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PRODUCT FUNCTION INDEPENDENT FEATURES IN AXIOMATIC DESIGN

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ABSTRACT

When developing products to be manufactured, the products have to be designed and described considering means of manufacturing.

Axiomatic Design captures the ”function affecting features“ of the product, that is, design parameters. As prescribed by Axiomatic Design the functional requirements on the manufacturing system is then developed in the process domain so independence is maintained in every step. This ensures that the means of manufacturing are capable to produce products with functions required by users without trouble-shooting in the manufacturing phase.

However, parts may have features that are satisfying needs of the manufacturing process itself such as gripping surfaces and reference planes.

This paper gives examples of different types of invisible DPs and ways of representing these during design.

Keywords: Axiomatic Design, Design domains, Concurrent Engineering, Design for Manufacturing, Process domain

1 INTRODUCTION

A technology shift in the heavy truck industry, moving from drum brakes to disc brakes, showed the necessity of considering manufacturing issues in the functional and physical domain of the product design.

A ring on the axle was designed for holding the drum brake system. Since this ring was the same on all variants of axles it was considered suitable for positioning, regripping and clamping during manufacturing. The development of fixtures and grippers in several cutting, handling and measuring machines were designed to use the ring. By doing that a coupling between product function (hold drum brake, in finished product) and functions necessary for the manufacturing (in intermediate states of part life) was created by internal production engineers and external equipment designers.

When the product designers chose to change brake technology, the brake system was redesigned. Consequently there was no reason for keeping the ring from a product function perspective. However, huge problems occurred in the production. The emergency solution was to keep the now obsolete ring only to fulfill the manufacturing requirements.

Real practice experience from the rear axle case highlights a need of capturing couplings between product functions and manufacturing functions. Axiomatic Design is supposed to give structure to information during design work, but the process domain has not yet been penetrated deep enough to handle this type of couplings [Almström (1998)], [Mårtensson, et al. (1998)], [Sohlenius (1992), (1997)], [Vallhagen (1994)]. Therefore we want to show how this can be handled by introducing manufacturing requirements in the functional domain of the product.

A case study was initiated in order to examine the ways manufacturing issues may impose features in the physical domain of the product and how this can be represented in the framework of Axiomatic Design. The studied case is described in section 3.

2 AXIOMATIC DESIGN

Axiomatic Design is a method that provides the designer with a logic approach to design tasks. Thus, the designer will get a good structure and documentation at all levels in the design work regardless of the extent of the task. The logic structure and its documentation help the designer to come to decisions based on solid foundation and also to transfer the design information to other designers in a comprehensible way.

Furthermore, Axiomatic Design states two design axioms that assist the designer to make the right decisions when choosing between different design concepts. The design axioms also provide rational means for evaluating the quality of proposed solutions at all levels.

The Independence Axiom (First Axiom):
Maintain the independence of functional requirements.

The Information Axiom (Second Axiom):
Minimize the information content [of the design].

Axiomatic Design divides the design process into four domains:

The first domain is the Customer Domain (CD). In CD the customer needs are collected.

The second domain is the Functional domain. In the functional domain the Functional Requirements (FRs) are stated. FRs are established from the needs that the final product or process must satisfy, that is, the customer needs.

The third domain is the Physical domain. In the physical domain Design Parameters (DPs) are stated. Every DP is a concept to fulfill one FR, that is, one DP corresponds to one FR.

The fourth domain is the Process domain. In the process domain Process Variables (PVs) are stated. Every PV is a process to fulfill the concept in a specific DP, i.e. one PV corresponds to one DP.

Axiomatic design also deals with the hierarchic nature of designs, which appears in the Functional-, Physical- and Process domain as trees with identical structure. The functional-, design- and process trees grows throughout decomposition of one level at the time in each tree. The decomposition must be made by zigzagging between the domains. This can also be stated as follows:

"There are two very important facts about design and the design process, which should be recognized by all designers:

FRs and DPs have hierarchies, and they can be decomposed. FRs at the ith level cannot be decomposed into the next level of the FR hierarchy without first going over to the physical domain and developing a solution that satisfies the ith level FRs with all the corresponding DPs. That is, we have to travel back and forth between the functional domain and the physical domain in developing the FR and DP hierarchies."[Suh (1990)]

3 THE PINION CASE STUDY

To confirm the hypotheses about features occurring in the physical domain when PVs are selected, a case study has been performed. The study is based on an existing pinion located in the rear axle of trucks, see Figure 1. By choosing an already existing part, the solutions to the design problem and the processes for manufacturing were already determined. By doing this the focus was on the method and not on the development of new solutions and processes.

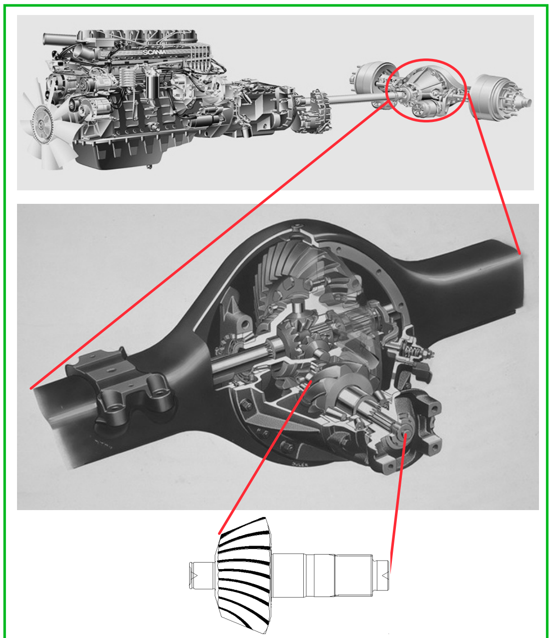

Figure 1. Location of the pinion.

3.1 THE APPROCH TO THE CASE

In the original design work, done by the company in question, Axiomatic Design was not used. To be able to perform the case study facts from original design work were collected and structured according to Axiomatic Design. That is, FRs, DPs and PVs for the design were put up and the lower levels in the functional-, design- and process- trees were settled, by zigzagging between the three domains, using the facts from the original design.

3.2 THREE DOMAIN ZIGZAGGING

Mapping over the functional-, the physical- and the process-domain results in a concurrent engineering process [Sohlenius (1992)]. That is, both the product design and the process design are developed at the same time. However, the process design will not result in a complete production system description [Sohlenius (2000)]. The process domain only impose demands for the designing of the production system. [Suh (1990)]

Constraints derived from the design of the production system could also be identified. They affect and put boundaries on the choice of PVs in the process domain. This also has an effect on the functional and physical domains. The process domain works as a bridge in both directions between the product and the productionsystem.

The highest level of design equation matrix for both the product design and the process domain, in this case, are shown below:

$$\{\text{FR1 Transmission of torque}\} = [X] \bullet \{\text{DP1 Pinion}\} \quad (1)$$

$$\{\text{DP1 Pinion}\} = [X] \bullet \{\text{PV1 Manufacturing cells}\} \quad (2)$$

3.3 DECOMPOSITION IN THREE DOMAINS

The decomposition from the highest level introduced here is not intended to perfectly describe the whole product and process design structures. To be able to illustrate the results relevant to the research, we only need a part of the design structure. The most illustrating FRs, DPs and PVs on the second level are presented bellow.

In this case, the second level in the functional domain describes the functions that the customer wants the product to have.

FR1:1 Good balance when rotating
FR1:2 Transmit torque into the pinion
FR1:3 Transmit torque out from the pinion
FR1:4 Hold the pinion fixed

In the design domain the designer tries to meet the FRs with DPs. By doing this the different parts that the pinion are built up by start to take shape.

DP1:1 Cylindrical body

DP1:2 Splines

DP1:3 Gear

DP1:4 Surfaces for bearings

When the PVs are selected, the constraints from the production system design have to be taken into consideration. [Fagerström, et al. (1998)] These constraints may also have effect on the possibility to choose DPs. This is an iterative process that works the same way as between FRs and DPs [Suh (1990)]

PV1:1 Turning

PV1:2 Cold rolling

PV1:3 Milling

PV1:4 Grinding

The design matrix for the product and the design matrix for the process, both on the second level in the design hierarchy, are presented below.

It is notable that the turning must be made before the cold rolling, milling and grinding can take place.

$$\begin{Bmatrix} FR1:1 \\ FR1:2 \\ FR1:3 \\ FR1:4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \bullet \begin{Bmatrix} DP1:1 \\ DP1:2 \\ DP1:3 \\ DP1:4 \end{Bmatrix} \qquad (3)$$

$$\begin{Bmatrix} DP1:1 \\ DP1:2 \\ DP1:3 \\ DP1:4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & 0 & X & 0 \\ X & 0 & 0 & X \end{bmatrix} \bullet \begin{Bmatrix} PV1:1 \\ PV1:2 \\ PV1:3 \\ PV1:4 \end{Bmatrix} \qquad (4)$$

3.4 EXAMPLES OF FEATURES IMPOSED BY PVS

A couple of examples on how the choice of PVs impose new features needed for the production of the part, were detected in the case study. Two examples were selected to illustrate two different types of imposed features, see section 3.4.1 and 3.4.2.

3.4.1 Example of New FR, New permanent DP

The first example is a decomposition of FR1:1, DP1:1 and PV1:1. Only the imposed feature is introduced. Naturally, there are several more features on this level but they are of no interest in this case.

When turning was selected as PV, the need for clamping occurred. FR1:1:1 then became a consequence of the chosen PV1:1.

FR1:1:1 Possible to clamp in fixed position when turning

The turning process was accomplished with a dog and two centers. These became constraints for the settling of DP1:1:1. To meet FR1:1:1, dowel holes were chosen and then became features on the product.

DP1:1:1 Dowel hole

The dowel holes are made by drilling as PV1:1:1 show.

PV1:1:1 Drilling

The design matrix for the product and the design matrix for the process, show the connections between FR1:1:1, DP1:1:1 and PV1:1:1.

$$\{FR1:1:1\} = [X] \bullet \{DP1:1:1\} \qquad (5)$$

$$\{DP1:1:1\} = [X] \bullet \{PV1:1:1\} \qquad (6)$$

3.4.2 Example of New FR, Existing DP

The second example is a decomposition of FR1:3, DP1:3 and PV1:3. Two imposed features are introduced. Naturally, there are several more features on this level but they are of no interest in this case.

In the cold rolling process there is no need for hardening since the rolling itself hardens the splines by deformation. In the gear case it is not possible to integrate these two demands in one process. This results in the need of another process to get the right level of hardness on the gear. This is illustrated by FR1:3:2, DP1:3:2 and PV1:3:2.

FR1:3:1 illustrates the same type of problem as FR1:1:1 did in the turning case, see chapter 3.4.1.

FR1:3:1 Possible to clamp in fixed position when milling

FR1:3:2 Manage pressure on surface

The difference from the turning case is that no new features are created in the physical domain. Instead an already existing DP is used. This causes no problem since the use of DP1:1:X during manufacturing and the use of DP1:1:X during usage are separated in time. However, if there would be any changes in DP1:1:X, it will subsequently affect the ability to meet FR1:3:1. This is the same problem that draw our attention to this kind of features, see section 1.

DP1:1:X Part of Cylindrical body

DP1:3:2 Right material structure

As a consequence of the use of DP1:1:X , PV1:1:X is also used here.

PV1:1:X Part of Turning

PV1:3:2 Hardening

There is no connections in this matrix but we know that there is a connection to the design equation (5). As a result of this there has to be a connection in design equations (3) and (4). This is shown in the modified equation (3a) and equation (4).

$$\begin{Bmatrix} FR1{:}3{:}1 \\ FR1{:}3{:}2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \bullet \begin{Bmatrix} DP1{:}1{:}X \\ DP1{:}3{:}2 \end{Bmatrix} \quad (7)$$

$$\begin{Bmatrix} DP1{:}1{:}X \\ DP1{:}3{:}2 \end{Bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \bullet \begin{Bmatrix} PV1{:}1{:}X \\ PV1{:}3{:}2 \end{Bmatrix} \quad (8)$$

$$\begin{Bmatrix} FR1{:}1 \\ FR1{:}2 \\ FR1{:}3 \\ FR1{:}4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \bullet \begin{Bmatrix} DP1{:}1 \\ DP1{:}2 \\ DP1{:}3 \\ DP1{:}4 \end{Bmatrix} \quad (3a)$$

$$\begin{Bmatrix} DP1{:}1 \\ DP1{:}2 \\ DP1{:}3 \\ DP1{:}4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & 0 & X & 0 \\ X & 0 & 0 & X \end{bmatrix} \bullet \begin{Bmatrix} PV1{:}1 \\ PV1{:}2 \\ PV1{:}3 \\ PV1{:}4 \end{Bmatrix} \quad (4)$$

4 THE GENERALIZED PROBLEM

The fact that a certain manufacturing process (in process domain) is selected implies that the part has to be fitted for the process. For design decisions on lower levels aspects may appear as constraints in the physical domain. It might also impose new FRs on the part. In some cases such FRs may be fulfilled by existing DPs. In other cases the FRs are not fulfilled by any aspect of the product. Then new temporary or permanent DPs have to be added. The following sections show how these types of situations can be handled in Axiomatic Design.

4.1 NEW FR, NEW PERMANENT DP

Where the selected process cause complicated sub-FRs during equipment design and these sub-FRs can be simplified by adjustment of the product design, the process impose sub-FRs in the functional domain of the product, see figure 2. A new DP fulfilling the FR is then introduced. By doing this coupling between ”product-FRs“ and ”manufacturing FRs“ can be detected and avoided.

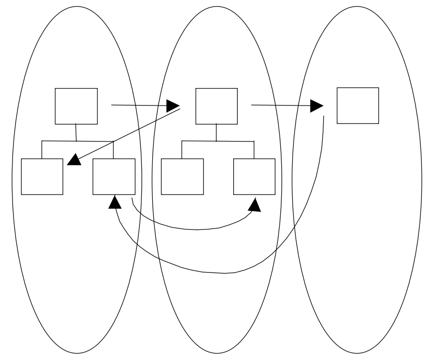

Figure 2. Process domain decisions give rise to new FRs and DPs.

4.2 NEW FR, NEW TEMPORARY DP

Where the selected process cause complicated sub-FRs during equipment design and these sub-FRs can be simplified by adjustment of the product design, the process imposes sub-FRs in the functional domain of the product. If constraints or other FRs prevent a new DP to be introduced one might introduce a temporary DP. At some state during the production phase of the product life cycle this temporary DP is removed, see equations 9 to 12. This is an example of the reasoning on what is called large systems by Suh (Suh, 1995).

@ t = manufacturing phase

$$\{FRs\}_{manuf.\ phase.} = \{FR1{:}1, FR1{:}2, FR1{:}3, ..., FRn\} \quad (9)$$

$$\{DPs\}_{manuf.\ phase.} = \{DP1{:}1, DP1{:}2, DP1{:}3, ..., DPn\} \quad (10)$$

@ t = usage phase

$$\{FRs\}_{usage\ phase.} = \{FR1{:}1, FR1{:}3, ..., FRn\} \quad (11)$$

$$\{DPs\}_{usage\ phase.} = \{DP1{:}1, DP1{:}3, ..., DPn\} \quad (12)$$

The time dependent FRs are also valid in the case mentioned in sections 4.1 and 4.2, but there are the time independent DPs not needed. There are effects in the functional domain of process and equipment design also for removing such temporary DPs, i.e. violating the effort of minimizing the number of FRs and by this introduce extra costs.

4.3 NEW FR, EXISTING DP

Where the selected process causes simple sub-FRs during equipment design as long as the product design is not changed, one might consider an existing DP on the product as used by the process. No situation of coupling will occur as long as that DP is constant. So by blocking changes, problems are avoided, see figure 3.

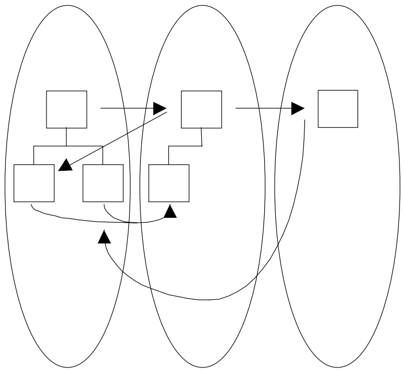

Figure 3. Integration of DPs, blocking design changes.

4.4 EXAMPLES OF DOMAIN SPECIFIC TYPES OF PV-FRS

Typically machining processes require the part to being possible to clamp and grip. Assemblies typically require master location points. Inspection may require inspection points.

5 CONCLUSIONS AND FURTHER WORK

The studied case show that there are features in the physical domain of the design object that are needed to fulfill requirements occurring as consequences from the selection of process variables at higher levels.

The present Axiomatic Design handles this type of problems, given that the designers are actually doing the three domain zigzagging, as described in this paper.

A candidate for further work and development is the connection that the process domain constitutes between the product design and the design of the production system. This connection should be considered bidirectional.

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