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UTILIZING AXIOMATIC DESIGN IN A MANUFACTURING SYSTEM DEVELOPMENT FRAMEWORK

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ABSTRACT

Many of today's manufacturing systems have evolved ad hoc and their performances rely on skillful shop floor personnel. A study of the implementation phase of a manufacturing facility reengineering project, revealed that there is a great need for a more systematic development process. The problems faced today are, among others: the lack of a holistic view of the system, the availability of information, and that knowledge from previous projects is not reused. According to literature, these problems are shared with many other companies.

Axiomatic Design (AD) has in previous cases proven useful when designing manufacturing systems. Concepts such as the top-down design, the control of couplings between design parameters (DPs) and the differentiation between FRs (Functional Requirements) and DPs are beneficial. However, the AD theory does not describe the development process and lifecycle aspects of the manufacturing system. Nor does the original AD theory handle all aspects of the system needed to make it function. Therefore, AD has to be put into a larger framework. There are several such architectures or methodologies proposed for manufacturing systems development. One of the most recent is GERAM (Generalised Enterprise Reference Architecture and Methodology). GERAM offers a very general framework where different methods and tools can be plugged in.

In this paper a proposal for how Axiomatic Design (AD) can be used as a modeling language in the GERAM framework is presented. The manufacturing system should be modeled in terms of FRs and DPs and these models should be used through out the system's life cycle. For example when a system is going to be reengineered in order to manufacture a new product, the framework can be used to asses which parts of the system that can be reused.

Keywords: axiomatic design, GERAM, manufacturing, systems

1 INTRODUCTION

In order to stay competitive on the marketplace, manufacturing companies have to continuously shorten their time-to-market, improve quality, and cut the cost. Thus, forcing the manufacturing firms to develop their systems faster and more accurate.

Many of today's manufacturing systems have evolved ad hoc, and their performances rely on skillful shop floor personnel. A study of the implementation phase of a manufacturing facility reengineering project, revealed the following problems:

- Knowledge from previous projects is not satisfactorily reused. The reuse of knowledge from previous project is dependent on the people that had been involved. If those people quit the knowledge is lost. There is no systematic method to facilitate such reuse.
- The availability of information. Routines and workflow are not established in order to facilitate information transfer across organizational boundaries.
- Lack of a holistic view of the system. People are sub-optimizing their own areas and the investments are not carried out in order to achieve the best system performance in the long run, i.e. the needs for the day have to be met.
- Unawareness of which functional requirements the system has to fulfill.

The problems of information availability and cooperation across organizational boundaries have been treated in the CONSENSUS project and results have been presented by Nelson et al (1998) and Samuelson et al (1999).

The above mentioned problems together with the demand for a faster and more effective development process, stresses the need for a systematic methodology for manufacturing systems development. The methodology must be suitable for use in industrial projects by engineers, yet based on scientific principles and established theories. This paper will focus on reengineering projects of existing manufacturing systems, since that is the most common situation. Greenfield projects, where the manufacturing system can be designed from the beginning are rare, at least in the discrete parts manufacturing industry. For example, one large Swedish manufacturing company have the ambition to perform "manufacturing process based product development" – meaning that the product development team have to adapt to the manufacturing systems in the existing factories. Because of the high investments in manufacturing equipment, the manufacturing systems can not be changed for every new product when the time between introductions decreases.

This paper outlines how a framework using axiomatic design (AD) for manufacturing systems development can be combined with an enterprise integration architecture: GERAM. Axiomatic design has proven useful, when developing manufacturing systems, in previous cases (Almström, 1998). Concepts such as the top-down design, the control of couplings between design parameters (DPs) and the differentiation between FRs (Functional Requirements) and DPs have been beneficial. However the AD theory does not fully describe the development process and lifecycle aspects of the manufacturing system. To achieve this, AD can be combined with enterprise integration architecture.

In the following section, the theoretical background on enterprise integration and GERAM will be established. That is followed by a discussion on the use of AD in the area of manufacturing systems development in general and the framework suggested by Yien (1998) in particular. The next section describes how the expanded AD theory will work in conjunction with GERAM in the different life cycle phases of the system. The paper is concluded with a discussion on certain important aspects of the framework.

2 GERAM AND ENTERPRISE INTEGRATION

The need for enterprise integration is obvious concerning the trends toward global competition and cooperation. Examples of enterprise integration architectures and methodologies are CIMOSA, GRAI, and PERA (see Vernadat (1996) for a comprehensive overview). However, the practical use of, for example, CIMOSA has been very limited. The main reason for this is that CIMOSA is a very theoretical design and that it has a rather limited focus towards CIM (Scheer, 1998). The fact that several architectures have been developed independent of each other has also had the effect that companies are reluctant to pick one, since they don't know which is the best.

The purpose of GERAM (General Enterprise Reference Architecture and Methodology) is to serve as a reference for the whole community concerned with the area of enterprise integration (Vernadat, 1996). GERAM does not incorporate a methodology, modeling language or enterprise engineering tool but encourage the user of the architecture to "plug-in" their methods, models and tools as long as they are consistent with GERAM. The basic components of GERAM are shown in Figure 1.

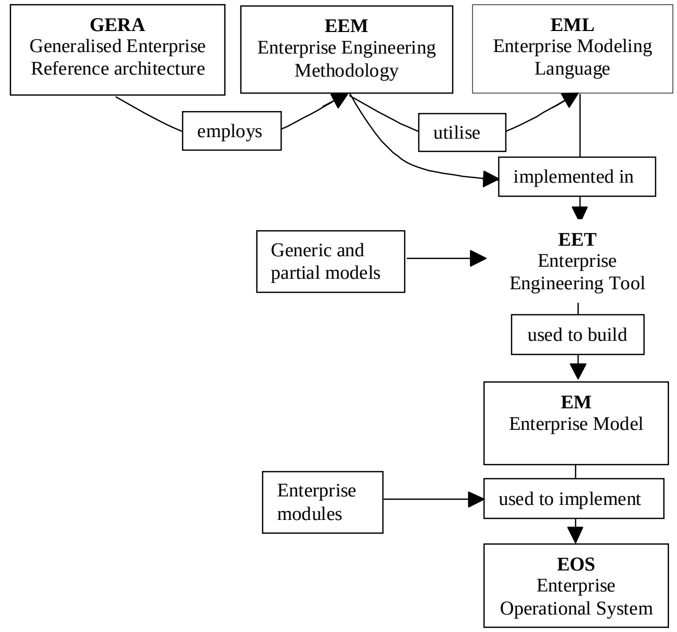

Figure 1 GERAM framework components

GERA incorporates a number of concepts. They are:
1. Human oriented concepts
2. Technology oriented concepts
3. Process oriented concepts

Human oriented concepts stress the importance of human factors in all activities. Knowledge, roles and responsibilities must be managed.

Technology oriented concepts describes requirements for (information-) technology that is used for enterprise engineering and operation.

Process oriented concepts defined in GERA are the life cycle and the life cycle phases (see the list below), life history (Figure 2), classification of different types of activities, and the different views of an activity or a system (entity), see Figure 3. The GERA life-cycle phases will be used for the discussion in section 4:

- **Identification** of a system and its boundaries.
- **Concept** is the definition of mission, vision, strategies, business plans and so forth.
- **Requirement** phase involves activities needed to make a description of the operational requirements of the system.
- **Design** phase includes all activities required to fulfil a system so that it can be physically realized. This phase is divided in Preliminary design and Detailed design.
- **Implementation** of the system, i.e. activities required for building and testing the system.
- **Operation** - activities needed to produce products.
- **Decommission** - activities that are needed when the system has reached the end of its useful time in operation.

Most manufacturing companies have divided their development process into a number of phases. These phases are often separated by gates. To proceed to the next phase the project leader must show that certain conditions are met. The GERA phases are intended to standardize the terminology in order to facilitate enterprise integration.

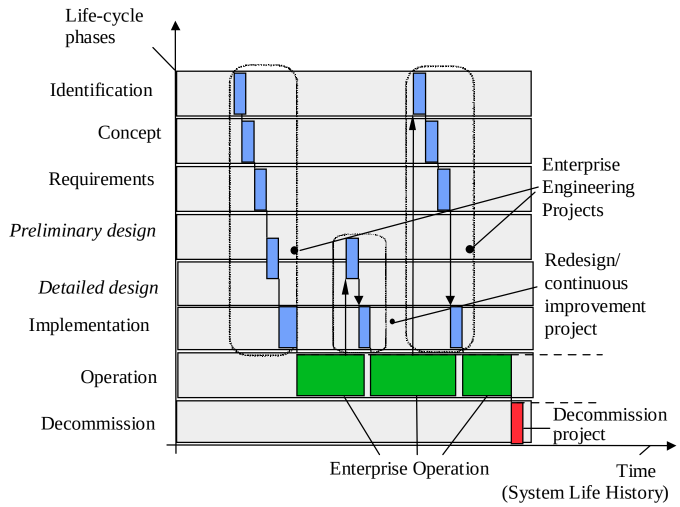

Figure 2 System life history (IFIP-IFAC Task Force, 1998)

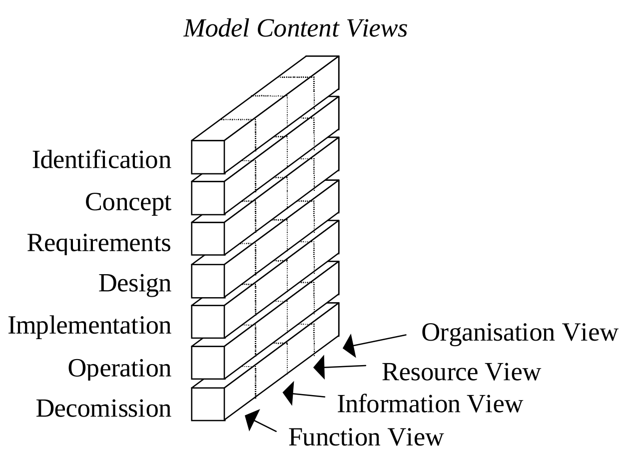

Figure 3. The Model Content Views of the General Enterprise Reference Architecture (GERA) (IFIP-IFAC Task Force, 1998).

3 A FRAMEWORK FOR MANUFACTURING SYSTEMS DEVELOPMENT

There have been a few suggestions for expansion of the original AD theory (as defined by Suh (1990)) in the area of manufacturing systems development. Among these are Vallhagen (1996). Vallhagen added several domains; one pair of process requirements and process variables for each relevant aspect of a manufacturing system. Vallhagen's intention was to create a framework for concurrent engineering, thus emphasizing the importance of integrating formal engineering methods such as DFA and FMEA in the development process. However, Vallhagen's framework did only incorporate those functional requirements on the manufacturing system that stem from the design parameters of the product. Moreover, the division in a number of sub domains of the manufacturing domain (world) was hypothetical and somewhat pragmatic. There seems to be a possibility to use a more general, theoretically based, division of sub domains.

Yien (1998) handles these drawbacks, by adding a separate track for the development of all supporting functions that are needed for the enterprise to work, besides those functions that are imposed by the product. Yien has also added a new domain: the System domain (Figure 4).

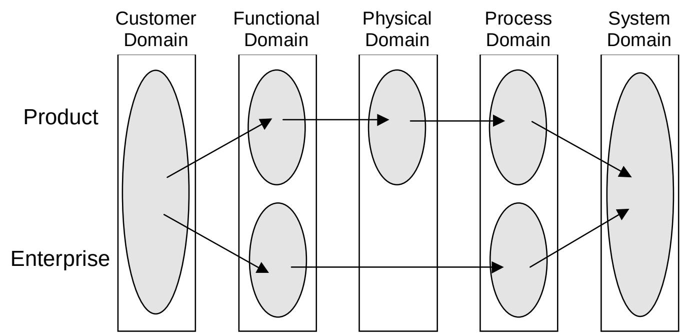

Figure 4 Yien´s five domain framework (Yien, 1998)

The **customer domain** is the least formal domain. The motivation for having this domain is that it is important to collect customer requirement as systematically as possible. For a manufacturing system, there are both external and internal customers. External customers are people that buy the products and others affected by the system activities, for example environmental authority. Internal customers are the workers in the manufacturing facility, stockholders, management etc.

The **functional domain** is the most important domain since it forces the engineer to state a functional requirement (FR), independent of the physical manifestation. Customer needs may be translated into functional requirements through methods such as QFD (Bascaran and Tellez, 1994). Yien divides the functional domain into product requirements and enterprise requirement. Enterprise requirements are independent of the product e.g. human resources and information system.

The **physical domain** is where product requirements are formed in design parameters (DP). This domain is unnecessary for the design of enterprise aspects since enterprise functional requirements can be directly translated into process variables.

The **Process domain** forms processes that consist of activities. For products, this means manufacturing processes and, for the enterprise, it is business processes. However, for example, assembly aspects are not taken into account, in spite of the fact that the assembly activities are imposed by the design parameters.

In the **system domain** the process variables are mapped to information, resource and organization views, i.e. a 1 to 3 mapping (Figure 5). This division is adopted from CIMOSA and is consistent with GERA (Figure 3). IDEF0 is used to map the process variables to system variables.

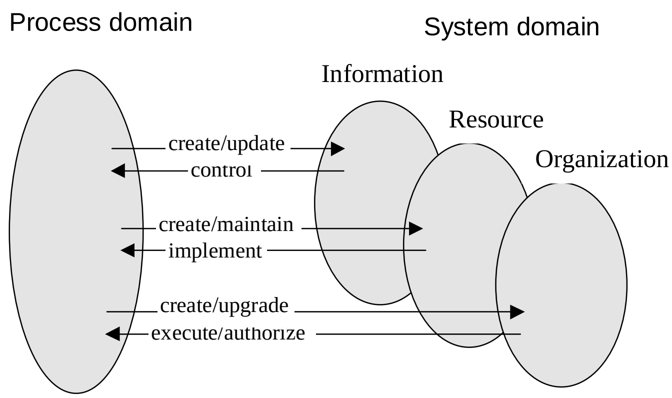

Figure 5 Relationships and interactions between process and system domain (Yien, 1998)

The most important idea in Yien's framework, is that for a manufacturing system there are requirements, that stem both from product design parameters and from other requirements that are not product specific, i.e. support functions. These requirements are for example maintenance functions, material handling systems and information systems. An example of application of the framework is presented in section 4.8.

To make the framework useful in an industrial project, it has to be implemented in software. This software should preferably be a standard product. The information should be stored in easily accessible databases that are structured according to the framework. The database can then be used in all development phases as shown in the next section.

4 AXIOMATIC DESIGN IN THE LIFE-CYCLE OF A MANUFACTURING SYSTEM

Based on the experiences from the above mentioned case studies in the CONSENSUS project, this section will describe how Yien's framework can be used in industry, in the different life cycle phases (Figure 3) of a manufacturing system.

4.1 IDENTIFICATION AND CONCEPT PHASE

In the early phases of a reengineering project the models in term of the framework can be used to identify which parts of the system that are needed to be reengineered and which parts that still fulfill the functional requirements.

In a project with the mission to design a new manufacturing system, the highest level functional requirements will be stated in this phase. These requirements could be generic and well known such as profit requirements and regulations. Cochran (1994) and Suh et al (1998) have discussed these highest level functional requirements and their propagation down in the hierarchies.

4.2 REQUIREMENT PHASE

According to IFIP-IFAC Task Force (1998) all requirements for a project will be stated in this phase. However, that idea is in contradiction with one of the fundamental ideas in the axiomatic design theory. Since axiomatic design states that functional requirements on a lower level in the design hierarchy can not be determined until the design parameters on the present level have been defined.

A better way to use the framework in this phase is to define the phase to involve the activities needed to determine the requirement specification, i.e. further decomposition of the highest functional requirements and design parameters down to a level that is suitable for an internal project organization or a subcontractor.

4.3 PRELIMINARY DESIGN PHASE

It is in the preliminary design phase that the framework has its obvious use. In this phase the concept for the manufacturing system is outlined. Yien has delimited his framework to be valid only for the preliminary (or conceptual) design phase.

4.4 DETAILED DESIGN PHASE

The concept generated in the preliminary design phase will be further decomposed in the detailed design phase. Since the embodiment and configuration of the design may result in a need for a changed concept, it is most likely that the concept from the previous phase will be modified.

4.5 IMPLEMENTATION PHASE

When implementing a system it is very important to have control of couplings between requirements and different system variables. When something goes wrong in the test series, that information has to be spread to all interested parties (stakeholders). A framework based on AD can achieve the necessary information transfer between stakeholders. To make this work the system domain has to be modeled as process models, with for example IDEF0 as a modeling language.

4.6 OPERATION PHASE

During the operation of the manufacturing system the framework can be used in order to track dependencies in the system. When a manufacturing facility is complex and large it can be difficult for the personnel to get the understanding of which part affects another. An example of this phenomena was a situation where a number of welding nuts, placed by robots, had drifted slightly from the nominal position and people in the body plant couldn't tell which parts of the assembly plant that could have been affected by this.

4.7 DECOMMISSION PHASE

Even when the physical system has reached the end of its useful life, the documentation in the framework will act as a support during the disassembly of the manufacturing system.

4.8 EXAMPLE

The following example will illustrate how Yien's framework can be used in a reengineering project, in the preliminary design phase. The example is taken from a real situation in the automotive industry, but the use of the framework is merely hypothetical.

The mission is to produce a small steel beam with a complex geometry. The functional requirements for the product, the corresponding design parameters, and processes are outlined in Table 1. The product is a typical example of how many functions are built into the same part, in a car body. The requirement "reduce vibrations" (FR4) was introduced on a later stage because of vibrations that was noticed during test of the prototype. In order to handle this requirement, a pair of brackets was added to the design. These brackets had to be welded to the pressed part. The welding process made it impossible to use a non-corrosive material, and therefore the part had to be painted in order to get the corrosion resistance. The resulting design is therefore highly coupled, as illustrated in the function/mean tree in Figure 6.

Additional functional requirements that stem and their corresponding processes are presented in Table 2. System variables are shown in Table 3. The mapping from DPs to processes and further on to system variables can also be illustrated in function / means trees. That mapping will reveal further couplings in the design of the manufacturing system.

Table 1 Product requirements

Functional req.		Design parameter		Process	
FR1	Support bearing	DP1	Beam main geometry	PR1	Pressing
FR2	Enhance body stiffness	DP2	Flanges	PR2	Painting
FR3	Non corrosive	DP3	Surface treatment	PR3	Welding
FR4	Reduce vibrations	DP4	Brackets		
		DP5	Steal quality		

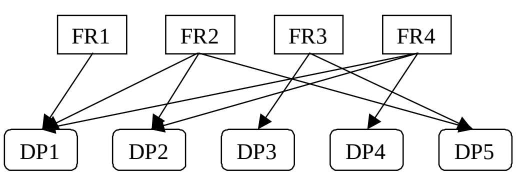

Figure 6 Function/ means tree

Table 2 Enterprise requirements

Functional req.		Process	
FR1	Meet specified quality	PR1	Quality control
FR2	Transport material	PR2	Transportation process

Table 3 System domain

System (Info.)		System (Res.)		System (Org.)	
SI1	Press process data	SR1	Press (mechanical)	SO1	Press operator
SI2	Geometry data	SR2	Tool	SO2	Sub contractor
SI3	Painting data	SR3	Painting facility	SO3	Painting facility operator
SI4	Welding data	SR4	Welding station	SO4	Welding operator
SI5	Quality standards	SR5	Quality control equipment	SO5	Operators
SI6	Production schedule	SR6	Transport equipment	SO6	Transport personnel

5 DISCUSSION

In previous studies (Almström, 1998) the following features of AD have been considered for further investigation:

- Separation in different domains
- Integration in the design process
- Couplings
- Design history

In this article all of the above issues have been addressed and therefore it is relevant to discuss them again.

5.1 SEPARATION IN DIFFERENT DOMAINS

In this paper Yien's five-domain framework has been discussed. However, it is not realistic to believe that the engineers will be able to use such an extensive and abstract framework in the near future. The engineers need methodological support. In large companies it is possible to have people whose main task is to support the engineers with structured methods, but for small or medium sized companies that is not economically justified. For these companies, the framework and separation in different domains might serve as something to support the thinking and to lift discussions in certain situations. In the long run, the framework will have to be included into their routines and thus making it a part of the development process.

The domains are only loosely coupled to the phase, which the development is in. However, certain domains are more used in certain phases as shown in the previous section. For example the customer domain is only meaningful to use in the early phases.

5.2 INTEGRATION IN THE DESIGN PROCESS

The life cycle phases in GERAM represent a generalized design process. In the previous section (section 4), it was shown how AD can be used in this process. Further efforts must be made to make the framework a natural part of the manufacturing systems development process.

5.3 COUPLINGS

The consequences of having a coupled or decoupled manufacturing system have to be further explored. All manufacturing systems where operations have to be done in sequence are decoupled. What are the implications of a coupled product design, for the manufacturing system? For example, the integrated automobile body design is highly coupled, which results in many iterations in the development project. Changes in the product design have immediate effect on the manufacturing system when they are developed simultaneously. If AD is used in a concurrent engineering environment in the early phases of the project the number of couplings will be minimized and therefore also the number of iterations. This approach could have the potential to dramatically shorten the time for reengineering projects in industry.

When reengineering a manufacturing system, it is necessary to have control of the couplings in order to determine which part of the system that is going to be affected by the change. The changes can be both in the FRs, i.e. new product introduction, and in the PVs, i.e. an improved process.

5.4 DESIGN HISTORY

As pointed out by for example Mårtensson and Tate (1998), it is important to keep track of the design history of the manufacturing system. The design rationale and the system life history should be recorded and documented in databases. Together with the selected DPs, there should also be the rejected ones with explanations or evaluations on why that particular solution was not selected. That will make it possible to go back in the history of the current design if a solution has turned out to be a dead end.

As pointed out by Yien and Tseng (1996), many manufacturing systems designs share the same FRs. It is therefore possible to develop sets with predefined FRs and DPs. These sets can be more or less general.

6 CONCLUSIONS

A more systematic procedure is needed when developing manufacturing systems in all lifecycle phases. This can be achieved through a combination of Yien´s five domain framework and GERAM. However, most of today's manufacturing firms are not mature enough to apply such complex theoretical methods, thus needing support in the application of the framework.

7 ACKNOWLEDGMENTS

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