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RE-USE OF PRODUCT MODEL THROUGH LIFE-CYCLE STAGES

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Design data management interpretation, product models, re-use, product life-cycle

Abstract

This paper discusses the requirements on product model presentations that are suitable for reuse. The aim is to define promising directions for future research by recognizing how the characteristics of reuse entities vary at the different stages of the product life-cycle. Reuse entities are roughly categorized into three types of presentation entities: macroscopic principles for the early stages of the life-cycle, product design patters for the intermediate stages, and microscopic features for detailed description at the late stages of the life-cycle. The idea of product design patterns is derived as an analogy to the design patterns utilized in software development, and a cut and paste based approach is shown as an application of the concept to product design. Product structuring is here considered through the data structuring entities that are needed as a suitable basis for a reusable, intelligible, and total product model.

1. Introduction

The reuse of product model information aims at capitalizing company knowledge by capturing the experience of product development and realization into a form that allows easy deployment in the design of later similar products. The objective is to speed up product development by collecting catalogues of already experimented solutions and by defining standards according to the found best practices. The development of new products as well as the generation of variant products can be made more efficient by reusing information and methods related to existing products.

Reuse appears to be a potential and crucial approach towards better efficiency of product design and engineering. However, companies do not find it as an entirely positive working style since they have experienced the disadvantages or even dangers that are related to reuse:

- Reuse causes repetition of the *errors* contained in the old design if they are not recognized and updated properly. Furthermore, it may cause new errors if the designer does not receive proper support in determining all necessary modifications that have to be made to match the changed specifications of the product.
- The reuse of existing product models *prohibits creative product design* and reduces the opportunity for manufacturing innovations that might be possible for novel

designs. The detailed level of the reused product model information contributes to the lack of innovation.

- Pure product data such as data provided by a geometric or feature-based product model is not sufficient for recognizing when reuse of some existing design is feasible. The product developer should be able *to comprehend the constraints and assumptions* that must be valid in order to make the solution applicable.

We suggest that these problems are a consequence of product model presentations that fail to take into account the requirements of reuse and how they vary along the product life-cycle. We propose that it is necessary to more carefully analyze how the characteristics of reuse change along the life-cycle of a product model in order to define appropriate entities for the reuse of product model information.

First the paper considers how the emphasis of reuse aspects changes along the way from conceptual design to the final detailed product definition. Secondly, the paper roughly categorizes the entities that support the varying reuse requirements, Then, the design pattern approach adopted from software engineering and the cut and paste approach for product design are compared and discussed. Finally, the conclusions suggest promising research directions of reusable product models.

2. Life-cycle requirements

Various product modeling approaches have been developed to provide facilities for the different engineering disciplines and stages. Figure 1 shows some examples of the modeling methods that are used during the product development and engineering stages.

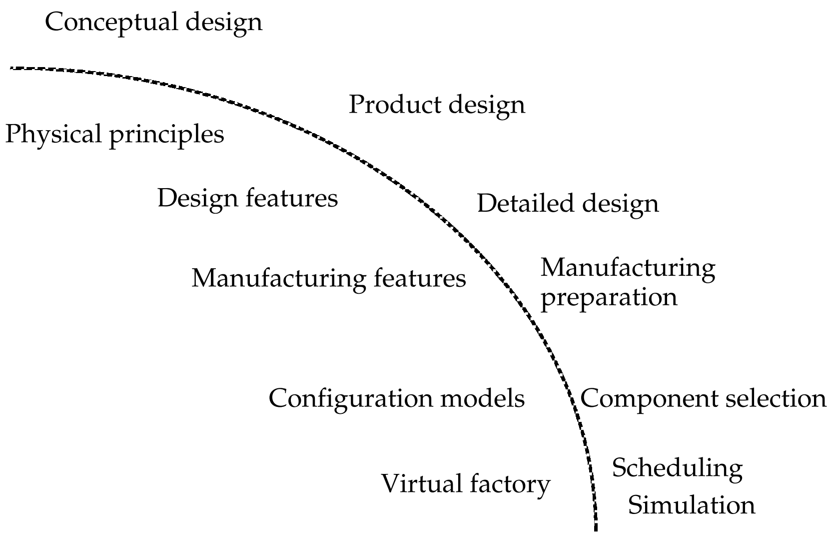

Figure 1. Life cycle of a product model

At the early stages of the product life-cycle the physical principles allow presentation of general concepts of the solution without yet dealing with the implementation details. The work proceeds into product design and the details of the physical appearance are described by design features and the implementation is defined with manufacturing features. Finally configuration models and virtual manufacturing facilities are defined and applied to finalize the product development.

The product model life-cycle of figure 1 is not at all complete; however, even according to the simplified view we can draw some obvious conclusions on the characteristics that are crucial for representing product data and knowledge. At the early stages of creative design of novel products the designer utilizes solution principles and is not yet concerned about the implementation details. At the late stages of the product development or engineering process the designer attempts to define the best possible realization of the product according to the knowledge on the application area. Thus, the most suitable structure and the constituent entities of the product model also change accordingly and different tools are needed.

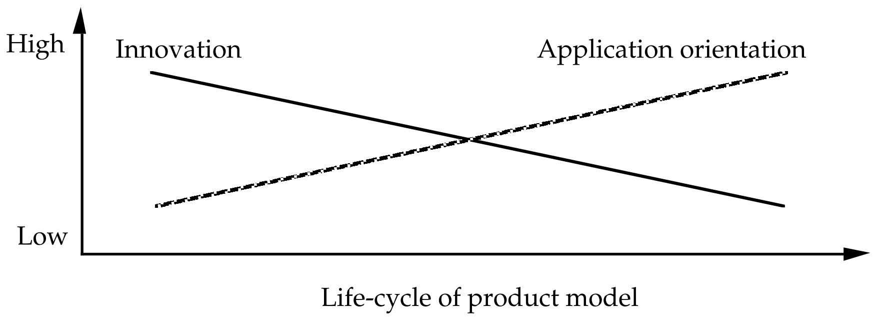

Figure 2. Innovation versus application orientation

Figure 2 illustrates how the degree of innovation decreases and the degree of application orientation increases during the product life-cycle. The degree of innovation is high during the creative and innovative early stages of designing a novel product. During these stages the product model still covers a wide variety of realization possibilities and physical principles or mechanical structures are the level of reusing previous knowledge. As the product model life-cycle proceeds, the design becomes less innovative and turns into routine design of implementation details. At the same time the degree of application orientation becomes higher and the designer is able to apply specific experience of the application field. The changing characteristics of the design process and the product model imply that the stages of the product model life-cycle require different product model presentations to support product model reuse at an appropriate level.

3. Re-use entities

From the previous section we can conclude that different stages of the life-cycle of a product model require different methods for knowledge capitalization and deployment. Here life-cycle refers to the development of the product model from a vague conceptual definition to a fixed detailed description. The aim is to provide means to overcome the difficulties related to the reuse of product model data and knowledge:

- The level of preciseness must be appropriate for the stage of the product development or engineering process. Unnecessary errors are avoided by not forcing the designer to work on too detailed a presentation at the very early stages. In the same way the product presentation at the late stages must emphasize and allow easy manipulation of the details.

- At early design stages the reuse entities should have wide applicability and the designer should not be restricted for example to certain manufacturing facilities. Thus, the designer is allowed to be creative, which may result in product or manufacturing innovations.
- The reuse entities should imply their feasibility for certain design tasks. In detailed design the entities set very precise requirements for their use. In conceptual design the solution principles apply to wide variety of tasks.

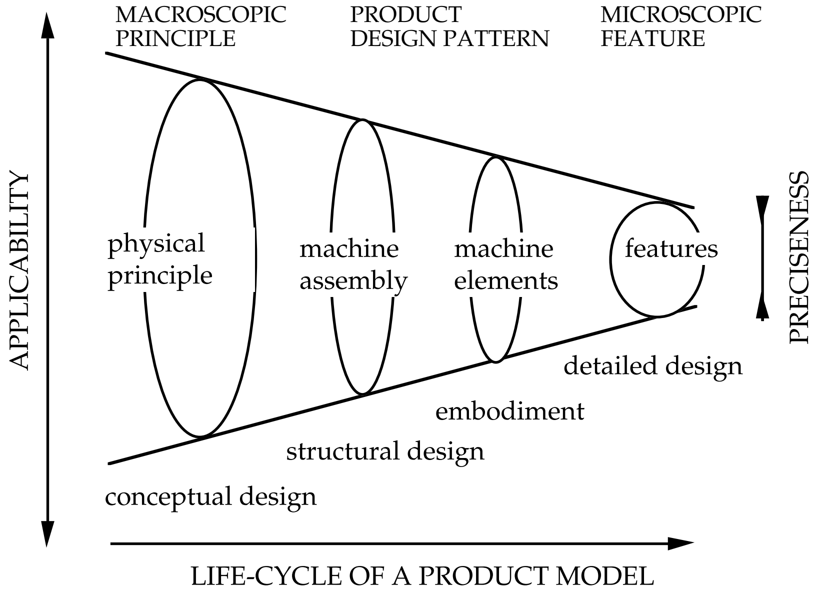

Figure 3. Reuse entities to match the life-cycle stages of a product model

Figure 3 shows how conceptual design, structural design, embodiment and detailed design may apply entities such as physical principles, machine assembly models, machine element presentations, and feature based models. As the life-cycle proceedss the applicability decreases and the entities become more focused and precise as the shrinking ovals illustrate. The top of the figure shows our classification of three categories of reuse entities: The early stages of conceptual and functional design apply presentations of macroscopic principles. Product design patterns are a suitable basis for the design at intermediate stages such as structural design and embodiment. Finally the detailed design is carried out using microscopic features.

	MACROSCOPIC PRINCIPLE	PRODUCT DESIGN PATTERN	MICROSCOPIC FEATURE
reuse entity	physical laws, mechanical structure, etc.	key aspects of a common structure	recipe for a detailed implementation
physical appearance	undefined	varies, not necessary	physical constituent of a part
scope	overall principle with wide scope	abstract, easy to customize	application oriented with narrow scope
size	wide	large	small
adjustment	flexible, vague	flexible, overlapping	precise, fixed

Table 1. Comparison of the re-use entities

Table 1 summarizes a comparison of the different re-use entities according to their characters, scope, typical size and adjustment capability. Each of the three categories as briefly discussed in the following.

3.1. Macroscopic principles

Macroscopic principles may be physical laws or mechanical structures or other kind of guidelines that contain the possibility for a wide variety of different realizations.

- The macroscopic principles are presented at a general level and they have no physical shape or appearance. For example the abstract idea of a “switch” may be a macroscopic principle that at the end of the development life-cycle may reach the shape of a contractor as in [1].
- They present a principle that is applicable for a wide variety of design assignments. It is not restricted by the manufacturing facilities and may in the very beginning even not limit the field of technology.
- As a macroscopic principle has no embodiment, it does not have a typical size either. However, it can be considered wide compared to the final product as a macroscopic principle typically covers major functions.
- Macroscopic principles appear vague as they still leave most of the design decisions open. Furthermore, they can be inserted into the conceptual or functional model in a quite flexible way. However, the combinations of macroscopic features may be analyzed to have desired or not desired side effects.

A lot of research work has been carried on the conceptual and functional design stages and the proposed models belong to the category of macroscopic principles. An example of such approaches is the SYSFUND system (Systematization tool of FUNctional knowledge for Design) created at the University of Tokyo [4][5]. It is intended for support the designer in function-based design and it offers a framework for presenting functions and behaviors.

3.2. Product design patterns

We propose the concept of product design pattern for referring to an entity that describes key aspects of a common design structure. The concept is an analogy to the approaches used in architecture and software engineering. Patterns in buildings and communities are discussed in [2]:

“*Each pattern describes a problem which occurs over and over again in our environment, and then describe the core solution to that problem, in such a way that you can use this solution million times over, without ever doing it the same way twice.“*

The pattern approach has been adopted into software engineering where it is seen as a next step and enhanced method for object based reuse. Design patterns are characterized as entities that capture the solutions that people tend to reuse in their software [3]:

“*Design patterns capture solutions that have developed and evolved over time. Hence they aren’t the designs people tend to generate initially. They reflect untold redesign and recording as developers have struggled for greater reuse and flexibility in their software. Design patterns capture these solutions in a succinct and easily applied form.”*

Product design pattern is here used to refer the product model re-use entity that falls between macroscopic principles and microscopic features.

- The product design patterns may have a physical appearance, i.e., they may be define forms to the product. However, a product design pattern does not fix the shape but may correspond to varying physical appearances.
- Although product design patterns are the next step from macroscopic principles towards concretized product they still present an abstraction. Design patterns are easily customized to different disciplines and products.
- Product design patterns are typically large entities and they may contain several disconnected physical shapes. In the case of reusing large patterns from existing designs the power of the approach is most obvious.
- Product design patterns are by definition flexible and customizable. In particular they can be adjusted to other product design patterns and the intersections are means for communication.

Currently approaches for product design patterns are still under development. For example some top-down design approaches appear to have some of the characteristics of product design patterns [6][7] as they attempt to bridge abstract models to their realizations. Furthermore, the study on the integration of functional modeling and feature-based modeling considers the type of product model presentation that could be used to mediate physical principles and microscopic feature models [1]. However, a proper approach for product design patterns requires more study on the guidelines indicated by the design pattern approach of software engineering.

3.3. Microscopic features

At the late stages of the life-cycle, the entities for reuse are microscopic features that describe a detailed and concrete result. Form features and manufacturing features have been found to be powerful tools for reusing quite detailed shape definitions and efficient manufacturing methods. According to [8] feature is defined:

“A feature represents the engineering meaning or significance of the geometry of a part or assembly. Features can be thought of as building blocks for product definition or for geometric reasoning.”

Microscopic features have the following characteristics compared to other reuse entities:

- The microscopic features are physical constituents of a part.
- They are application oriented and thus have a narrow scope of application. On the other hand the strength of feature-based modeling lies in the ability to efficiently reuse the best recipes found in the application area.
- Microscopic features are typically simple and small entities that can be as building blocks for product models.
- Features are precise and fixed definitions which reflects the requirements of detailed design.

Wide research on feature modeling approaches has proven features to be a successful method for reusing detailed product knowledge [8].

4. An approach for product design patterns

An obvious gap exists between the methodologies for reuse on the level of macroscopic principles and the level of microscopic features. Therefore it is necessary to study the requirements of product design patterns and to evaluate how well current product modeling approaches suit or could be extended to fulfill the reuse characteristics. We propose that the cut and paste features can be applied as product design patterns. Their feasibility and requirements for further development are discussed in the following.

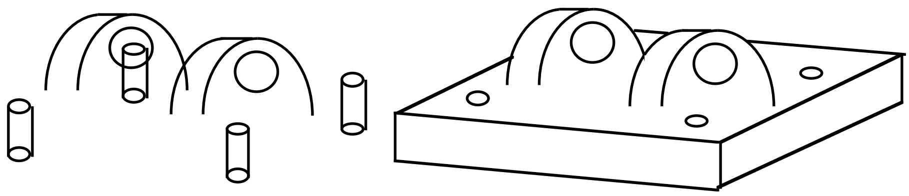

Figure 4. A simple example reusing boundary portions

The cut and paste methodology that is based on constrained boundary features is described in [9][10]. The left hand side of figure 4 shows four boundary portions that have been cut from an existing product model to be used as a boundary feature that can be pasted to new designs as the right hand side demonstrates. Figure 5 illustrates how position and size constraints are cut along a constrained boundary feature and applied in the pasting that adjusts the feature to fit the new environment. The cut and paste approach was introduced in order to realize customer defined features. However, these very flexible entities are now found to maybe better fit the definition of product design patterns than design features. Here we shall concentrate on the characteristics of the approach that demonstrate its feasibility for product design patterns.

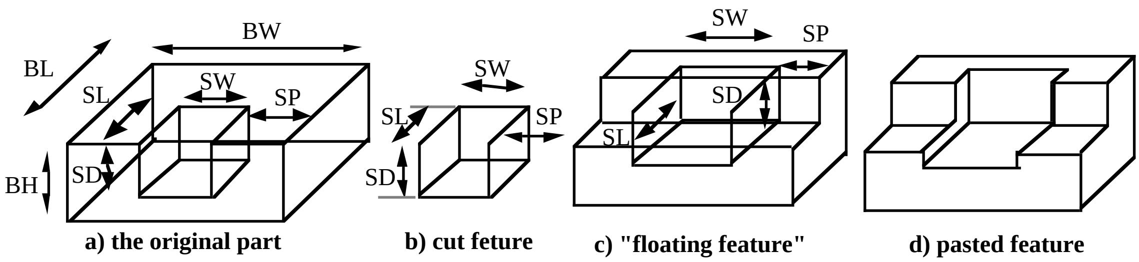

Figure 5. An example of constraints and adjustment in paste operation

According to table 1 the cut and paste patterns have the following qualifications as product design patterns:

- A cut and paste pattern presents just the key aspects and avoids over specification. The designer chooses the set of faces that are relevant for the reuse purpose and the boundary portions are allowed to be incomplete as solids. For example figure 4 shows how the designer has chosen two carriers and three holes as a design pattern that fulfills certain functionality.
- The cut and paste patterns are not fixed to their initial physical appearance but may vary according to their relation to other patterns. For example in figure 5 the "slot" feature changes size and shape according to the constraints that define its relation to the intersecting patterns.
- The cut and paste approach was developed to allow designers to collect their own catalogues of reusable solutions and thus to overcome the disadvantages of the conventional feature libraries that are very application dependent. Thus the approach as such has a wide scope and the designers may decide how specific or general features they prefer to define.
- Typically cut and paste patters are large complicated entities – the cases in figures 4 and 5 were greatly simplified for the sake making the techniques clear. The attractiveness of the cut and paste patterns is in the way they allow the designer to create new products by combining just a few large patterns.
- The cut and paste patterns adjust according to their environment as demonstrated in a simple case in figure 5. The flexibility is based on application of constraints that relate the patterns to its environment and determine the final geometry. The utilization of incomplete solid models promotes the adjustment.

The analogy to design patterns of software engineering [3] suggests many possibilities for improving the reusability of the cut and paste implementation of product design patterns. Two of them are briefly discussed in the following.

4.1. Abstraction level of patterns

The abstraction level of cut and paste patterns can be made higher. When cut and paste was seen as a method for creating features the aim was to offer the user means for reusing very detailed product information. Now the aim is to recognize from the cut entity those aspects that are common design structures and generate a pattern of appropriate abstraction level.

An obvious problem with the initial cut and paste implementation was that the user had to bear the full responsibility of maintaining the feature catalog. As the system does not check what is inserted, the designer can easily add to the catalog entities that essentially represent the same pattern. In order to establish product design patterns the user should be assisted in recognizing similar patterns. In addition, the system might suggest creation of a more general product design pattern when it recognizes resembling patterns appearing in the catalog of previous products and patterns. Data mining and pattern recognition methods are potential approaches to this problem.

4.2. Evolution of patterns

The discussion on the abstraction level of product design patterns suggests that the pattern catalog evolves constantly. Not only are new patterns added, but also existing ones are improved as the designer gains better understanding of their reuse possibilities. This approach is compatible with the initial idea of cut and paste as a means for designers to collect personal design catalogs. It has proven troublesome to define a complete feature catalog for even a limited application area, so it is hardly feasible to define a sufficient catalog of product design patterns of wide applicability. The strength of the cut and paste patterns is in allowing designers to easily define new patterns and let the catalog grow.

The design patterns of [3] enhance the reuse based on class inheritance by for example object composition, delegation, and parameterized types. In analogy the cut and paste system should be extended to allow product design patterns to have a structure of components and parameters that allow more variation and alternatives in its behavior. This requires enhancements to the object-oriented presentation of cut and paste patterns and development of some kind of a definition language for the compositions and parameters.

5. Conclusions

This paper was written in order to present a vision of how product models should be structured in order to support reuse over the life-cycle of a product model. We have not introduced new research results but rather tried to present pieces of existing research and lessons learned and, moreover, searched for new challenges for the existing approaches.

From the discussion on reuse and the life-cycle of a product model we may draw the following conclusions:

- The life-cycle stages require specific tools for product modeling, since the level and aim of design and reuse are clearly different. Feature modeling has proven very successful in presenting detailed product data and it is becoming a de facto approach of product models. However, features cannot be used at the early design stages where the design does not yet deal with concrete shapes. Furthermore features are not a promising approach for the intermediate stages of structural and product design where a lot of the product definition is still incomplete or missing.

- We propose three types of entities for structuring the product model at the life-cycle stages. Macroscopic principles are used during the conceptual and functional design. Product design patterns are applied during the structural and embodiment design. Finally microscopic features are utilized during the late stages of embodiment and detailed design. Of these three categories microscopic features are most established, macroscopic principles are being researched intensively, and product design patterns appear as a gap to be covered.

- Design rationale models [11] are a promising approach for avoiding the errors that are easily created during product model reuse. Furthermore they offer means for presenting the different product models as a wholeness to the designer.

We propose product design patterns as a promising approach for product modeling in the intermediate stages and we further suggest cut and paste approach as a promising basis for the realization of product design patterns. Following aspects require further research:

- Data mining and pattern recognition methods appear promising for classifying product design patterns and for recognizing promising reoccurring patterns from product models.
- Cut and paste patterns need capabilities for representing structures that present the component patterns or alternative patterns. Some type of pattern definition language seems to be necessary for the user to build more flexible and abstract patterns.
- It is necessary to add and present some level of semantics in the context of the user defined patterns.
- The cut and paste patterns should be extended to include other types of information presentations than geometric model and constraints. For example manufacturing methods and design rationale would enrich the model.

Finally some conclusions on how this paper may contribute to the research on product structuring:

- Our paper discusses the type of entities that are needed to structure the product data and knowledge for reuse purposes. Thus the work belongs to the design data management interpretation of product structure. Obviously we consider product modeling as something more than product data management which offers a tool for implementing product models.
- The reuse requirements are considered according to the life-cycle of a product model which differs from the life-cycle of a product. However, the paper concentrates on the product modeling methods and omitted any details of the variety of views. A product model should provide facilities and access to the variety of structural views, although the product shape related tendency and pictures of this paper may be misleading.
- The cut and paste approach to product design patterns allows the designer to decide on the entities and structure according to which the created data is presented. Thus the product design patterns reflect the designer’s view more than for example feature based product models. Thereby we hope to learn more about the design interpretation of product structure by examining the designer defined patterns.
- The paper omits discussion on design process related data. However, we see product and process models as two sides of a coin and their relation is an important topic of our future research.

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