*, the usage of kill also presupposes someone that kills (young Morris) and that someone gets killed (the wasp).
- *Logic*. What is the meaning of a word depending of its context? How valid is a definition of a word in different sentences? Young Morris did deprive the life of the wasp in the example above. However, the word *kill* can also be used in the phrase “Sara was dressed to kill”. Here is it indicated that Sara was dressed up to make a markedly favourable impression rather than that she will kill anyone.

Similar thoughts are found behind concepts like semantic webs, content management, etc. that is used to support web techniques, or express logic, which is used to support artificial intelligence solutions.

1.4.2 Information

Information is central in this thesis. In this section information is defined and the value of information is discussed.

Data, Information and Knowledge

Information is an important part of the decision process. Figure 3 illustrate the decision process based on data, information and knowledge. Data is considered as the base in this process with the following definition:

“Data are symbols (or functions) which represent information for processing purposes, based on implicit or explicit interpretation rules” [SCH94]

The following step of the decision process is when data is put in a context. This gives the following definition of information which is used in this thesis:

"Information is data put in a context" [LOO87].

In order to continue the decision process information is used to make decisions and to develop knowledge through understanding. However, the focus is here on information why knowledge, etc. will not be examined further.

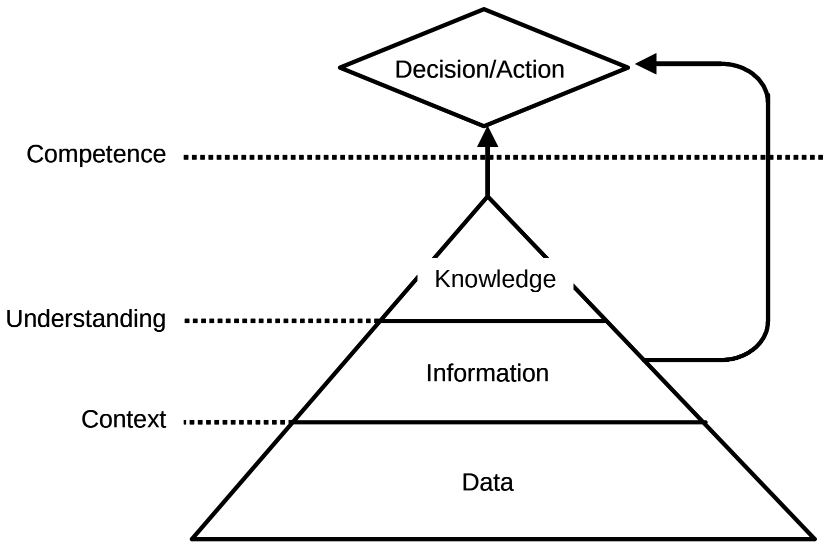

Figure 3: The relationship between data, information and knowledge in the decision process [NIE03]

To exemplify data, information and knowledge we can imagine how we observe a thermometer at home in the morning. When the thermometer shows the four characters "-2°C", those characters can be considered as data. When those four characters then are put in the context of "outdoor temperature" this turns out to be information. With this information we get the knowledge that it is cold outside, given that we understand the meaning of this information. With this information we can also make the decision to wear a winter jacket when we are going out, given that we have the competence to know that a winter jacket is an appropriate clothing to wear in cold weather.

The value of information

In the very first section of this chapter it was stated that improvements within manufacturing always are of interest. Efficiency is fundamental optimizing an economy at any level. This is applicable on a personal level, in a company and even globally.

Information can and should be considered as an asset. It has been stated that decisions are made based on information. Better information, than the competitors, is an advantage when making decisions. Further, information is a reusable resource as long as the information is accurate and accessible. It does not lose its value or disappear when it is used. However, information loses its value if it is not current, updated or accurate.

Information is often shown to be very long-lived, compare product information of an aeroplane. It is not unusual that information outlives the computer software and hardware where it was created, which is schematically illustrated in Figure 4.

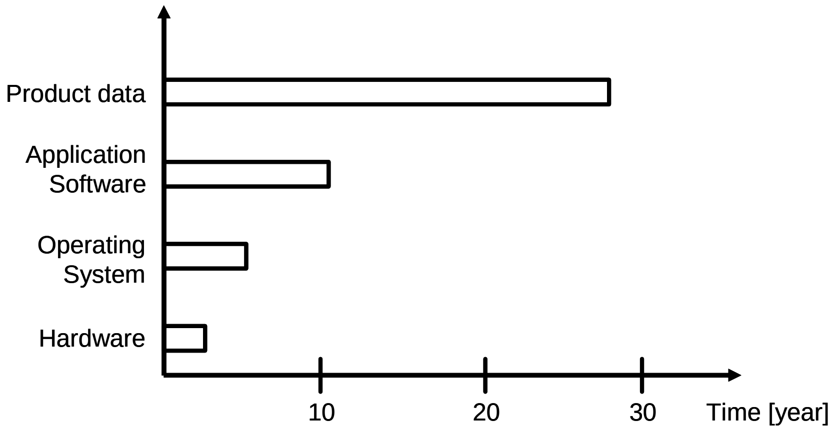

Figure 4: The useful life of product data information [DEC92]

1.4.3 Information models

Definition

The value of a model for communication has been treated in section 1.4.1 and the value of information has been treated in section 1.4.2. An information model is used in order to communicate information and by that model combines values of communication and information. For an information model the following definition is used in this thesis:

"The information model is a formal description of types of ideas, facts and processes which together form a model of a portion of the real world and which provides an explicit set of interpretation rules" [SCH94].

Modelling languages

In order to document and practically communicate the information model, there is a need for a modelling language. Creating an information model is technically a work that requires tools in order to simplify the work. In this thesis, the modelling language that has mainly been used for documentation and communication is the EXPRESS language [ISO11]. EXPRESS is exemplified graphically in Figure 5 and textual in Figure 6. If an information model is written in EXPRESS or any other computer sensible representation, it has the additional quality of being computer processible. Another modelling language is the Unified Modelling Language (UML) that is today commonly used for software application structure, behaviour and architecture [UML04].

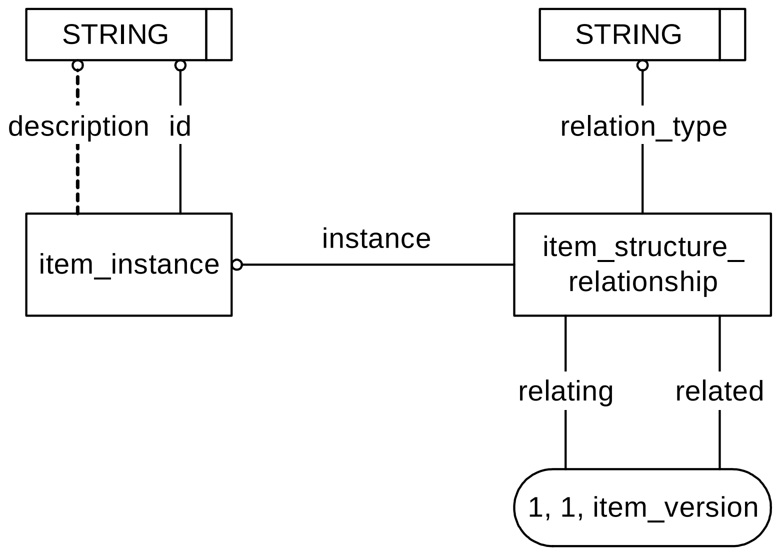

Figure 5: Sample of EXPRESS-G (Graphical) information modelling language

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

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

Figure 6: Sample of EXPRESS (textual) information modelling language

Interpretation

Information is vulnerable to misinterpretation as treated in chapter 1.4.1. From the definition of an information model it is stated that the information model is a formal description and provides an explicit set of interpretation rules. The described description and interpretation rules are the key to successful interpretation. Also from other research it has been stated that the meaning of defined words, concepts and connections are fundamental for an information model [WES04]. When modelling a manufacturing system, there are properties that are easier to communicate than others, for example physical facts such as geometry or known process properties where all mutual relations are carefully studied. However, even well-defined properties of a manufacturing system signify different information depending of the context. That means that the purpose and the viewpoint of an information model are just as important as the definition of specific properties, for correct interpretation.

1.4.4 Activity models

An activity model certainly fit into the definition of an information model. However, an activity model has the specific purpose to describe activities. An activity model represents the activities of a system and the relationships between those activities [MAR88]. The role of the activity model is to capture *what* process is to be done, but not *how* the process is to be done [TIM96].

Activity modelling is the practice of modelling the functions of a system, also referred to as functional modelling [JOH01]. An activity model is well suited to be used to provide requirements on the information model. IDEF0 [IDE04] is one tool that models activities in this manner. IDEF0 is derived from Structured Analysis and Design Technique, SADT [MAR88], capturing input, output, controls and mechanisms of the activity. See Figure 7.

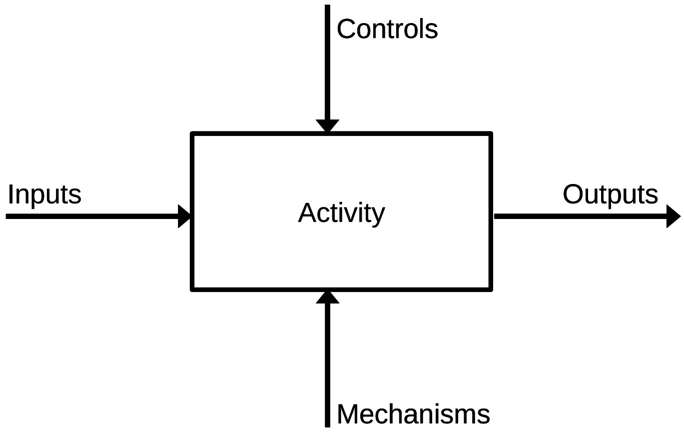

Figure 7: IDEF0 model of activities, of an organization or a system [IDE04]

1.4.5 Information standards

Standardization

Standardization is the work of systematically creating order and regulations with the purpose of obtaining optimal technical and economical solutions of reoccurring problems [NAT05]. However, in practice it would be more correct to say that the purpose is to obtain an optimal compromise. Many of the problems discussed in this thesis are treated entirely or in parts in other domains, such as product development, as a reoccurring problem where standardized solutions are created. Standardization in general mainly focuses on facilitating communication by securing exchangeability and compatibility by determination of dimensions, sizes, interfaces, etc. Standardization is based on the participation and acceptance of those affected by the standard, such as producers, end users, authorities, etc.

Information standards

Information standards is the type of standards specialized on information. To exemplify the use of information standards for communication, Figure 8 shows how the number of translations required between dissimilar systems can be controlled when the numbers of systems that are to communicate grow.

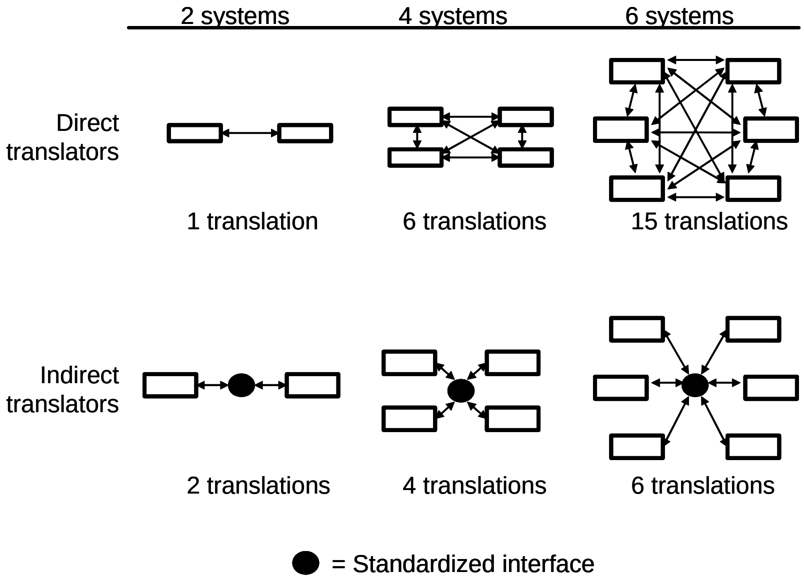

Figure 8: The number of translations as a function of the number of dissimilar communicating systems, without and with a standardized interface [ZEI91]

International information standards

This thesis is strongly influenced by open international information standards. Especially ISO10303 [ISO1], also known as STEP, with related parts such as AP214 [ISO214] and AP238 [ISO238] as well as ISO14649 [ISO14649] have been important for this thesis. International information standards are an extensive source of information where the following points exemplify different types of content in the standards [TIM96]:

- Description methods: language definition by which aspects of product data can be specified. For example the EXPRESS language [ISO11].

- Implementation methods: specification of a format structure for data access and exchange. For example how a product structure should be defined in the EXPRESS language.
- Application protocols: product data model specification applicable for a range of sectors. For example ISO10303 contains application protocols such as AP214 [ISO214] describing the information of the automotive mechanical design process.

1.5 Manufacturing systems development

There are some important issues to consider when modelling and communicating about how to develop a system. Although the manufacturing system is in focus in this thesis there are several issues that are not unique for a manufacturing system. This section is treating manufacturing system characteristics and general system requirements. A system can be a manufacturing system, but also a support system to the manufacturing system. The manufacturing system is described to be complex and difficult to develop and manage. But it is also a description of a research area with great improvement potential.

1.5.1 Manufacturing system complexity

Figure 9 represents a product development process for mechanical products. A manufacturing system itself can be considered as a product being the output of the manufacturing system development process. In fact, a manufacturing system and a product differ only through their intentional usage, not in any physical properties. A product is intended to meet customer needs, where a manufacturing system is intended to produce products. So a manufacturing system can be considered as a special type of product where the customer need is to produce products. However, a manufacturing system tends to be more complex to describe, than when considered a product, often closely connected with the description of products that the manufacturing system can produce. When doing this process connection, the description of the product as a resource is more complex than just describing the resource as a product.

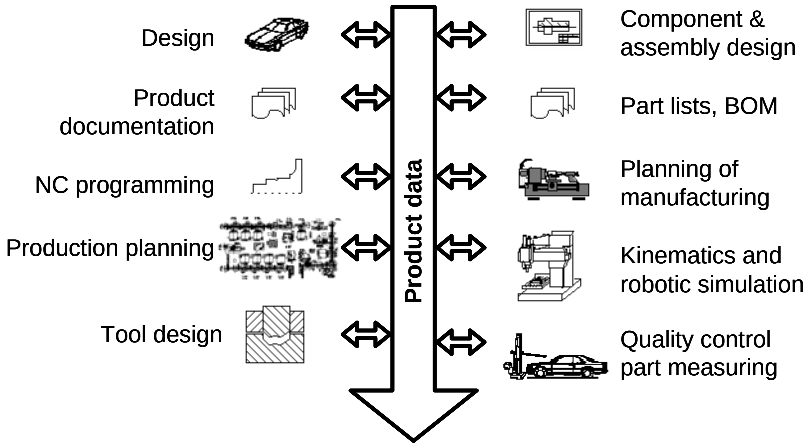

Figure 9: Adapted from the scope of AP-214 [ISO214], Core Data for Automotive Mechanical Design Process

Flexible manufacturing system

In order to be a competitive manufacturing company, flexible manufacturing systems are required in order to respond to changing market demands of different products. A flexible manufacturing system is suited to handle a large variation of products. By handling larger variations of products, a manufacturing system is more useful during a longer period of time for the manufacturing company. However, in order to handle a larger number of products for a longer period of time, the complexity of the manufacturing system gets higher, since each product adds different requirements on the manufacturing system.

Manufacturing system development collaboration

Developing a larger manufacturing system requires a project team with different roles and functions. Each function of the project team can face the manufacturing system from a unique viewpoint, with a unique purpose and at a unique point in time during the development process. One function, for example assembly design, creates data or information that will serve as input to another function, for example production planning. In order to manage the development process, the information management and collaboration between functions have to be handled. Widen the scope further, the entire lifecycle of the manufacturing system can be considered and also how experiences from one manufacturing system can be used when developing another manufacturing system.

1.5.2 Manufacturing system detailing

A manufacturing system can be an assembly of objects, tools, etc. that have different functions. To facilitate the overview, a manufacturing system can be put into a hierarchical tree structure. Using one definition stated by National Institute of Standards and Technology (NIST) the tree structure is, from top level: facility, shop, cell, workstation, equipment. This structure is illustrated in Figure10. A facility, as well as equipment, can be considered as a manufacturing system.

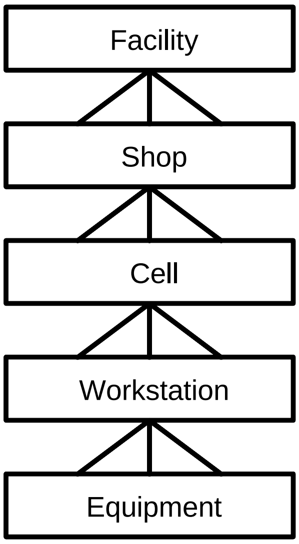

Figure 10: A manufacturing system in a hierarchical tree structure defined by NIST [HUA96]

A manufacturing system can be described from many different levels of detailing. For example it can be a factory or a machine tool. This means that one manufacturing system, for example a factory, can be composed of other manufacturing systems, for example machine tools, which can be described independently. Consequently, a manufacturing system can be part of a larger manufacturing system, for example an engine block machining line where the engine is the final product.

1.5.3 System requirements

A system that supports development methods, for example Concurrent Engineering, must be capable of enabling simultaneous and controlled access to the same data pool by different team members, to carry out their different tasks. These systems must provide portability, interoperability, longevity and extensibility [TIM96]. Although there are different ways to handle these issues, the recommended direction from the perspective of this thesis is commented respectively:

Portability

It is not only necessary to be able to run a given application using different hardware and operating system environments, but also to move data between applications.

It is of importance to identify the borderline between where data is applicable and not. It is my opinion that the portability issue mainly should be treated through concepts definitions. By very well-defined concepts, the number of possible interpretations can be lowered. As an example, in a model the concept "date" may be defined by day, month and year, in that order. The use of the information is then very much dependent on the accuracy requirements in the application. An application that requires time with the accuracy of seconds does not get sufficient information from the date only.

Portability is discussed in more detail in the papers that are closer to operations. Paper II handles control information and how it can be made portable between different applications and hardware interfaces. Field Study A describes the purchase of manufacturing equipment and the information portability from the vendor into the purchasing company and its operation over the lifecycle of the equipment.

Interoperability

For team members to be able to work on different tasks and in parallel require that different applications are capable of sharing the same data.

When a task gets large, such as the development of a vehicle or a factory, it is necessary that several team members can work on different subtasks in parallel. In order to cooperate within a team, the team members should be able to work using the same set of information. However, the information produced from one part and its relation to other parts must be controlled and handled. A team member can work independently of others, although it is important how a change of information may affect its surrounding information. The changes, for which the consequences can be described, are representative for the limitation of the work that is allowed to be performed within a subset of information. Changes outside the limitations in a subset of information may affect the work of another team member in a negative way.

Interoperability is treated in Paper III where an information module is stated to represent PLM-Capability context of information in order to tie runtime data together with designed and intended output. The same type of data, produced from different contexts is then related.

Longevity

Data will outlive the software and hardware on which it was created.

Depending on the timeframe, there is always difficult to assure information on long terms due to its connection to the human language. There is normally a connection to a human language for definitions used when created information as well as interpreting information. The signification of a concept may slightly change in meaning during time, compare with languages in 1.4.1. However, with a well-defined open information model it is possible to handle differences over time. As well, it is possible to interpret differences from other open information models. The data that are structured according to an information model can be translated into another information model knowing the relationships between the models. Just observing the data would make correct interpretation almost impossible.

Longevity is naturally treated in Paper III, securing the manufacturing system capability during its lifecycle. Longevity is also treated in Paper II where information from several domains of the manufacturing system development is gathered as foundation for the control code development. Defining these sources, using information standards instead of proprietary data models, is the most obvious method for securing data longevity.

Extensibility

Design and data modelling techniques are constantly evolving. It is important that data and tools can be extended to take advantage of new and innovative techniques.

In order to maintain the validity of a model in a changing world, the model should allow for changes and the data created before a change should still be valid and interpretable. This is a challenge for every model development. In my opinion, this is a very difficult issue, to be prepared for the unknown. To some extent it is a question of being foresighted, considering possible changes in the future, for example be able to represent the year 2000 when creating a data model in 1998 (!). Furthermore, it is an issue of managing the history of a model. A model should be able to work with data created in a former different version of the model. Again definitions, together with management of the differences, are crucial for successful interpretation. For example, year in “date” could be defined as two digits until the year 2000 where it is changed to four digits. Managing the model history, data from the old model could easily be adapted to the new model by adding 19 in front of the old data, meaning that 98 would be read as 1998.

Extensibility is treated in Paper II where the information from several domains is gathered for the control code development. The sources of information are made traceable since the history is handled. For example, control code created at one point in time to be reused at a later point in time can be evaluated out of the conditions as they were then and how the conditions possibly have changed. Safety or environmental regulations might have changed, but by handling the history, only the changes have to be treated and the control code can be reused with defined changes.

1.5.4 Development methods

Concurrent Engineering

To improve the development process one way is to work in a concurrent engineering (CE) manner. The goal of a CE system for a product realization is to produce products that meet given cost, function and quality requirements, as rapidly as possible (short lead time) [KIM92]. The major potential improvement when using CE is that development can be done within a shorter time span, not that the total development time consumption decreases. This is achieved where various engineering activities are integrated and performed as much as possible in parallel, rather than in sequence [SOH92]. Figure 11 illustrate the difference between traditional product development and CE.

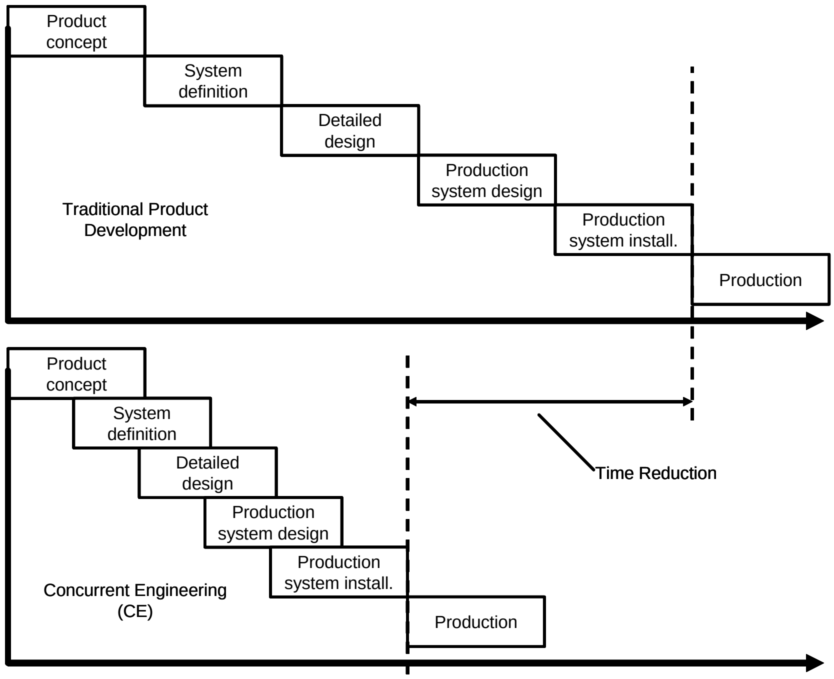

Figure 11: Shorten lead time through Concurrent Engineering, from [JOH01]

In order to achieve CE management of change, availability of information, deep common understanding, integration and standards are required [KIM92]. Those are all issues that are dealt with in this thesis in order to model manufacturing system capability where manufacturing system information and manufacturing process information are treated concurrently.

Manufacturing system capability

One important part of the product development is its relation to the manufacturing system or manufacturing system development, in order to realize the product physically. Although this part of the product development differ in extent from time to time, depending on many factors, for example develop a product or a group of products through different configurations, it is likely to believe that it is a considerable part of the process in terms of time and resources. Manufacturing knowledge, easy accessible and suited for product development, would shorten the product development process and facilitate manufacturing system development. Available manufacturing systems could be used closer to its limits for what is possible. Product designs that are impossible to produce can be sorted out at an earlier stage.

1.6 Modelling manufacturing systems information

1.6.1 The Digital Plant – A vision

Accurate and accessible information of a manufacturing system makes a more efficient usage of the system possible when it can be reused by different users and do not have to be recreated. The Digital Plant, see Figure 12, signifies an accurate digital information representation of the real plant. It is in fact mirroring the real plant to be the premier source of information. The current and reliable product information, resource description and used process control code is found in the Digital Plant and the very same information is used as base for the real production. This computerized environment helps to understand the behaviour of the manufacturing system [JOH01].

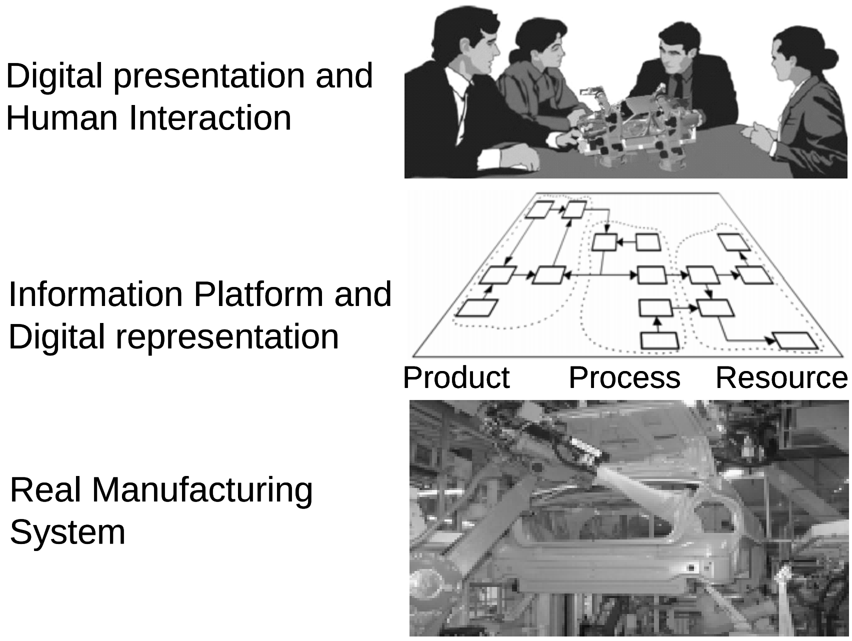

Figure 12: The Digital Plant signify an accurate and reliable digital information representation of the manufacturing system [KJE04]

The users, man as well as machine, work towards the information of the digital plant. Information can be copied out to applications working in parallel with the real plant for change analysis, simulation etc. Decisions are not taken from observing the physical plant, but preferably from the digital plant and its information content. The Digital Plant can preferably be observed through a filter that will filter noise away and amplify what is important in order to make right decision in a particular case. The digital plant will enhance the possibility to cooperate using the same set of data and share experiences. These are objectives that are shared with methods like concurrent engineering and collaborative engineering discussed in section 1.5.4. In the manufacturing system investment process one can communicate internally and externally using tools where a new manufacturing system can be realized and verified in the digital environment before the order is made. The vendor can be delivering a digital representation of a machine tool together with a physical machine which will fit into the buyer's digital model of the manufacturing system.

1.6.2 Modelling manufacturing systems

A manufacturing system can be modelled as a product since the difference is determined of the usage whereby the type of information is the same, as discussed in 1.5.1. However, a manufacturing process is by definition related to a product that the manufacturing system is able to produce. Thereby it can be stated that modelling a manufacturing system involves a relation to a product domain. It is also stated that there is a third domain connected – the process domain. Modelling a manufacturing system can consequently be divided into three domains:

- Product domain.
- Process domain (a manufacturing process)
- Resource domain (a manufacturing system)

This view is used in this thesis and is partly shared in other manufacturing system descriptive research work [JOH01], [NIE03]. Nevertheless, modelling a manufacturing system embracing the process domain and the resource domain, each domain initially can be treated separately. The relations between those domains can then be treated as a separate issue.

Modelling products

Since manufacturing systems from a modelling aspect, are closely related to products it is of interest to evaluate different types of product models. A product model can be classified into four different types of models [JOH01], to some extent shared by [NIE03]:

- *Structure-oriented product models:* Emphasizing the structure of a product. For example an assembly structure or variant structure.
- *Geometry-oriented product models:* Emphasizing the geometrical representation of a product. For example a solid model in a CAD system.
- *Feature-oriented product models:* Emphasizing the semantic signification of a product. A feature-oriented product model works as an extension to a geometry-oriented model where the functions of the geometric model can be described. For example maximum load capacity of a vehicle, where the maximum load volume is related to the geometry of the vehicle.
- *Knowledge-oriented product models:* Emphasizing the human knowledge of the product in terms of constraints or guidance. For example how a product within a product family is allowed to be composed with regards to a set of rules.

Modelling manufacturing system capability embraces all described models in order to be related to the process and product domain.

1.6.3 Modelling manufacturing processes

A manufacturing process represents the relations between events and activities in a manufacturing system. A manufacturing process description can be used to describe how a manufacturing system can act but also as control and supervision of how a specified manufacturing system should act.

Standards for manufacturing process description

Many open international information standards are able to represent a manufacturing process at a general level. ISO10303, Application Protocol 214 (AP214) [ISO214], is one standard that is found useful. AP214 is a comprehensive work produced by and for the automotive industry. Even though AP214 was originally intended for the design process, it is shown that the model can be used for representation of the design information of a manufacturing system. This embraces the representation of integrated product, process and manufacturing system information through the use of one single information model [DIG03]. This process representation is suited for the detailing level of a factory, a manufacturing line or similar. For slightly higher detailing, for instance an assembly cell, it is convenient to enlarge AP214 in order to represent different states of changing components, such as fixture, robot, etc. during the process cycle. The use of information standards for manufacturing process control at different levels of detailing is further treated in Paper II.

1.6.4 Modelling machining manufacturing processes

Numerically controlled (NC) manufacturing systems are commonly controlled using “G and M code”, defined in ISO6983 [ISO6983]. The tool transportation is here defined in relative or absolute terms of the defined Cartesian coordinate system. Although the G-code has been dominating for many years the extension of ISO6983 is limited. This limitation has lead to enlarged editions from the vendors that are outside the standard and thereby interpretable only using the actual vendors control system hardware.

Standard development within machining manufacturing process control

There are standard approaches to cope with the limitations of ISO6983 and also to better use the opportunities of today’s technology. ISO14649 [ISO14649] is one such approach with a scope to specify the manufacturing process rather than a tool path. Another approach is ISO10303, Application Protocol 238 (AP238) [ISO238]. AP238 has a similar scope, and some direct relations to ISO14649. The shortcomings within ISO6983 to be treated within those standards are summarized underneath [XU04]:

- ISO6983 focuses on programming the path of the cutter centre location, rather than the machining tasks with respect to the part.
- ISO6983 defines the syntax of program statement, but in most cases leaves the semantics ambiguous.
- Control vendors supplement the ISO6983 language with extensions that are not covered in the limited scope of the standard; hence the NC programs are not exchangeable.
- ISO6983 is developed as a one-way information flow from design to manufacturing. Information from the shop floor is hard to communicate back to the designer. Hence, any feed-back loop is hard to manage and valuable experience can hardly be preserved or used.
- CAD data are not used within ISO6983 directly on the machine, but by a set of low-level, incomplete data as result of a machine specific post-processor. This makes reverse reuse of information, for example simulation, difficult or even impossible.

To clarify the difference between ISO6983 and ISO14649 the process of making a hole is taken as an example. Making a hole, ISO6983 will describe the path of a given tool, for instance a drill or a broach, along with the number of revolutions and feed rate of the tool, in order to make the hole. In addition to this, ISO14649 would be able to separately describe the geometry of the hole to be machined, referring to standards for geometry representation. The geometry of the hole is compared with parameterized geometries that are defined for different processes and tools, such as drilling and milling. This parameterized geometry, called a *workingstep*, is a high level machining feature with associated process parameters. In fact it is a library of specific activities that might be performed by a CNC machine tool. A *workingstep* can be selected automatically out of preset criteria. For a *workingstep* is then specified a tool, cutting data, etc. to make the hole. All components are working on the same data format enabling a closed-loop process chain.

1.6.5 Manufacturing system classification

A manufacturing system can be described for many different purposes. In order to describe manufacturing systems different types of classification systems are commonly used for different purposes. One way of classifying manufacturing systems is to group those who have a number of defined properties in common, for instance Rotes Buch [ROT04]. Efforts have been made in order to classify all types of manufacturing system after the processes they perform [TOD94]. Classification of manufacturing systems often serves its communication purpose within a limited well-defined application area. To clarify this, purchase of handheld drilling machines is taken as an example. Vendors can market handheld drilling machines where the buyers know its typical function and properties; it does not have to be redefined. The buyer know that the specified number of revolutions for a handheld drilling machine signifies the maximum number of revolutions the drill tool will obtain, not the engines number of revolutions which might be different.

However, the classifications of manufacturing systems are frequently made limited. Classification is made limited if the manufacturing system is allowed to be member of one class only. A multifunctional manufacturing system would suit multiple classes but is unluckily forced into the most appropriate class. Although, the very same manufacturing system may be suitable to be described in different ways for different views and purposes and consequently classified differently. The classification systems are often seen as: class a, class b, etc. and at the end typically a class others. Such classification would be weak in handling new manufacturing system, very different from others for which the classification was designed. A member of a class is consequently best interpreted as a not-member of the other alternative classes. This means that correct interpretation of such classification system requires knowledge not only of the class in question but also of the entire classification system.

1.7 Manufacturing systems capability

Developing a manufacturing system or working with an existing system, a great amount of information is developed and used. It has been stated that many functions of an organization are using the same, or part of the same information during the manufacturing system lifecycle. One comprehensive description of the manufacturing system that can be used extensively is its capability. The following definition is used as a base describing capability in this thesis:

Capability is the inherent ability to deliver performance [NIE03].

However, the focus in this thesis is on the manufacturing system and its performance in terms of its value adding output in product property change. That is, tangible products that can be offered to the market. This thesis definition of manufacturing system states an object comparable to a product that has certain abilities. In order to handle this ability, illustrated in Figure 13, the capability of the manufacturing system is used. Therefore the following refined definition of manufacturing system capability is used in this thesis:

A manufacturing systems capability is the inherent ability of the manufacturing system to perform change in the properties of a material in order to produce tangible products.

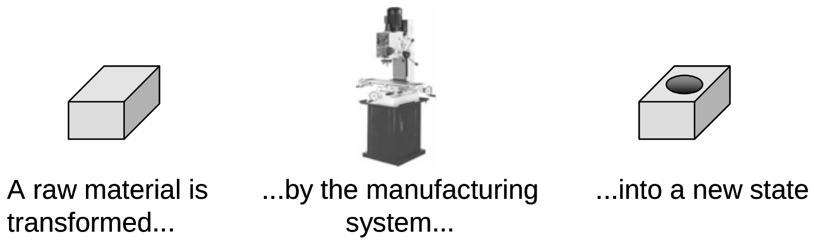

Figure 13: The manufacturing system is able to perform changes of a material

Position and direction may be considered as properties in some applications. In this thesis it is not included as a property in the product description since it is not adding permanent value to the product. However, although not in focus, non-material property changing systems sometimes are considered and connected to the manufacturing system since it may be such a vital part of the manufacturing system. For example the revert movement of a drill during a drilling operation not letting the drill stay in the work piece or a cooling system that make a cutting process possible to perform. Such systems are when described distinguished as a secondary supporting system. Further, due to their usage transportation and positioning systems may be part of the manufacturing system. As an example, we can consider a machining operation of a machine tool. The feed rate is generated towards tool by the movement of the table where the work piece is fixed. In this example the table is certainly part of the manufacturing system. Although, the same type of table used in another context can be considered as a positioning system.

Certainly a manufacturing system can deliver performance that is not connected to the product. But if there is no direct or indirect relation between manufacturing system ability and the product, such as the sound of a machine tool, it is out of scope in this thesis due to the definition of a manufacturing system. It has been shown in that the manufacturing process is highly integrated with the manufacturing system and its performance, see Paper I. Further, it has been stated that the use of a manufacturing system capability description is for making decisions. Issues like cost and time are then highly relevant and considered.

Manufacturing system capability can be used to determine products manufacturability, which is to perform a defined change in the properties of a work piece in order to produce a product. Manufacturing system capability would be one way to analyse and present a base for deciding between different products during product development, for example the cost to manufacture two similar products. Succeeding with such description would integrate product development and manufacturing system development more closely than otherwise, which is further discussed in Paper I.

1.7.1 Machining manufacturing system – an example

This section is a detailed example from present situation within NC machining, as described in 1.6.4. The purpose is to illustrate the challenge and potential of modelling manufacturing system capability.

Manufacturing system development

In order to produce a product in a NC manufacturing system (machine), the manufacturing system has to be developed. The points below describe the main activities performed today in such development. In Figure 14 the described activities are illustrated, as well as the information produced from each activity. In this context, developing a manufacturing system include configuration of an existing manufacturing system.

- The final product geometry is defined. This geometry is a target geometry that is to be achieved. Also information about the geometry of the raw material is defined. Changes in the geometry of the raw material, as result of the machining operations, will lead to the final product.
- The process is defined. This means that each machining operation is defined with regard to tool selection, tool path, process parameters, etc. Further, each operation is defined in what order it is to be executed in relation to the other operations.
- The process information is converted to M and G code. Although G and M code is defined as a standard in ISO6983 [ISO6983] control vendors supplement the ISO6983 language with extensions, which is discussed in 1.6.4.
- A control system, suited for the current manufacturing system and the M and G code, execute the M and G code into machine code. The control system can to some extent verify that the G and M code is executable at the current manufacturing system. However, if the code is found not to be executable in the controller, the control system offer little, or no, help to come up with a solution.
- The machining is performed.
- Finally there is an optional activity to verify the result. The produced product geometry can be measured and compared to the specified product geometry.

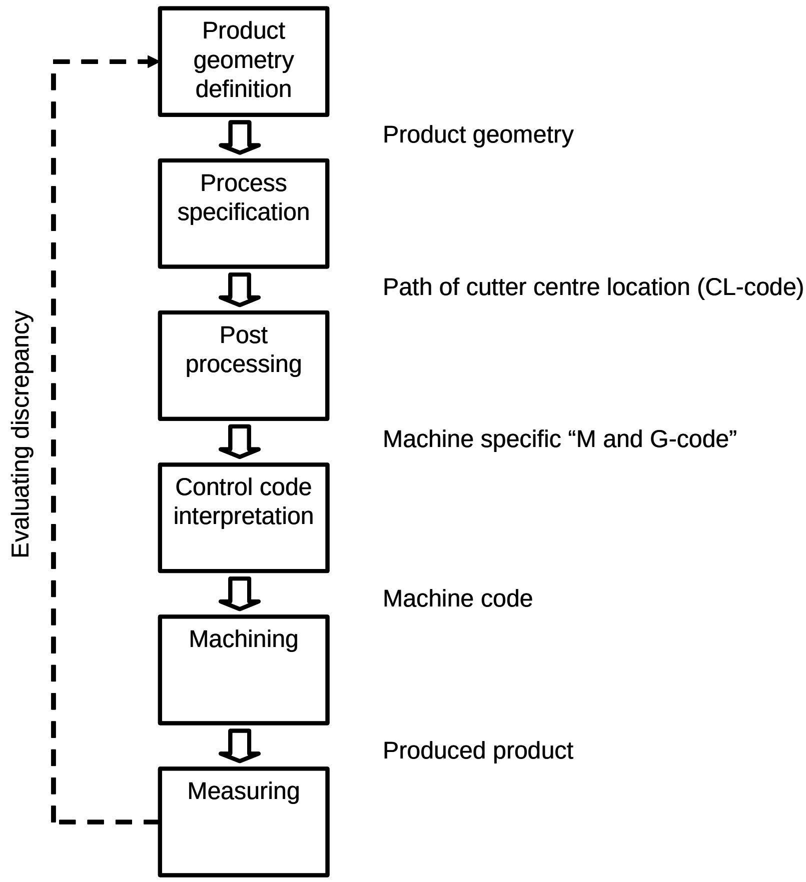

Figure 14: Manufacturing system development activities and produced information, for NC manufacturing systems (machines) of today

Some reflection of the described example is here made, from the aspect of modelling manufacturing systems capability. In order to define the process, an extensive knowledge about the manufacturing systems capability is needed. The result of the manufacturing system development is consequently dependent of the knowledge about the manufacturing system capability.

When the product is produced a possible lack of correspondence between the wanted product and the current product can be evaluated. However, in case there is a difference, there are no means to identifying the source of error in the information flow.

Manufacturing system development – problems and potential

Several shortcomings of the manufacturing system development are illustrated in the section above as well as in 1.6.4. The following points describe the activities of an alternative manufacturing system development process. These activities are also illustrated in Figure 15, together with the information produced from each activity. The described development process is adopted from STEP-NC [ISO14649] [ISO238].

- Like the other example, the final product geometry is first defined. Also information about the geometry of the raw material is defined. Changes in the geometry of the raw material, as result of the machining operations, will lead to the final product. In this example the product geometry is documented in a standardized format that is possible to integrate with the subsequent steps. Application Protocol 203 (AP203) [ISO203] can be used for standardized geometry representation.
- The process is defined using a reference library of parameterized processes. Each machining operation is defined with regard to tool selection, tool path, process parameters, etc. However, the process description is made using well-defined parameterized standard operations defined for machining in general. Further, the order in which each defined operation is to be executed can be defined, but can also be defined in the following activity. The process information is documented in an open format, for example AP238 [ISO238] where also the product geometry is documented.
- The process description is verified and defined in detail. A control system, suited for the current manufacturing system and the process information, verifies the documented process description. This verification implies that the control system is able to match the process description with a manufacturing system capability description. Any difference can be analysed and possible solutions can be found. For example, a milling process with a certain tool is chosen during the parameterized process specification. When verifying this milling process with the current manufacturing system, the chosen milling tool might not be available. Then another milling tool that fulfils the requirements can be selected. This verification process lead to detailed process description that can be suited, optimized and verified to the current manufacturing system. The detailed and verified process information is documented in an open format, for example AP238 [ISO238] where also the product geometry is documented.
- The control system executes the detailed process description into machine code.

- The machining is performed.
- Finally there is the optional activity to verify the result. No conflicts should be encountered due to mismatch between the process description and the manufacturing system since the process description is verified. However, any discrepancy in the produced product geometry can be transferred to the manufacturing system capability description. Consequently it is possible to create an autonomous self correcting manufacturing system.

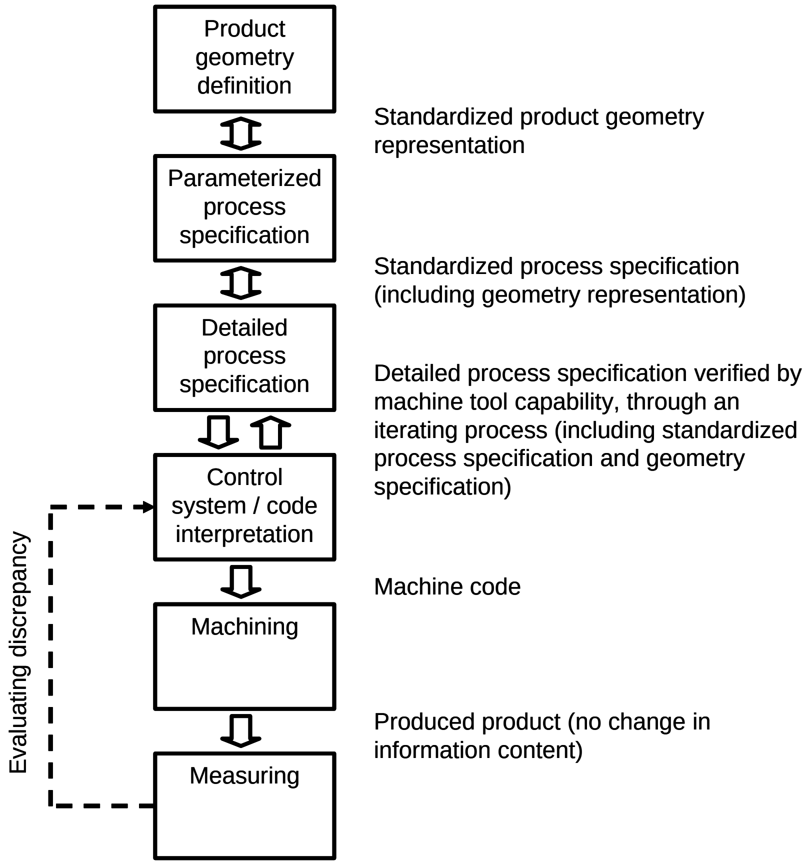

Figure 15: Alternative manufacturing system development activities and produced information, for NC manufacturing systems (machines) adapted from STEP-NC [ISO14649] [ISO238]

After the second activity described above, the parameterized process specification, the process is fairly well-defined. This is made without specific knowledge of available manufacturing systems capability. The separation of process description from the manufacturing system selection is important, generically describing process information. The information defined to this stage can be generally used in different manufacturing system environments, with no consideration of specific machine tool or control vendor.

At the third activity, the process detailing and verification, manufacturing systems capability is introduced. Using manufacturing system capability at this stage allows the process specification to be optimized to current manufacturing system. Different process solutions can be compared to the capability description. With set decision criteria the best solution can be found through an iterating process. Further, any change of the manufacturing system capability, for instance tool wear, can be captured so that corresponding changes in the process description can be made.

1.8 Scope of the thesis

1.8.1 Problem description

The potential of modelling manufacturing system information has been illustrated from several perspectives. Efficient manufacturing system information management is shown to be a key to make manufacturing industry more efficient. This thesis is focused on modelling of manufacturing systems capability and comprehends products ability to be manufactured. There are today several possibilities to describe manufacturing systems during its lifecycle, although mostly common is to describe the manufacturing system as a product, compare 1.5.1. As base for this thesis and its justification, it is stated that:

The description of a manufacturing systems capability is a comprehensive valuable description of the manufacturing system.

Describing the capability of a manufacturing system is to focus on the defined purpose of the manufacturing system – to produce products. However, the scope is wider than traditional manufacturing system descriptions, considering different areas of interest and how these areas relate to each other.

1.8.2 Objective

The main objective of this thesis, and the appended papers, is to:

Describe manufacturing systems capability in order to determine products manufacturability.

The manufacturing system is to be described in order to tell what it can produce and if so, how that production will be performed. That includes its ability to perform in the product domain, such as can this shape be machined? It also includes how it is performing, for instance how fast and to what cost and quality that shape can be machined?

1.8.3 Areas of interest

In connection to the description of manufacturing systems capability in 1.8.1 a number of sub areas, illustrated in Figure 16, are established in this section.

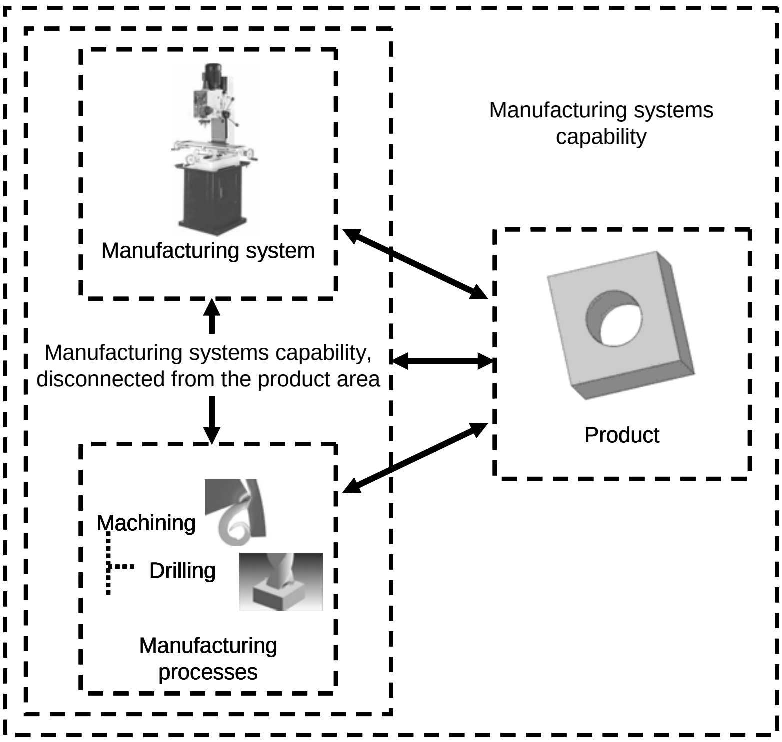

Figure 16: The description of manufacturing systems capability is divided into a number of sub areas with mutual relationships.

The purpose of this division is to lower the complexity and facilitate reuse of information. A manufacturing system and a manufacturing process are both easier to describe alone, separated from their mutual relations.

Manufacturing systems

In this area a manufacturing system with its characteristic properties is intentionally treated disconnected from specific manufacturing processes and produced products. Issues for information systems supporting a product description are likewise considered for a manufacturing system, such as portability, interoperability, longevity and extensibility as described in 1.4.3. A manufacturing systems relation to manufacturing processes and products can be considered as a manufacturing system property. However, these relations are treated separately. Research from product description can be applicable describing a manufacturing system, cp. 1.5.1.

Manufacturing processes

In this area general manufacturing processes is considered and described in a similar comparable way. Using a general process description different process types can be combined. For example, a drilling process and a milling process can be combined as an alternative process or sequential process. The relation between a manufacturing process and a manufacturing system or a product is treated separately. Research performed describing manufacturing processes are applicable in this context [NIE03].

Manufacturing systems capability, disconnected from the product area

In this area the relations that a manufacturing system and a manufacturing process exercise on each other is described. For instance, what type of manufacturing processes is a manufacturing system able to perform and how? A manufacturing systems capability is certainly related to the product. However, that relation is treated separately. The research performed in the area of manufacturing systems capability is mainly connecting the manufacturing system considered as a product with the manufacturing processes.

Manufacturing systems capability

In this area the influence of the product on the manufacturing systems capability is described. This includes dependencies between the product description, the manufacturing system description as well as the manufacturing process description. The application to analyse product manufacturability will use a manufacturing system capability description. The research performed in the area of products manufacturability is focused on the relation between specific manufacturing processes and their performance. However, the relation to the manufacturing system is weak. The manufacturing system is validated to be able to fulfil certain requirements within the solution area where the manufacturing system in fact may be capable of more.

General system development

This problem description so far indicates how manufacturing system capability is divided into different sub areas. Thereafter the relations between the sub areas are described. However, for descriptions in general there are several issues to consider, as discussed in 1.5. Since those general issues are applicable also when describing manufacturing systems capability, some of those issues are also treated in this thesis.

The information validity is highly dependent to changes. If a change occurs in the real world but not in the information model that is representing the real world, there will be a discrepancy. Consequently may the information model be invalid.

Time and space are found important to consider. What is true at one point in time at one place is not necessarily true at another point in time or at another place. How can it be specified what is relevant respectively not relevant for one purpose and viewpoint compared to another purpose and viewpoint? What is valid for, a type of machine, for a specific brand and model, for a specific individual?

1.9 Delimitations

This thesis treats information that is a part of a manufacturing systems capability description during its lifecycle. It is limited to describe measurable properties, which also signify computer interpretable information. That means that the man-machine interaction is out of scope in this work. From the information model aspect the focus is limited to reproducible facts such as physical geometry, working process knowledge, etc. Non-reproducible facts could for example be the sound of a machine, although it is possible to record.

This thesis model manufacturing systems capability generically, using international information standards, in order to be generally applicable. That means that very specific manufacturing systems capability descriptions, such as for a specific individual machine, may be described in more detail. Implementations from a practical point of view, such as Graphical User Interface (GUI) or specific database technology, are not treated.

The application area is limited to mechanical industry and mainly limited to machining and a machine tool. However, an assembly cell successfully has been used to study manufacturing process control representation in Paper II.

1.10 Research method

This thesis acts within the area of applied engineering. While natural science is concerned with analysis, engineering is concerned with synthesis. Synthesis in this work is performed according to Prof. Gunnar Sohlenius who states that engineering should when approaching a problem [JOH01]:

1. Analyse what is
2. Imagine how it should be
3. Create what has never been
4. Analyse the results

Used tools, such as modelling language and information models are described as they appear.

The research is based on a literature study, reasoning and case studies. Inspiration and knowledge is collected and used from existing and developing international information standards. The case studies are used to verify the used models and methods without specifying its validity further.

2 RESULTS

This chapter present a short summary of each paper this thesis is based on. The papers separately deal with the subject of describing the manufacturing system from different perspectives. Also Field Study A is summarised although it is used mainly as reference. An introduction is first given to the relationship between the papers.

2.1 Introduction to the papers

As treated, in chapter 1, the manufacturing system can be described from many different viewpoints and with different purposes. For example, a manufacturing system can be supported by different applications during its lifecycle. Figure 17 gives a rough positioning of the papers out of their scopes. The scope of each paper is evaluated with regards to two things that are used as axes in the figure. The Y-axis illustrates to what degree the scope of the paper is applicable in various applications. A low value signifies specific types of applications, which allow a high level of detailing. For instance Paper II copes with information down from components up to the assembly line. The X-axis illustrates what parts of the life cycle stages that are in the scope of each paper.

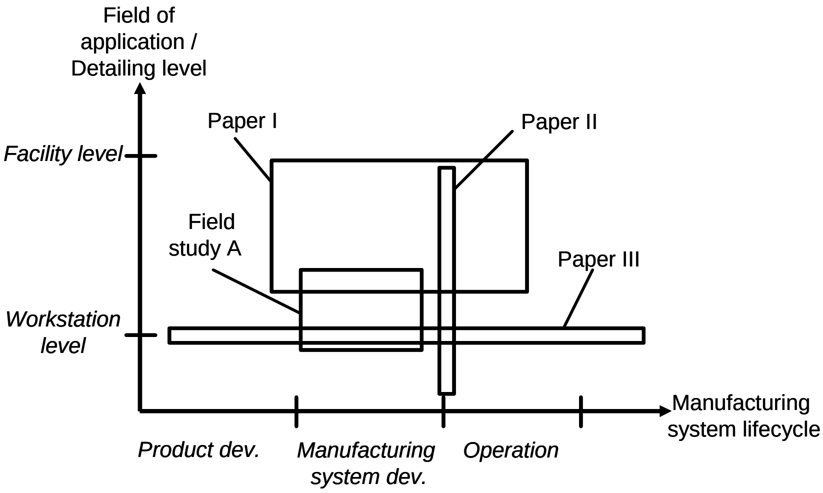

Figure 17: Paper positioning with regards to the scope of each paper

2.2 Paper I – Modelling Manufacturing Resource Capability

- A discussion of the industrial benefits.

The purpose of this paper is to discuss and analyse how manufacturing systems capability can be described predicting produced output. This paper addresses the definition of manufacturing systems capability. It is discussing the purpose and the benefits modelling manufacturing systems capability and how such model can be used. The focus is on product manufacturability as a decision tool for product design. Manufacturing system knowledge is made easy accessible, where control code even can be automatically generated to manufacture a specific product. Manufacturing systems capability information is exemplified. For instance, what geometries can be machined or what are the geometrical boundaries for a work piece?

To model manufacturing systems capability the manufacturing system is initially considered as a product. The characteristics of a specific manufacturing system configuration, from Field Study A, are described out of intended functions of the manufacturing system. If intended function of the manufacturing system is changed, it is proposed that the initial manufacturing system description then can be used as a base for changes. Making changes in the initial manufacturing system description can be an easier way to obtain a valid manufacturing system description than to start describing the manufacturing system from scratch.

Another way to illustrate the manufacturing systems capability is that the manufacturing system has a set of available performances. The performances can be defined after used manufacturing processes and other performing conditions, for example product properties or working temperature. Such description of manufacturing systems capability signifies a set of specific solutions rather than a general solution space. Specifying every possible solution would lead to a large number of solutions that can be hard to survey. With a general solution space, described by important facts and relations of the manufacturing system, a specific solution can be evaluated when needed. Such general description of the solution space is better suited to handle a complex manufacturing systems capability description.

Main conclusions of the paper:

- Manufacturing system capability description is introduced as a decision tool predicting product manufacturability.
- Using Field Study A, it is presented how manufacturing systems capability description can be used for a specific manufacturing system configuration. Further, in order to handle the complexity of manufacturing system capability information, a separation is suggested. It is suggested to separately describe: manufacturing systems, manufacturing processes, their relations to each other and their relation to external conditions, including the product.

2.3 Paper II – A Neutral Representation of Process and Resource Information of an Assembly Cell

- Supporting Control Code Development, Process Planning and Resource Life Cycle Management.

The purpose of this paper is to model a specific type of manufacturing process and relate that process to the manufacturing system information. The paper presents a representation of the process control of an assembly cell, using AP214 [ISO214] although slightly modified.

The paper studies the collection of information to the Programmable Logic Controller (PLC) code realization. The PLC code realization is interesting since it is one of the last activities in the manufacturing system development process before the production starts. Thereby the realization process is partly synthesising information from the entire manufacturing system development process.

In the paper the PLC code is described, considered as a manufacturing process composed by process steps. Each process step can have a relation to the others in order to describe the internal relations between the process steps, for example sequence, alternative, etc. Further, each process step is described, having a relation to parts of the manufacturing system and their state. The described state of a part of the manufacturing system can be defined as a requirement, as a goal, etc. to that specific process step. The relation to the manufacturing system can serve as triggers in the manufacturing process description. Further, the process steps can also be described with a relation to time, defining the start or the end of a process step. With the relations summarised in this section it is possible to fully represent and control the manufacturing process.

Standardized software components are used in order to realize the communication with the hardware components, for example fixation pin and positioning valve. The use of standardized software components leaves the process of changing the state of a hardware component outside of the discussed manufacturing process description.

Main conclusions of the paper:

- Information standards is shown to be useable to represent and document the manufacturing process control information, combined with standardized software components. The manufacturing process control information is made accessible in a higher extent to be reused in other applications, such as verification, optimisation, etc.
- The presented manufacturing process handles the interrelations between different process steps. Also the change of the manufacturing system is captured, describing the state of components in different process steps. However, the describing states of manufacturing system components do not explicitly describe how the transformation is performed.

2.4 Paper III – Manufacturing system capability representation with runtime information for reliable prediction of produced output

The purpose of this paper is to predict a products geometrical manufacturability within machining. An applicable method is presented using a parameterized model dictionary. Using the same information standard for geometry representation, the geometrical output of the manufacturing system and the geometry of the intended product are connected.

This paper presents the manufacturing system and the manufacturing process without recommending any specific information standard, although the ISO10303 [ISO1] AP214 [ISO214] is used. AP224 [ISO224] is used to represent parameterized features as part of the geometry representation. AP224 is adjusted for machining.

The following number describes a method for how products manufacturability in a manufacturing system can be predicted. The described method is illustrated in Figure 18.

1. A manufacturing system is described without relations to manufacturing processes or products.
2. The described manufacturing system is defined to be able to perform one or several manufacturing processes. Each manufacturing process is selected out of a parameterized manufacturing process library. Each parameterized manufacturing process, for example a drilling process, is characterized by a number of process properties. Out of the limitations of the manufacturing system, boundaries are set for each selected manufacturing process.
3. The expected performance of a specific manufacturing system configuration is described. Expected performance is described, using AP224, as performed product geometry. The product geometry is derived from defined feasible manufacturing processes of the manufacturing system.
4. The complete ability of the manufacturing system is now described as a collection of parameterized geometry descriptions. For example, for a specific drill tool, all depths of the hole can be performed from zero up to the maximum drilling depth of that drill.
5. This described manufacturing system capability description can now be used to evaluate a product design. In order to make the evaluation, and to predict if the product can be produced, the same geometry description is used for the product design.

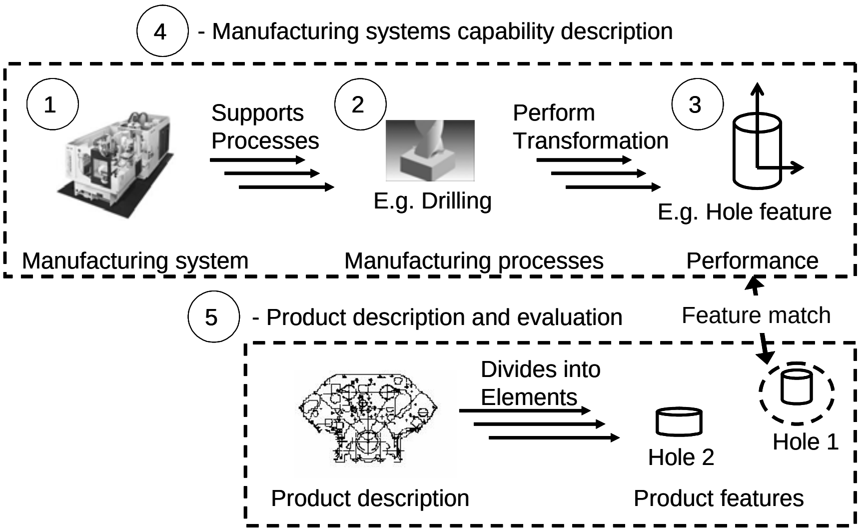

Figure 18: Manufacturing systems capability within machining to predict products manufacturability

Another purpose of this paper is to handle variations in manufacturing systems capability during the lifecycle of the manufacturing system. A solution is presented relating theoretical capability and real performance in the same information model. Using measurement data from produced output of a manufacturing system the theoretical description can be compared and updated continuously. During the lifecycle of the manufacturing system, the manufacturing systems capability can be verified and thereby continuously accurate and reliable represented. Such verification would be valuable when using the description for decisions that requires reliable information.

Main conclusions of the paper:

- Products geometrical manufacturability is described within machining. A manufacturing systems description is related to a number of parameterized manufacturing processes. The parameterized manufacturing processes are restrained by the manufacturing system description. A parameterized geometry description (AP224) is related to the restrained manufacturing process description in order to describe manufacturing systems capability. Products geometry is described using the same parameterized geometry description. Comparing products geometry with manufacturing systems capability, the products geometrical manufacturability is determined.

- The manufacturing systems capability description is connected to the measurement information. This allows the manufacturing systems capability description to be verified continuously.

2.5 Field Study A - Data exchange during the realisation process of machining manufacturing equipment

– A field study

The purpose of this field study is to explore the potential of using information standards communicating machining equipment information. In the case study the investment process of a machining line for engine blocks at a larger automotive company is studied. This investment process goes from a manufacturing need to an installed and fully working machining line. The manufacturing need is to perform a large number of machining operations on a raw material. The raw material comes from the foundry and after the performed machining operations the material should be an engine block ready for final assembly.

Technical documentation was studied, produced during the commercial process between the manufacturing system vendor company and the manufacturing company. Also the documentation delivered with the manufacturing system was studied. The field study gives an insight of the information to its contents, extent and format of a larger machining manufacturing system in conjunction to the investment process.

The study found a manufacturing system that was described by the vendor primarily as a product. The description included information such as machine tool geometry, specially designed tool and fixture information, proposed maintenance instructions, operations manual, to mention some. Typical manufacturing system information was found such as: the product that is to be produced, the process specification in order to produce the product, capacity constraints, to mention some. However, the found manufacturing system information was only for one specific product: the engine block. Little general manufacturing system information was found, useful when manufacturing another product than the current engine block.

The information standard AP214 [ISO214] was used to represent parts of the manufacturing system. The manufacturing process was defined according to AP214. The manufacturing system and the product were referred to from the manufacturing process description accordingly.

In order to examine the possibility to simplify the communication during the investment process the manufacturing system was represented in part, by using the information standard AP214 [ISO214]. Besides simplified communication during the investment process, the purpose was also to facilitate reuse of information from the investment process to other similar projects. The study is used influencing the subsequently written papers: Paper I, Paper II and Paper III.

Main conclusions of the field study:

- Manufacturing system information communicated during an investment process of a machining line for engine blocks was studied. The studied manufacturing system was described from its intended function for one specific product, rather than a description of its full potential, outside the specified configuration. Manufacturing process information and product information was represented although only one specific manufacturing process related to one specific product.
- Standardized information representation was used to describe the manufacturing system. Using a standardized description facilitate reuse of the manufacturing system information.

2.6 Summary

The potential in accurate and accessible manufacturing system information is pointed out in Field Study A. Further, the potential in describing manufacturing systems capability is discussed in Paper I. Information standards are used to describe manufacturing systems processes, for control purposes in Paper II. A method is presented in Paper III where manufacturing systems capability and products manufacturability are described, in the application of machining manufacturing systems.

Manufacturing systems are described in all papers with various characteristics in focus. In Field Study A, a practical integration of manufacturing system information, manufacturing process information and product information is illustrated. Manufacturing systems capability is described in Paper I, for a specific configuration.

Manufacturing processes are treated in Paper II. A sequence of interrelating process steps are described and related to manufacturing system components and their state. The changes of a manufacturing system components state, consequently describes a manufacturing process. However, even though the difference between two separate states can be described and thereby the manufacturing process, it is occasionally desirable to explicit describe the process. For example has an industrial robot, when moving a tool, a start position and an end position. It is not convenient to describe the path between the start and the end position as a set of states, due to the infinite number of positions that robot can have on the path.

Paper I states that the relation between manufacturing systems and manufacturing processes is to be developed, in order to represent manufacturing systems capability. In Paper III a number of parameterized manufacturing processes are connected and defined in accordance with a machining manufacturing system. The approach using parameterized manufacturing processes opens possibilities for a generalized manufacturing systems capability description. Any type of parameterized manufacturing processes can be connected with any type of manufacturing systems.

In Paper III, products manufacturability is described for machining geometries within AP224. Manufacturing systems capability is analysed and interpreted as a set of product geometries that can be performed by a specific machining manufacturing system, using a specified set of manufacturing processes. However, there is no explicit description of how the manufacturing system or the manufacturing processes relate to the product properties, such as material hardness, etc.

3 DISCUSSION AND CONCLUSIONS

This chapter is a discussion out of the research area as described in the first chapter and my contribution up to the present as described in the second chapter. It primarily discusses and concludes the direction of a continuation of research, without detailing any future work description. The discussion and the following conclusions are made out of the problems encountered and experiences made during the research work until present time. The outline of this chapter follows the first chapter, starting broad getting more specialized.

3.1 Modelling systems information

Accurate and accessible information is valuable and it is desirable to reuse information when possible. The importance of information fundamentals such as definitions, reliability and detailing, are further discussed in this section.

3.1.1 Information reliability

The same data can be reused in different applications and in different contexts, interpreted differently. However, as discussed in 1.4.2, the value of information is highly related to the ability to manage changes.

Managing accuracy

When data are reused, data are interpreted at a different point in time from when it was created. Due to the difference in time between data creation and data interpretation, data may differ from reality since the present conditions may be different from the time of the data creation. For example, a digital thermometer is observed. If there is a time delay between the measurement and the presentation, the shown temperature may be misleading.

Things tend to change, although at very different pace. The hardness of diamond is fairly stable. The number of car models produced per year globally, tends to grow rapidly. In order to handle accuracy of data it is important to handle the data alteration over time. Also, it is important to control the eventual influence that an alteration may have in a specific application. Handling accuracy signifies that the alteration is described for a context. But accuracy is also handled when the alterations is considered negligible within the context. For example, the stretch of steel is defined as a linear function of the stress (up to a certain level of stress). So within a certain application and in a certain context, the length of a steel bar can be declared constant, or the length can be defined as a function of the stress.

The accuracy requirements on a property certainly differ depending of the application or the context. For example, the resistance of an electrical component used in a radio probably do not have the same accuracy requirements as a similar component used in an aeroplane. How changeable data are may depend on how an application is chosen to be used. For example, the *available time* of a manufacturing system depends of the maintenance strategy. The *available time* can also depend of how the manufacturing system is used, such as the number of different product variances, the batch size, etc.

It is often hard to predict how changeable data are. However, a distinction can be made between reproducible data and non-reproducible data. Reproducible data are possible to measure and evaluate statistically, thereby can the accuracy be described. Reproducible data could for instance be the physical properties of a manufacturing system. Non-reproducible data, further mentioned in 1.9, could for instance be taste.

Model reuse

Once a model is developed for certain application, that model might be useable also in other contexts. Instead of developing a new model, earlier developed models may be usable as a base when interpreting the implications of new conditions. Interpolation can be one way to interpret a model out of earlier interpretations at dissimilar contexts. For example can the first model be of a drilling machine that drills holes in metal with known material properties. The cutting force for a new material with known material properties would then be evaluated. The effect of the new material may be predicted, using known relations for cutting force defined for similar materials.

3.1.2 Detailing

The model describes a portion of the world [SCH94]. That portion of the world can differ a lot in its nature, as well as the level of detailing can vary. Compare a model of a product flow in a factory with a model of the steel cutting process. Also for a specific object the nature of the model and the level of detailing can vary. Taking an industrial robot as an example, the robot can be modelled as a type of robot, the robot model or a physical individual robot operative on the shop floor. As discussed earlier, it may be efficient to reuse models. Continuing with a robot as an example, a robot model can inherit properties to a certain level of detailing from the description of that robot type.

Modelling manufacturing systems capability, it is likely that the manufacturing system is directly dependent of the capability of its underlying parts at different levels of detailing. Thus, it is crucial to understand and describe the manufacturing system as a system of underlying components, and how these components act as a system.

Synthesizing information

The section above discusses models at different levels of detailing. A general model usually has a lover level of detailing, such as a factory description. A specific model usually has a higher level of detailing, such as a cutting tool description or a cutting process description. Modelling a manufacturing system, for instance a machine tool, it could be done simply summarizing the specific models of every component the manufacturing system is composed of. However, such approach would not be suitable due to the amount of information. Changing viewpoint from a high to a low level of detailing, for instance from machine tool level up to factory level, it is important to avoid information overflow and still capture important properties for the new general viewpoint. Only important information for the actual viewpoint and detailing level should be filtered out. Of course it should likewise be possible to change detailing from a general model to a detailed model. For instance, show detailed machine tool information, or even tool information, for a bottleneck in a machining line, exploring information that is normally unnecessary for the machining line survey.

This research treats products manufacturability in terms of geometrical output from manufacturing systems. Modelling a function, it is important to balance the level of detailing. A model to general would not carry out the target to describe the function. A model to detailed would lead to an extensive amount of information that is hard to interpret, and thereby not reaching the goal of describing the function.

3.2 Modelling manufacturing systems capability

This section discusses how manufacturing systems capability is modelled using the fundamentals pointed out in section 1.6. Further is the implementation of a manufacturing system capability model within machining examined.

The information base

The foundation of a manufacturing system capability model is the description of what it is able of performing. Modelling manufacturing systems capability should be based on fundamentals of a manufacturing system, its components and possible configurations. The fundamentals of a manufacturing system are well-defined properties of the resource.

In some cases it can be suitable to model a manufacturing system at one level of detailing, observed as a black box and described from that level of detailing only. Describing and representing for example a factory in this general way, hiding all underlying relations and phenomena, might serve its purpose for the top management or any other group working with the manufacturing system from this specific viewpoint and detailing level. However, in order to be able to change viewpoint in a hierarchical tree structure, for instance from facility to equipment that could be a machine tool, it is crucial to understand and to capture relations and properties of the entire manufacturing system. This necessity to handle change of purpose and viewpoint is also treated in Paper I. Further, a method is proposed in Paper III to describe relevant information of a machining manufacturing system in a structured way. It is shown that it is central to understand and capture the consequences for the facility of a change in the equipment in order to get an accurate facility representation. Therefore it is important that a manufacturing system description is based on fundamental properties of the manufacturing system.

Multiple classes

A model with classes that allows multiple belongings is a suitable way to meet the requirement of extensibility, described in 1.5.3. The modelling of an industrial robot is taken as an example. One model may have a specific class for industrial robots where a robot is described. If that model does not allow multiple classes, the members of a specific class are not allowed to be member of any other class. Another way of modelling industrial robots would be to represent its different types of properties like positioning, movement, etc. in different subclasses. The complete description is then defined to be a member of a class for industrial robots where the properties are defined in the sub-classes that are referred to from the class of industrial robots. Further, a subset of the robot description may be member of other classes as well, such as positioning system.

Manufacturing process

Modelling a manufacturing process is to describe how a manufacturing system performs. That could be to take models of machine tool, tool, fixture, part and process model with parameter into account. The scope of ISO14649, described in section 1.6.4, includes the description of the manufacturing process and the product as well as the description of how the properties of the product are changed during the manufacturing process. However, there is no relation combining a process description to a manufacturing system description. Adding an explicit relation in ISO14649 to a manufacturing system description is an interesting approach combining the resource, process and product domain in order to model manufacturing systems capability.

3.2.1 Manufacturing systems capability within machining

The Computer Aided Manufacturing (CAM) software tools found on the market today certainly do have and use a manufacturing system capability description to some extent. However, the possibility for the CAM user to inspect or revise the manufacturing systems capability description is very limited. Generally a CAM user chooses a predefined standard machine and standard tools. The predefined machines can be configured to some extent, although within limitations to what the software and the capability description is able to manage.

STEP-NC to enable manufacturing systems capability description

Manufacturing system development within machining is described and discussed in 1.7.1. The described development process adopted from STEP-NC would make it possible to include and use a manufacturing systems capability model. Information is transferable between the different activities of the manufacturing system development. As discussed, a verification loop can be developed of the complete manufacturing system development. The advantages modelling manufacturing systems capability in combination with STEP-NC can be summarized:

- The manufacturing process can be better adjusted to the manufacturing system potential, when iterating different process solutions against a capability description.
- Performing detailed manufacturing process specification will adjust not only towards limitations of the machine tool but also towards the limitations of the control system.
- Any change or discrepancy in the manufacturing system capability description, for example wear, can change the process description continuously, when verifying information can be fed back to the manufacturing system capability description.

The manufacturing process is initially, in the described scenario, modelled with no consideration of specific machine tool or control vendor. Thereby, the geometry description and the parameterized process specification can remain intact when different detailed process solutions are examined.

Example

To examine the described scenario the machining of a hole is taken as a specific example. The manufacturing systems development is following the activities described in the second scenario of 1.7.1, where the differences are examined below:

STEP-NC relates to the geometry that is to be machined with a corresponding machining feature, as described in 1.6.4. In this example the geometry description would be defined as “round_hole” and the corresponding machining feature could be defined as “drilling”. The *detailed process specification* is an iterative activity that is validated using the manufacturing system capability description. In order to validate the process specification, the selection of a machining feature is verified with a manufacturing system capability model. This means that when the geometry is defined, all machining features that are capable to perform that geometry can be found. Out of the capable machining features, one suitable machining feature can be selected. In this case it can be related to the sequence of operations; “drilling”, “centre drilling” and “multistep drilling”. The machining features are compared and decision criteria are applied which results in the selection of operations.

Summary

STEP-NC of today is capable to describe a selection of manufacturing features that relate to geometry that is to be machined. In order to apply manufacturing systems capability, the <u>range</u> of the manufacturing features has to be defined. It is important to know that the manufacturing feature “round_hole”, with its operation “drilling” is capable to perform the round hole within range of the tolerance, surface finish and drilling performance.

3.3 Conclusions and future research

Modelling manufacturing systems capability, three sub areas of interests are established in section 1.8.3. The three sub areas are: manufacturing system, manufacturing processes and the product. In this thesis, each sub area has been treated as well as the relations between these sub areas.

3.3.1 Summary

The information of a manufacturing system, and the components it is composed of, is described with different perspectives in all Papers. The information is mainly described in a structure-oriented way. Properties of the manufacturing system are represented and structured, such as geometry, component configurations, possible movements of a component, physical relations between components, reference coordinate system, etc.

Representing different states of a manufacturing system is described in Paper II in order to represent manufacturing processes. Manufacturing process information is represented by describing the relations between a number of events and activities with attributes, such as sequence, substitution, etc.

Manufacturing systems capability can in part be described without directly considering the product area. Describing a manufacturing system with manufacturing processes would give a property description such as, possible movement of a tool, force, etc. Paper III initially presents such a manufacturing system capability description where no other properties than geometry is described in the product area. Allowed processes are defined out of a generic process library, instantiated and connected to the manufacturing system description.

Manufacturing system capability information is used to define the product manufacturability, which means the change in the product that the manufacturing system is able to perform with a process. Paper III presents a manufacturing systems capability description considering the product area. The product is defined out of a parameterized product geometry library for machining.

From reasoning in this thesis, STEP-NC is found useful as an enabler to describe manufacturing system capability. STEP-NC is shown to describe manufacturing systems within machining where the product, process and resource are collectively described. In order to describe capability and evaluate products manufacturability, STEP-NC has to be extended from describing one configuration of a manufacturing system to describe a set of configurations.

3.3.2 Future research

Relations between the sub areas

The three sub areas of manufacturing system capability are established as: manufacturing systems, manufacturing processes and the product. All three main relations have been treated in this thesis. However, it is suggested to further explore those relations in order to get a more detailed manufacturing system capability model. Further development would also allow the model to be applicable in a wider context than machining, such as assembly. Most desirable would be to further explore the influence of the product properties on the manufacturing system performance. For example that can be material property dependencies, a products surface finish as consequence of initial surface finish of the raw material, etc.

Reference libraries

Closely related to further explore the relations between sub areas discussed above, is to develop reference libraries. Paper III showed how reference libraries were used within machining representing specific processes and specific geometries. A reference library would be a source of information capturing knowledge within a specific area. The use of reference libraries facilitates the reuse of information in different applications.

Manufacturing processes

The manufacturing process is shown to be central of the manufacturing system capability description, describing how the system performs. In this thesis the manufacturing processes has been described through the change of the manufacturing system, in order to produce tangible products, as in Paper II. The manufacturing processes are not explicit described. If, for example, the movement of a tool is described, the start position and the end position of the tool are described, not the tool path. This approach may be detailed through higher resolution, for instance defining several positions along the tool path that has to be passed. However, an explicit description of the manufacturing process is desirable in order to better represent process specific information.

STEP-NC

STEP-NC is shown to describe manufacturing systems within machining, collectively representing a manufacturing system, processes and product in the same information model. Using STEP-NC, as a base for development would, be a feasible way to implement manufacturing systems capability. STEP-NC is able to represent how specific manufacturing system configurations perform. Therefore, developing a model to represent a set of manufacturing system configurations or a range of possible performances would make it possible to determine products manufacturability.

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