

# **A MODEL FOR PROJECT-BASED EDUCATION IN MANUFACTURING SYSTEM DESIGN AND ITS APPLICATION ON TESTING RESEARCH RESULTS**

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*Keywords: engineering education, engineering design, manufacturing systems, research methodology*

## **1. Introduction**

When designing products and the corresponding life-cycle systems, engineers apply various technologies to aid the development process. These technologies provide effects that are needed in order to employ the functions of the designed product. The engineers apply both different systematic and ad-hoc methods as well as computerized engineering tools, when working on solutions to engineering problems. Products and their corresponding life-cycle systems are often developed in an organization consisting of niche professionals responsible for executing different design tasks. This way of working is characterized by an intensive information exchange between the different tasks.

However, the engineering education of today is primarily focused on teaching: (i) fundamentals of inherent characteristics of natural phenomena and their application as technology, (ii) application of a dispersed set of engineering tools on the engineering sub-problems without relating sub-problems and tools to each others, (iii) “soft” subjects such as general management. What is needed is an engineering education model that within a single logical framework provides support in teaching students how an engineer together with other engineers should approach and solve a complex engineering problem, using various methods and tools for various purposes during the execution of the engineering design process.

Furthermore, academic research within the area of engineering design is not always easy to conduct. Although the engineering companies are often willing to discuss the engineering design problems and even to allow the academic researchers to study current internal engineering practices, most of new engineering design methods developed within academia are not properly tested. A novel engineering design method implies changed work-procedures, which together with the absence of success stories from a relevant industry branch leaves an engineering company reluctant towards an operative test of the novel method proposed by the academics. This attitude is not only an expression for a lack of business courage but it also consist a serious threat to the creditability and the evolvment of the engineering design research.

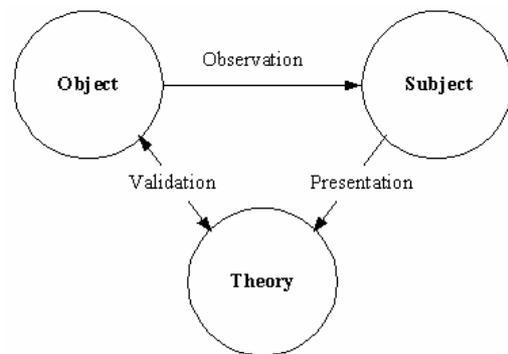
This barrier to the industrial testing and dissemination of research results may be avoided through the utilization of student projects within engineering courses, where undergraduates learn to apply a novel design methodology by solving a real engineering problem. In this setting, a company that demands a solution to a problem will get not only the solution but also a demonstration of a problem solving methodology that hopefully is superior to current practices. When the methodology is successfully demonstrated on a company-specific problem it is easier to motivate its implementation. In addition, newly graduated engineers will continue application of the methodology and thereby continue the initiated industrial dissemination.

The purpose of this paper is to present a method for project-based education in engineering design methodology, focused on manufacturing system development, in collaboration with industrial partners. This method might be used as a framework for conducting the engineering design research and testing the research results within the context of undergraduate engineering projects.

## 2. Research Method

The research presented in this paper is based on a research model presented by Fagerström et al. (2002) and Aganovic (2004). It is a comprehensive map of the relationship between elements of a scientific theory-building process in a general model of scientific research and it consists the following elements:

- Object – physical things, processes and behaviors observed in the real world. In this paper: engineering design methodology, engineering education approaches, research methodology.
- Subject – researcher(s) who perform the observation, analyze the data and present the theory.
- Theory – result of research activity that answers research questions. In this paper: A model for undergraduate engineering projects and validation of research results.
- Observation – collection of data about the object. In this paper: case study and its sources of evidence like interviews and documentation/literature surveys.
- Presentation – result of data analysis performed by the subject and description of used research method. In this paper: Section 3.
- Validation – securing of consistency between the presented theory and relevant objects. In this paper: a case study on manufacturing system development in collaboration between a group of students and a small engineering company.



**Figure 1. Model of research, Fagerström et al. (2002)**

## 3. Results

### 3.1 Observation of the Research Objects: Frame of Reference

The theory that will be presented and tested on the following pages is based on a number of case and literature studies previously conducted by the authors of this paper (i.e. the subjects). Engineering design theories and methods have been surveyed and presented by Aganovic et al. (2003). Manufacturing system design (MSD) methodologies have been surveyed and a novel methodology based on MSD-methods, engineering design theories, and industrial case studies has been presented by Aganovic (2004). Engineering design process models has been surveyed by Fagerström et al. (2002) and a deep analysis of two different process models has been conducted by Aganovic et al. (2001) and Aganovic and Svensson (2002).

Engineering education methods at ten European and American universities have been studied and presented by Bodmer et al. (2002). The content of Swedish engineering programs and their correspondence with the short- and long-term industrial needs has been discussed by Nyberg (2003). The engineering education framework CDIO has been developed in collaboration between nine universities from Canada, Denmark, South Africa, Sweden, UK, and USA. CDIO has been presented in numerous papers that can be downloaded from the CDIO-website ([www.cdio.org](http://www.cdio.org)). Engineering education by applying IT is discussed by many authors, e.g. Gibson et al. (2002).

A unified research methodology consisted of elements from research methodologies applied in both natural and human/social sciences has been presented by Aganovic (2003).

### 3.2 Presentation of the Theory: A Model for Project-based Undergraduate Education

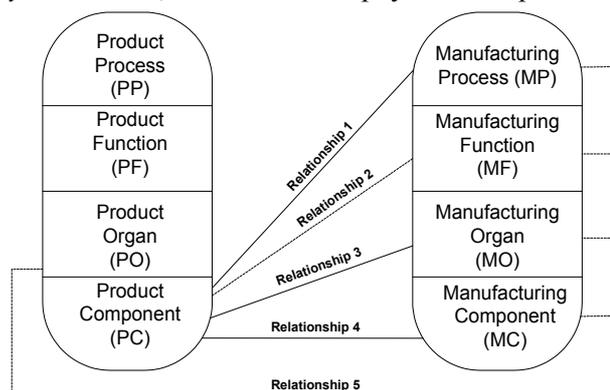
Education of undergraduates in manufacturing system design methodology can be conducted if students are actively involved in a manufacturing system design project. During the course of the project, the methods consisted in the manufacturing system methodology are utilized in solving sub-spaces of this complex engineering problem. Different methods enable collection, analysis, and synthesis of manufacturing system data in different perspectives.

When viewing a manufacturing system from these different perspectives different system models are managed. A model can be described as a simplified representation of a system that aims to represent a system's content and relationships between elements of the content. The representation contains only properties that are important for the purpose that the model is going to be used for, while all other properties are excluded. Models can be used to create an artificial world where experiments can be performed.

#### 3.2.1 Design Objects

The goal of the design activity is to develop detailed structural models of a product and its corresponding manufacturing system. The manufacturing system and the product instances are thereafter implemented in their physical incarnations. During the execution of the design process four structural models for each technical system, i.e. the product and its manufacturing system, are developed: (i) *process system model*, which contains processes, i.e. transformations of objects (material, energy, signals) in space and time based on various technological principles; (ii) *function system model*, which contains functions, i.e. abilities to create desired effects that enable the transformation; (iii) *organ system model*, which contains organs, i.e. entities that carry the functions and thus create the effects; and (iv) *constructional system model*, which contains physical components and assemblies thereof that embody (realize) the desired organs (cf. Figure 2).

These four system models were first introduced by Andreasen (1980) as Theory of Domains (ToD), and then applied within the manufacturing system design area by Andreasen and Ahm (1988). The new approach to the ToD, as depicted in Figure 2 and applied within the theory presented in this paper, is introduced and detailedly discussed by Aganovic (2004). This set of eight structural models must be populated continuously during the execution of the design process. The information in these models is the result of design decisions made by the designers using various design methods and tools.



**Figure 2. Structure model for the product and its manufacturing system**

#### 3.2.2 Design Methods

Within the manufacturing system design methodology framework for undergraduate education, following methods and tools are used:

- IDEF3 can be used for creation of product- and manufacturing process structures,
- IDEF0 can be used for creation of corresponding functions and organs and for analysis of functional couplings,
- Process Flow Charts (PFC) can be used for capture and analysis of the relationship between value-adding and other manufacturing processes,
- Relationship and precedence diagrams can be used for determination of high-level, primary spatial, manufacturing organ and -component structures,

- Discrete Event Simulation (DES) can be used for creation and analysis of high-level manufacturing organ and -component structures,
- Method-Time-Measurement (MTM) can be used for determination of cell-level manual manufacturing organs and –functions, i.e. spatial relationships and work procedures,
- Computer Aided Manufacturing (CAM) can be used for creation and analysis of spatial and behavioral properties of numerically controlled manufacturing organs and –components on the cell-level,
- Computer Aided Design (CAD) can be used for modeling the geometric shape of product- and manufacturing components.
- Design of Experiments can be used for determination of sets of key product parameters and their relationship with corresponding functional requirements, as well as for determination of sets of key manufacturing system parameters and their relationship with the corresponding product parameters.
- Design for Manufacturing and Assembly (DFMA) can be used either proactively during product development in order to implement product components that allow creation of optimal manufacturing process and –component structure or reactively to evaluate product components’ manufacturability from the perspective of available manufacturing processes, -organs, and – components.

### ***3.2.3 Design Process and Project Control Model***

During the course of the manufacturing system design project, a number of sub-problems are solved by a team of students. These students conduct the design work by utilizing the above mentioned methods and corresponding tools to continuously shift their perspective on the manufacturing system and thereby bring the design problem to a final solution. The methods and tools are taught prior to the start of the manufacturing system development project in separate course modules. Since a manufacturing system development project involve several individuals and organizations that utilize different work methods during different time intervals, a project control model that systematizes the interaction between different design methods is needed. This project control model can be implemented as an internet application. Such an implementation has already been done by the authors (see [www.iip.kth.se/~dag/teaching/tis0304/kthipm](http://www.iip.kth.se/~dag/teaching/tis0304/kthipm) for a detailed description) and it is the principles of that implementation that are to be briefly explained here.

The manufacturing system development process is an aggregation of five sub-processes: (i) preparation, (ii) concept design, (iii) system design, (iv) detailed design, and (v) completion. Each of the sub-processes is then described in terms of its inputs, its outputs, and the activities that need to be executed in order to transform inputs into outputs. The activities are executed using the above mentioned methods and tools. During the course of work the students will generate a set of manufacturing system models and project documents. The format of the manufacturing system models is controlled by the used methods, and project document format is controlled by pre-defined templates that can be downloaded from the internet. By clicking on the arrow that symbolizes a sub-process, a student arrives at a page where inputs, outputs, and activities for the sub-process are described. From the sub-process page, project document templates are downloaded.

#### **3.2.3.1 Project Assignment and Project’s Internal Organization**

The main input that triggers a project is an assignment specification prepared by the faculty and the partner company whose product is to be industrialized. Generally, there exists a concept proposal for a product that is going to be manufactured. A group consisting of 5 students is assigned to prepare the product for manufacturing by designing a manufacturing system concept and by generating concrete proposals for how the manufacturability of the product is to be enhanced, i.e. proposals on changes of product organ embodiments. In the assignment specification different roles within the project are defined and assigned to the project members. The defined project roles are: project manager, system designer, manufacturability analyst, assembly engineer, and discrete manufacturing engineer.

### 3.2.3.2 Steering Group and Project Gates

The project is monitored by a steering group consisting of the project course manager, members of the faculty, and partner company representatives. Prior to the initiation of each sub-process a gate-meeting is held between the project group and the steering group. At gate meetings the project assessment is performed, i.e. fulfillment of project goals is evaluated, and three optional outcomes of the decision are identified; *go*, *no* and *redirect*. *Go* means that the objectives of the previous phase are fulfilled and the next phase can be initiated, *no* means that the process is terminated and will not be continued and *redirect* means that the objectives of the previous phase are not fulfilled and, consequently, some rework has to be done. There are at least six gate meetings, one meeting prior to each phase and a project completion meeting.

### 3.2.3.3 Project Stages (Sub-processes)

During the execution of the sub-process *preparation*, students need to understand the operations strategy of the company, its existing processes and resources, as well as product design rationale. In this stage the project specification is generated. *Concept design* is the first manufacturing system design sub-process. Here, a high-level manufacturing process, -function, and -organ structure is established. Methods like IDEF0, IDEF3, and PFC are used. Naturally, DFMA and CAD are also used during the course of the whole project for manufacturability assessment and generation of product design change proposals. Preliminary supplier lists and an investment plan are generated. In *system design* phase the decomposition of structural models (manufacturing processes, -functions, -organs, and -components) is continued until the manufacturing station level. A special attention is directed towards selecting appropriate manufacturing components and the corresponding workshop layout (using relationship and/or precedence diagrams) as well as manufacturing system operation principles. Based on the manufacturing system business requirements and the proposed manufacturing system design, a simulation experiment plan is created and a DES-tool is used to build the system model, and through experiments find and/or verify an optimal manufacturing system configuration. The next phase is *detailed design*, where manufacturing stations are designed. Here, structural models are further decomposed and methods/tools like MTM and CAM are used for design of manual and automatic manufacturing station components. When station design is proposed the all-over manufacturing system concept, i.e. stations arranged according to the workshop layout and controlled according to the proposed operation principles, are analyzed through conducting the simulation experiments using a DES-tool. The project is terminated in the sub-process *completion*, where necessary design adjustments are made and a final project report is compiled from the generated project documents.

### 3.2.3.4 Information Management

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

### 3.2.3.5 Project Control and Support Organization

Normally, several independent projects are executed concurrently. Every project is conducted in collaboration between a student group and an engineering company. In order to be able to control and support all the projects an overall management/mentoring structure must be established. The approach here is to regard the whole student group and relevant faculty members as an engineering consulting company specialized on manufacturing system development. The overall organizational structure resembles the matrix organization with vertical functional departments and horizontal processes. The key business process is the manufacturing system development process (as described above), which is utilized as project control model. Every project is an instance of the manufacturing system development process that has its own *project mentor*. A project mentor is a faculty member that helps

the project manager and the project members to carry out the project, e.g. advising in task prioritization, helping in establishment of project documentation, referring to appropriate advisors in specialist issues. Project mentorship may be seen as an instance of the process ownership, i.e. a project mentor is a manufacturing system development process specialist and a project facilitator. The vertical functional departments are managed by different *scientific area mentors*, who have specialist knowledge within different areas related to manufacturing system development, e.g. simulation experiments, engineering design methodology, metal cutting, manufacturing automation. Students are expected to either on own initiative or on the recommendation of the project mentor ask scientific area mentors for support regarding specific issues that fall within the scientific area mentor's competence profile.

### **3.3 Presentation of the Theory: Testing Research Results through Student Engineering Projects**

Now, how can the project-based model for undergraduate education, presented in the previous section be utilized for testing research results? The undergraduate project can be utilized as an experiment, where certain effects can be observed in order to produce basis for answering a set of research questions. When conducting observations the subject needs to develop and apply a suitable investigation strategy. One such strategy is the concept of case studies. Case studies are especially suitable for studying complex phenomena, often social ones, where research objectives are expressed as *how-* and *why-*questions about research objects. The following procedure is a suitable approach for testing research results through using student engineering projects as observation cases:

1. Identify the problem within the existing body of theory
2. State the research questions
3. Select an engineering assignment together with the partner company and appoint a student project group
4. Propose answers to the research questions or state formal hypotheses that can be tested within the presented project-based model for undergraduate education.
5. Perform the observation, i.e. collect the evidence by interviews, documentation study, study of archival records, study of physical artifacts, direct observation, and/or participant-observation.
6. Map the evidence to the propositions (cf. 4) and interpret the findings
7. Present the conclusions

### **3.4 Validation of the Theory: Attana Case Study**

#### **3.4.1 Case Study Data**

In this case study a part of the research presented by Aganovic et al. (2003) and Aganovic (2004) is tested. This research is a basis for the theory presented in Section 3.2. Therefore, it is possible to claim that this case study will be used to test some of the principles (research results) that lie behind the manufacturing system design methodology framework used in undergraduate engineering education. The case study of two student projects was performed in collaboration between students from KTH's Department of Production Engineering and the engineering staff of Attana AB during the period between January and May 2003.

##### **3.4.1.1 Research Question:**

How can various manufacturing system development tools be utilized throughout different development process stages for generating a manufacturing system concept for an already introduced product?

##### **3.4.1.2 Proposition**

- The model presented in Figure 2 can be utilized as a master structural model during the development of the manufacturing system.
- The structural model can be continuously fed with the data based on the development decisions, these are in turn made through the utilization of appropriate manufacturing system development tools.

- A stage-gate manufacturing system development model (cf. Section 3.2.3) can be used to coordinate utilization of different development tools depending on the level of completeness in the design object.
- A PDM-system can be utilized for development information management where the structural model is used as a blueprint for the PDM item structure.
- Activity modeling, as conducted in IDEF0, can be used in transferring processes (MP) into uncoupled functions (MF) and corresponding organ (MO) structures.
- Process flow chart can be used for aiding the decisions on e.g. location of buffers and quality controls, transportation routes and for understanding the relationship between value-adding processes and other, more or less necessary, manufacturing system functions. A process flow chart thus supports IDEF0-modeling activity.
- Manufacturing system layout where overall structure and spatial relationship between physical components (MC) that embody organs are specified can be developed using layout tools such as trip matrix, REL-chart or precedence diagram.
- Job design tools, e.g. MTM, can be used together with process flow charts and activity models in definition of manual processes (MP and MF) and resources (MC). Thus, the human system is treated as an integral part of overall manufacturing system.
- Simulation Digital Prototyping-tools (SDP) such as DES and CAD/CAM can be used for validation and improvement of developed system concepts as well as for generation of corresponding control programs and 3D manufacturing resource models.

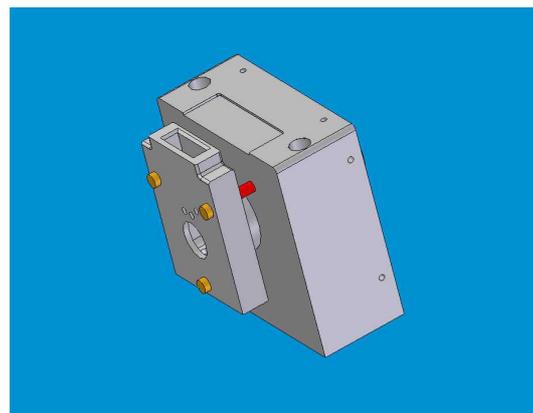
#### 3.4.1.3 Sources of Evidence

- Documentation: Product documentation; Manufacturing system documentation; and Project documentation.
- Open-ended interviews: For each of the two projects project there is a Project Manager, a System Designer; an Assembly System Designer, a Manufacturability Analysts, and a Discrete Manufacturing System Designers; and there is also a common Product Designer.
- Participant-observation: The case study researchers have defined the assignment and working methods used in the projects; the researchers have also participated in the development projects as advisor and chairman of the project advisory board respectively.

### 3.4.2 Case Study Report

#### 3.4.2.1 The Product

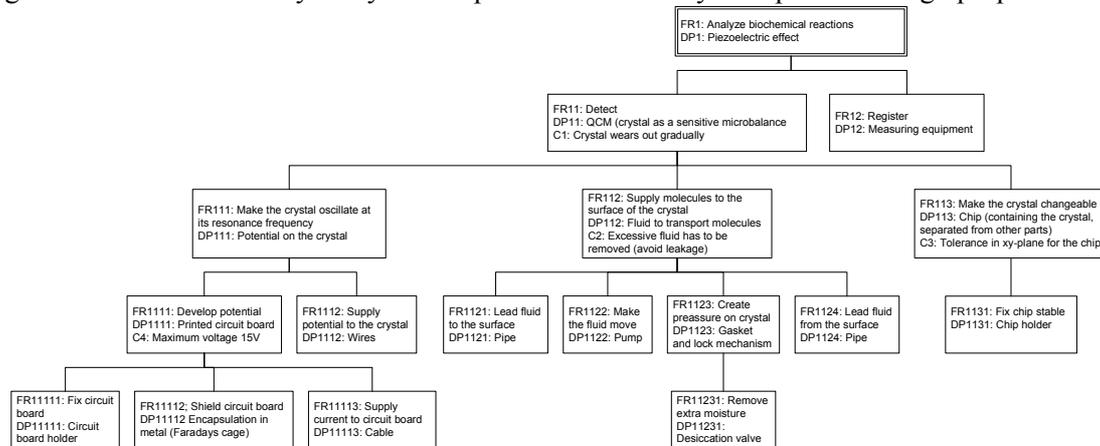
A manufacturing system concept has been developed for a product realized by a Stockholm based biotechnology start-up, Attana AB. Attana's product, Attana 100, is used for chemical analysis in for example development of pharmaceuticals. The product applies Quartz Crystal Microbalance (QCM) technique and is built up of several mechanical subsystems. Some subsystems are developed by Attana while others are standard components acquired from external suppliers. The project was focused on the two product subsystems developed by Attana, namely the analysis unit and the exchangeable chip containing the quartz crystal (cf. Figure 3 for analysis unit).



**Figure 3. CAD-model of Attana 100**

When the preparation phase started, each group got, besides an assignment specification, a 3D product model and a set of drawings representing each component in the existing product. In order to be able to assess manufacturability and propose product design improvements, project members of each group performed a functional analysis, which resulted in a FR-DP-tree depicted in Figure 4. The functional

analysis gives a better understanding of the product components' raison d'être. Thereafter, an initial manufacturability analysis (DFMA), was performed. The manufacturability analysis resulted in a set of product design improvements, of which some were accepted and some were rejected by the Product Designer. A manufacturability analysis was performed for every new product design proposal.



**Figure 4. A high-level FR-DP-tree for Attana 100**

### 3.4.2.2 The Manufacturing System

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

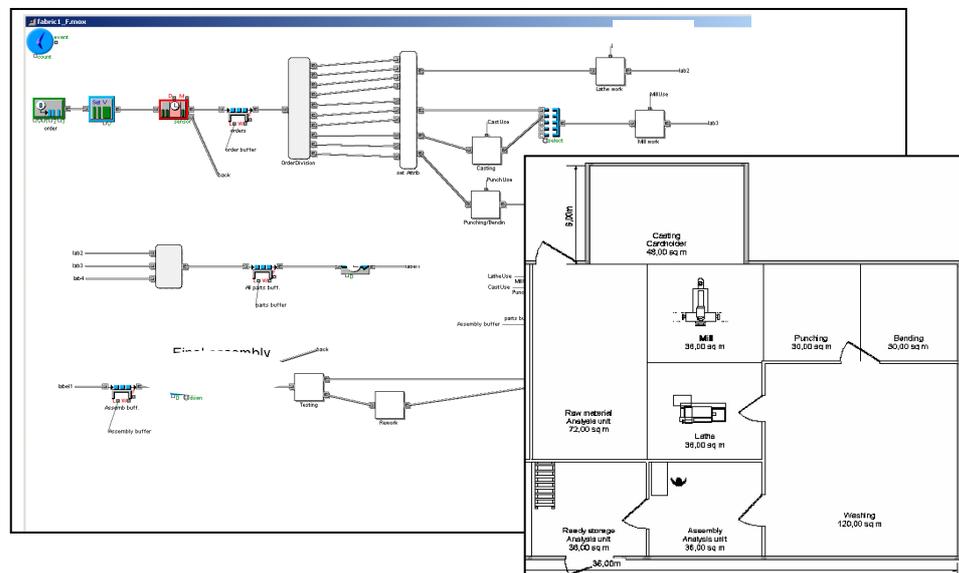
In the Concept Design phase the activity modeling method, corresponding to the standard IDEF0-method, has been utilized to create structures for manufacturing functions (MF). First, an overall manufacturing process (MP) structure was proposed. MPs express the value-adding operations that transform input material into components with desired features, as specified in the PC-structure. The MP-structure is product centric and it does not say anything about which manufacturing processes (e.g. turning, milling) are going to be used in order to create a desired product features. These processes are expressed in the MF-structure created using the IDEF0-method (cf. Figure 7).

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

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

After an initial layout had been created the manufacturing system was optimized and validated using a DES-tool. Operations times for different MCs were in this stage theoretical, i.e. estimated using formulas for e.g. milling. Figure 5 shows a snapshot of a simulation model created with Extend and the corresponding workshop layout. The structures of the MP, MF, MO, and MC are established concurrently; therefore a change introduced due to a DES-optimization can cause certain changes in a REL-chart and/or IDEF0-activity model.

When a high-level structure has been established, the detailed resource-level structure must be created. In the Detailed Design phase, MP- and MF-structures were first developed by breaking down the IDEF0-activity models. On these levels, internal manufacturing resource operations, e.g. fixturing of the work piece and material removal, are specified. Operation lists, including operation- and setup-times and -costs are generated together with IDEF0-models (cf. Figure 6).

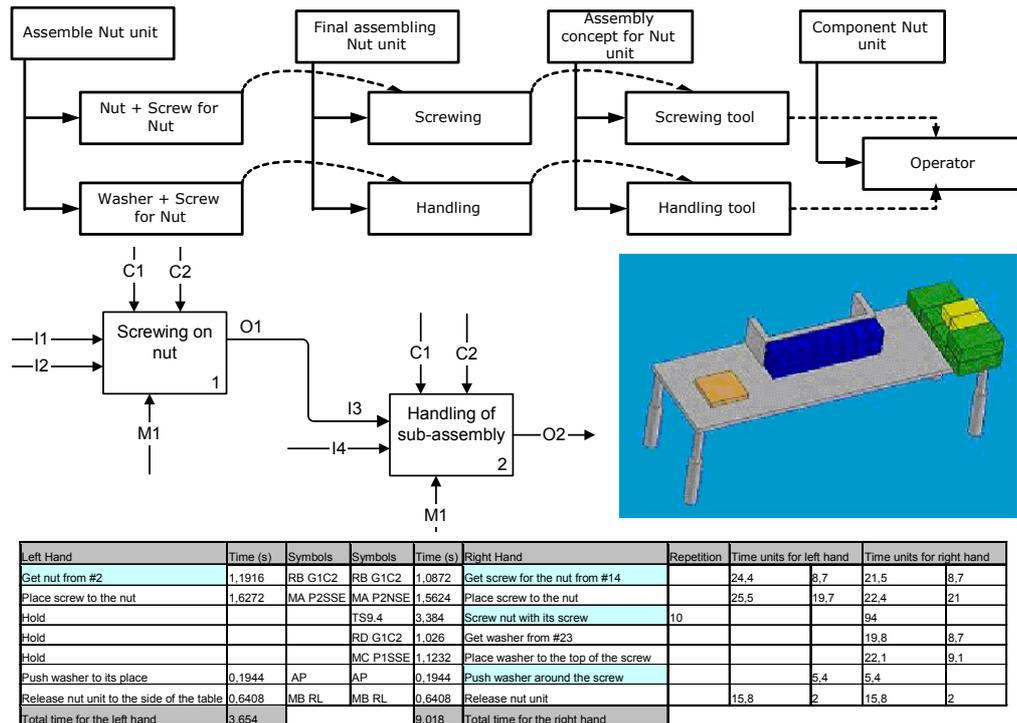


**Figure 5. A snapshot of the DES-model for manufacturing of Attana 100's analysis units, and the corresponding layout of the workshop**

Article:	Screw for handle	Ordersize	5 pieces	Material cost		
Department:	Manufacture	Annual sales estimation	1000 pieces	Mfg. Cost		
Material	AI	Description	Number	Styckekostnad [SEK]	Kostnad [SEK]	
Op-nr	Operation	Part time [hr]	Setup time [hr]	Total time [hr]	Time cost [SEK/hr]	Operations cost [SEK]
1	Feed bar	0,00056				
2	Level cape side with 1mm	0,00109				
3	Level side with 1mm	0,00089				
4	Remove 5mm material with length 15,5mm	0,00061				
5	Remove 7mm material with length 15,35mm	0,00059				
6	Toolchange	0,00060				
7	Remove material with depth 1mm for flat surface for	0,00059				
8	Toolchange	0,00060				
9	Remove material with depth 18mm for hole with radi	0,00071				
10	Toolchange	0,00060				
11	Remove material with depth 12mm for hole with radi	0,00084				
12	Toolchange	0,00060				
13	Remove material for use of screw with radius	0,00093				
14	Toolchange	0,00060				
15	Cut off work piece	0,00062				
Total time:		0,01043	0.415	0,42543	400	170

**Figure 6. Operations list for subpart of Attana 100**

IDEF0 also helps in generating MO-structures, e.g. fixture- and tool types. MOs are thereafter embodied into specific MCs. Realization of resource-level MPs/MFs into MOs/MCs is supported by SDP-tools. Fixtures for Attana 100 components were modeled using a 3DCAD-tool. Material removal operations, specified in the IDEF0-model, were modeled and simulated using a CAM-tool. Operations times from CAM-simulations were also used for updating the DES-model. Finally, CAM aided in generating the control code for NC-machines that shall manufacture the Attana 100 components. All manufacturing functions are not realized by machines. Operations, such as manual assembly, executed by human resources must also be modeled. In cases where a manual MF is selected, job design tools can be utilized along with IDEF0 to define details of lower-level MP-, MF-, MO-, and MC-structures. MTM was used as a modeling tool for development of Attana 100 assembly work-cells. Figure 7 shows a MTM-table with corresponding physical model, structural model, and IDEF0-model for an Attana 100 component assembly cell.



**Figure 7. A MTM-table with corresponding physical model, structural model, and IDEF0-model**

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

### 3.4.2.3 Reflections on the Design Methodology

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

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

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

- A software tool or a set of software tools that implement the complete methodology capability (ToD, IDEF0, REL, MTM ...) and that operate on the same set of data should be sufficient in order to be able to use all the strengths that a multifaceted methodology provides.
- Regardless of availability of a software tool, it is crucial to use a consistent terminology between different methods. For instance, a function in the MF-structure of ToD and a

corresponding function in the activity diagram of IDEF0's should have the same name in order to enhance understanding of how different methods treat the same conceptual entity.

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

Third, during the Attana-project the transition between PC- and MP-structures was carried out ad-hoc. Modeling of MP-structures could be aided by IDEF3-method. IDEF3 is a standardized method that belongs to the same methodological framework as IDEF0, and it may facilitate the data transition between the models. Finally, robustness of the manufacturing system was not evaluated within the project. It might be possible to manage robustness of the manufacturing system if the Robust Design method is applied. Quantitative parameters that characterize MOs/MCs could be identified using Design of Experiments method and might be regarded as system inputs that together with noise factors impact on system output, i.e. quantitative parameters that characterize POs/PCs.

### **3.4.3 Case Study Conclusions**

- ToD can be utilized as a master structural model during the development of the manufacturing system. In order to capture different system views as proposed in original TTS/ToD and to facilitate functional independence analyses, manufacturing operations, e.g. milling and assembly, should be regarded as technical solutions (MOs) rather than manufacturing system capabilities (MFs).
- The structural model of a manufacturing system can, coordinated using a stage-gate manufacturing system development model, continuously be fed with the data created by appropriate manufacturing system development tools.
- A PDM-system can be utilized for development information management where the PC- and MC-structures were used as a blueprint for the PDM item structure.
- IDEF0 and IDEF3 can be used for modeling of MF- and MP-structures, respectively. IDEF0 gives also a first hint about the MO-structure. Modeling in IDEF0 can be supported with process flow charts during the development of overall manufacturing system concept. Operations lists and MTM support IDEF0 in development of manufacturing cells.
- Manufacturing system layout where overall structure and spatial relationship between MCs that embody MOs are specified can be developed using layout tools such as REL-chart.
- Quantitative parameters that characterize MOs/MCs, i.e. PVs, and quantitative parameters that characterize POs/PCs, i.e. DPs, might be found through the application of DoE and utilized to enhance robustness of the manufacturing system.
- DES and CAD/CAM can be used for validation and improvement of developed system concepts as well as for generation of corresponding control programs and 3D manufacturing resource models.
- In order to enhance methodology efficiency and effectiveness when applied, the methods should be integrated. This integration can be supported through implementation of methodology as a software toolbox and through use of consistent terminology between different methods.

## **4. Discussion**

A method for project-based education and research validation in the field engineering design methodology, focused on manufacturing system development, was emphasized. First, the frame of

reference that led to the presented theory was presented. Thereafter, a new theory was presented and validated in a case where a manufacturing system for an electromechanical product was developed.

In the case study in Section 3.4.2 certain research results were tested and some of the key implications were discussed in Section 3.4.2.3. Since the key components of the theory, i.e. manufacturing system design methodology, tested in Section 3.4.2, are identical with the fundamentals of the method for project-based education in engineering design methodology presented in this paper, the discussion in Section 3.4.2.3 is also valid here.

However, one limitation with this work is the lack of reflection about issues that concern the pedagogical value of the presented education method. The absence of this reflection can be explained with the fact that the validation of the theory presented in Section 3.4 was primarily focused on testing the feasibility of the manufacturing system design methodology and thereby showing how the research results can be tested, rather than making an effort to pinpoint the inherent educational aspects.

## 5. Conclusion

In this paper, a method for project-based education in engineering design methodology, focused on manufacturing system development, is presented and validated. The method is suited for manufacturing system development projects in collaboration between student groups and industrial partners. This method can also be used as a framework for conducting the engineering design research and testing the research results within the context of undergraduate engineering projects.

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