Optimization of the Conceptual Phase of Design using Feature-based Methods

BORUT GOLOB, GORAZD HREN, ANTON JEZERNIK
Faculty of Mechanical Engineering
University of Maribor
Smetanova 17, 2000 Maribor
SLOVENIJA

Abstract: - Early phases of design process still lacks of the computer support due to informal and highly complex data that has to be managed. Appropriate structure of data is therefore needed for optimal support and connection of conceptual design with downstream application of the product development process. Paper introduces an approach towards a feature-based product model incorporating representation scheme for capturing product semantics handled in the conceptual design phase.

Key-Words: - Conceptual design, feature-based modeling, data-structure

1 Introduction

CAD/CAM/CAE systems of the future will have to manage a much broader range of information than geometry. It becomes more and more crucial to capture, represent and process the function and the functional behaviour of a product. This should already be done in the early phases of the product development process in order to: (1) support the flow of information without loss along the process chain in order to realise a constant computer supported engineering environment for an integrated product development; (2) assist designers in all phases of the product development in developing syntactical correct and semantically consistent product models by providing intelligent and intuitive computer support that minimise the possible sources of engineering errors and maximise the capability to map designers’ creativity into corresponding mathematical models of the product. The presented approach to these objectives is a feature-based modelling of product semantics and in particular of product function that takes place already in the conceptual design phase where the most fundamental decisions about product structure and solution principles to meet requirements of the product idea are taken. Features are then the information carriers that allow modelling the relationships between requirements of a product, its functional descriptions and physical solutions. They will also bring this information to the downstream applications for embodiment, analysis, detail part design, and assembly. This will allow, for instance, to keep track of the consistency between the concept, the design, and the manufacturing of a product. Existing approaches towards a feature-based integration of different phases of the product development to support concurrent engineering include extracting and mapping different views of a parametric representation of a product, expressed in terms of geometric form features [1], [2]. Products semantics are there expressed in terms of explicit geometric or functional constraints [3], [4]. Product semantics as it is handled within the conceptual design is not supported. Therefore, it is the aim of this paper to come up with a concept to extend these feature-based integration approaches in a way that it is possible to represent the conceptual design information, to support the evolution of product semantics along the product development process, and finally to improve concurrent engineering and top-down design by supporting an early feature-based prototyping of the different views to the overall product model making use of captured feature information to the largest extend possible. Major prerequisite of such an approach and therefore focus of this paper is a suitable representation scheme to store, manage, and retrieve product semantics including conceptual data.

The paper is organised as follows. After introduction, the second section will give a short introduction into the fundamentals of conceptual design and its role in the product development process. The third section will then present the definition of features. The fourth section is then dedicated to a discussion of the relevant information.
units and their inter-relationships, a computer-aided conceptual design system has to deal with, before giving an example of an feature-based integrated product model. Finally, some conclusions and perspectives for future work are outlined.

2 Design Process & Conceptual Design

Product design is an iterative, complex and decision making process. The design process has been analyzed by many researchers and within design science, a large number of overlapping design methodologies have been developed. Reviews of these design methodologies have been published, for instance, in [5] and [6].

Internationally accepted representative of the European school of design is the Systematic Approach to engineering design proposed by Pahl and Beitz (SAPB) [7], which is the starting point for the work presented. It was developed in the 1970’s and stems for a long tradition of German research, with roots in the 19th century, having influenced also recent American textbooks on the subject [8], [9]. Furthermore, it is comparable with work done in the same tradition, such as that of Hubka and Eder [10], [11] and Andreasen [12].

SAPB divides the design process into four phases, after which certain decisions will have been made. The steps between the phases are approximate and are based on iteration and recursion (see Fig. 1).

The first phase addresses the clarification of the design task to be performed and involves the collection of information about the requirements and constraints that the product should meet. This phase results in a detailed design specification. The second phase is that of the conceptual design that starts by an analysis of the specification in order to identify the essential problems to be solved. The design problem is then formulated in an abstract, solution-neutral form. This makes the solution space as wide as possible, in order to avoid prejudices that may tempt the designer to decide on a certain solution before other alternatives have been considered. The problem may then be decomposed into sub-problems and function structures (or several alternatives) established. Solutions to the sub-functions are then sought. This process is supported by creative methods (e.g., brainstorming or method 635), conventional methods (patent searches etc.) and systematic methods. The systematic methods make use of design catalogues with physical and chemical effects and machine elements. Morphological matrices are used to combine sub-function solutions into system solutions. Afterwards, promising system solutions are further developed into concept variants.

Finally, use-value analysis (ensuring that a rational and objective decision is made) is used to evaluate the concept variants, and the “best” concept is selected for further development. The details of the single steps in conceptual design are illustrated in Fig. 2. SAPB emphasises heavily the importance of
decision taken in the conceptional design phase, because it is very difficult to correct fundamental shortcomings of the concept in the later embodiment and detail design phases.

The concept design phase is followed by the embodiment design phase. A feature-based approach to embodiment design has been reported in [13]. During embodiment design phase the designer develops the layout and the form of the final system, using the concept as the starting point. Also in this phase, several alternative designs may be considered, for example layout variants. In this phase, the system will be developed to the point, where a clear check of function, durability, production, assembly and other requirements can be carried out. It is also the phase where CAE and simulation software are typically used nowadays, even if due to the shortcomings of today’s CAX systems engineers have to start with modelling details in CAD in order to perform analysis’s. SAPB provides support to the embodiment design by means of rules, principles and guidelines. If the design is to meet requirements, the rules state three important conditions that must be fulfilled: clarity, simplicity and safety. The principles state fundamental engineering design knowledge. Examples are the principles of sub-division of tasks and of the use of self-reinforcing solutions. The guidelines are more domain-specific, such as design for assembly guidelines. Finally, in the detail design phase, detailed product models (e.g., CAD models, and production documents) are completed.

3 Feature Definition

According to the results of FEMEX (Feature Modelling Experts) working group, established in 1996 by a number of international researchers, CAD system developers and larger CAD user companies (see, for instance, [14]). a feature is defined as follows:

A feature is an information unit (element) representing a region of interest within a product. It is described by an aggregation of properties of a product. The description contains the relevant properties including their values and their relations (structure and constraints). Furthermore, it is defined in the scope of a specific view onto the product description with respect to the classes of properties and to the phases of the product life-cycle. Finally, a feature is described by properties out of several different classes of properties, thus relating these (classes of) properties to one another.

There are four special aspects in the definition above: (1) It is necessary to find a structure of properties suitable to express conceptual design information like function, working principle, physical effects, and solution principles in terms of such product properties. (2) A feature is not limited to physical elements and exist only in the world of information models. (3) “Properties” are the base in the definition and at the same time the basic implementation mechanism. (4) “Classes of properties” and “product life-cycle phases” are distinguished in the definition above. Some properties are meaningful in more than one phase, for instance, geometry – in different phenotypes – is considered in nearly every phase of the product life-cycle. The product information expressed in terms of properties aggregated by different features in different application contexts is therefore the key mechanism towards an integrated product development.

![Fig. 2 Steps of conceptual design](image-url)
4 Representation of Information in Conceptual Design

Effective computer support during conceptual phase of design process is obtainable via properly structured information. Due to highly complex and informal data used in this process, feature-based representation seems to be most appropriate to achieve this goal.

Following, the basic information units managed in the early phases of the design process are presented and an information structure is discussed for handling these information units that is suitable for implementation purposes.

4.1 Requirements

The requirements list results from the very first task clarification phase (see Fig. 1 & 2) and describes the general constraints a product has to or should fulfil.

- **Description of requirements**
  - name
  - type $\in \{\text{Demand, Wish}\}$
  - class $\in \{\text{functionality, manufacturability, economy, user/environment}\}$
  - $\in \text{subclass}\{\text{geometrical, kinematical, forces, energy, material, signal, ..}\}$
  - qualitative/quantitative
  - properties - geometrical {size, height, width, length }
  - operator
  - value, unit

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An important prerequisite to enable automatic validation of proposed solutions against given requirements is a structured and formalised description of these requirements that has to handle the following information:

### 4.2 Product Function

In technical systems conversion of energy, material and/or signals is performed. This conversion can be described as flow through the system, where one is the main flow and others, if any, are supporting flows. For the design of a technical system, a clear attitude between the input and output must be defined in form of the function of the system. This function is an abstract formulation of the task. The overall function can often be divided into sub-functions, and function structures can be established. With further sub-division of the sub-functions, basic functions - also called generally valid - can then be recognised. These functions, according to the definition by Rodenacker and Krumhauer (see for instance [7], [15]) are change, vary, connect, channel and store. They represent a conversion of type, magnitude, number, place and time, respectively.

Functions are usually fulfilled by physical, chemical or biological processes, whereas mechanical engineering solutions are based mainly on physical processes. Selected physical effects and the determined material and geometric characteristics result in a working principle that fulfils each function. If a function cannot be fulfilled with a simple effect, a structure of effects has to be used instead. In the following phase of the design

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*Fig. 3 Function fulfilled by working principle.*
process – embodiment - qualitative and quantitative parameters such as surfaces, dimensions and material properties are defined according to the physical laws given by the effects.

Fig. 3 shows the mapping of a function structure into a working principle. To fulfil the main function of a product, an appropriate principle solution has to be selected. As described later, a principle solution is defined by an effect, an effect carrier, properties and physical laws. To perform the main function, auxiliary functions may be needed to supply supporting flows, to eliminate side effects or to meet given requirements (for example, in order to convert water into steam, additional flow of energy is necessary). Auxiliary functions could be solved by the same or by additional principle solutions. In the functional structure sub-functions therefore have to be related with the principle solutions.

In the example of a vice illustrated in Fig. 4 the main function is channel of material – fixing a part on a distinct position. Friction is chosen as effect and solid body as effect carrier. To perform this effect, an additional flow of energy – in this case force – is needed. The auxiliary functions are supply and magnify force. For magnifying manual force - function vary(magnitude) - effects of lever and eccentricity are used, while a solid body as effect carrier and appropriate dimensions, according to physical laws, forms working the principle of an eccentric contrivance.

### Description of function

- **Intent** - purpose
- **Type** (change in){
  - change (type),
  - vary (magnitude),
  - channel (place),
  - connect (number),
  - store (time)}
- **Class** {main, auxiliary}

### Description of flow

- **type**{ material, energy, signal }
- **class**{ main, working, side }
- **orientation**{ input, output }
- **properties**
  - **material**{ solid{ body, grains, powder, dust }, fluid, gas, space }
  - **energy**{ mechanical, thermal, electrical, magnetical, acoustic, optical, chemical }
  - **signal**{ measure, data, value, control impulse, message, ... }

### Description of function structure

- **Main function**
- auxiliary flow(s) and sub-functions to provide them
  - input/output(value, unit)

A feature-based representation scheme for capturing the product function must provide a means of explicitly modelling the sub-function structure as
illustrated in fig. 5. Within such a function model functions are represented by function features, which not only represent the static function information mentioned above, but also carry the knowledge about its intent and its concretisation in terms of principle solutions.

4.3 Principle Solution

A principle solution consists of a chosen effect and the appropriate effect carrier. Usually, the same effect can generate several principle solutions, depending on material and geometrical properties; for example, the thermal dilatation effect can be combined with a solid body or a fluid as the carrier. The relation between function and principle solution is normally not one to one. Sometimes, one principle solution can solve several functions at once, however, a lot of functions cannot be solved by only one principle solution. In this case, a principle solutions structure is needed, which is the working principle.

As the number of known physical effects is deterministic, some authors have collected related principal solutions for use in a design process [17], [18]. These catalogues of principle solutions are structured appropriately for a computer implementation. (See, for instance, [19]).

4.4 Working principle

An appropriate structure of principle solutions, which fulfils the main function of a product, is a working principle. Together with given requirements, a working principle determines the embodiment of a product. Due to links/connections to auxiliary functions and a hierarchical structure of data, a working principle describes the principle solutions structure and implicitly also the function structure.

Description of principle solution

<table>
<thead>
<tr>
<th>Identification (name, description, sketch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• functions</td>
</tr>
<tr>
<td>• effect {list of effects for each type}</td>
</tr>
<tr>
<td>• type $\in {\text{mechanical, fluid, electrical, optical, ...}}$</td>
</tr>
<tr>
<td>- effect carrier $\in {\text{solid, fluid, gas, space}}$</td>
</tr>
<tr>
<td>- material and geometrical properties</td>
</tr>
<tr>
<td>• input, output</td>
</tr>
<tr>
<td>- (for mechanical effects) type $\in {\text{force, path-volume, speed velocity, acceleration, torque, angular speed, angular accel., mass, temperature-heat, time, frequency, amplitude, sound, light, stress, ... material A, mat. B, mat. mixture AB}}$...</td>
</tr>
<tr>
<td>• physical laws describing the relations between the input and output.</td>
</tr>
</tbody>
</table>

Description of working principle

<table>
<thead>
<tr>
<th>Function to be fulfilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>principle solution used</td>
</tr>
<tr>
<td>input/output (value, unit)</td>
</tr>
<tr>
<td>auxiliary flow(s) provided by auxiliary function(s), if they are needed</td>
</tr>
<tr>
<td>side flow(s) or effects and the auxiliary functions(s) to handle them</td>
</tr>
</tbody>
</table>

Note that auxiliary functions may have a sub-structure themselves.

In the introduced representation scheme the principle solutions and their inter-relationships in terms of input/output parameters and their properties which make up a working principle are kept within a working principle model, where each principle solution is connected to the one ore more functions it realises. In this way it is possible to establish a parametric relationship between this working principle model and the function model as illustrated in fig. 5.
4.5 Embodiment

The embodiment represents the materialisation of a concept where the overall layout of a product is determined. Embodiment is defined by geometrical properties - shapes, and properties of material from which part or parts are built. Both are influenced by a working principle and requirements. Shapes consist of surfaces - working surfaces, required by working principle and free surfaces. General dimensions are defined either by physical laws governing various effects used in working principles, or from requirements, or by material properties according to a strength and stress analysis, for instance.

Fig. 6 shows the relations between the geometrical and material properties, which both are influenced by given requirements and the chosen working principle.

Usually, the physical realisations of a working principle require more than one part per solution. Therefore, an assembly model should contain information about embodiment.

**Description of embodiment**
- working principle
- requirements
- assemblies / parts
- interrelations/positions
- geometrical properties (working and free surfaces, dimensions and material properties
- calculations( physical laws describing relations between material and dimensions)

Principle solutions, as mentioned above, are defined by effects and effect carriers, where each effect carrier has to be considered as a starting point for detailing the layout of an assembly that, once the design is finished, has to have a representation in the assembly model of a product. Therefore, to capture the assembly information obtained during the embodiment design phase, the previously introduced assembly model is extended and related to the working principle solutions model as illustrated in fig. 7. The extensions are a means of representing the product structure and critical relations between assemblies instantiating the parametric relations between principle solutions, which are either basic functions or physical laws manipulating and controlling the input/output parameters of the functions and their principle solutions, respectively.

5 Conclusions

The presented work is a result of an ongoing research towards a feature-based conceptual design system that is able to capture the relevant product semantics of the early design phases and to allow reusing this information in later phases for the purpose of consistency check and significant user support. Therefore, the paper introduced in the systematic approach to engineering design process as proposed by Pahl and Beitz, which is a widely applied methodology within the European design schools. Afterwards, the FEMEX feature definition was introduced as an underlying base for the semantic description of products because of its characteristic to include not only geometric properties of a product, but also all other relevant information like function. Consequently, this paper presented a structural description of the product information handled within the conceptual design phase including information units like function, working principle, physical effects, and requirements and their interrelationships.
In the future, the results of this research will be used by the authors to come up with a representation scheme for conceptual features in order to realise a prototype realisation of a system that has the following capabilities: enabling co-operative design on Web, easy expression of design ideas, and enforcing the systematic approach in design process. In addition, work will be undertaken to combine the feature-approach with conceptual 3D sketching and feature recognition, intuitive interaction based on gesture sketching, and with functional feature recognition.

References: