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MODELLING OF MEANS IN CONCEPTUAL DESIGN

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1. Introduction

The systematic design approach proposes functional decomposition as a central element of conceptual design [Pahl; Beitz 1999]. This paper treats the objects used during conceptual design of such a systematic design process on the example of several student projects. It is commonly agreed upon that the choice of an adequate concept is crucial for the following embodiment and detail design phases, as a bad principle solution cannot be compensated even by a good detail design. Tools for concept generation are available, but often paper-based, e. g. design catalogues [Roth 2001], and not optimal regarding quick access and large amounts of information. “Building blocks” of principle solution elements with higher degree of aggregation suitable for search and reuse are desired, but require the prior knowledge of how objects of conceptual design, and specifically means, can be modelled.

2. Background

During *conceptual design*, the second step of the general procedural model in Figure 1, the clarified task is described in terms of a *function*, which is decomposed into *sub-functions,* together forming a *function structure*. Each sub-function is solved by principle solution elements (denoted as *means*, similar to *organs* in the WDK school or *function carriers/wirk principles* in the approach of Pahl and Beitz). Depending on the model, the functions or means are in turn decomposed into sub-functions until the task is satisfactorily described.

2.1 Functions

Design methodology research changed the view of the designed artefact to considering *functions*, suitable for describing behaviour and handling complex tasks [Hansen 1995], prior to *components*. Functions are defined as the unambiguous assignment of a set of (independent) input quantities to a set of (dependent) output quantities [Roth 2001]. Less formal definitions exist, e. g. capability of performing the transformations inside a technical system [Hubka; Eder 1988] or, in value analysis, tasks fulfilled by means of an object, process or activity [cf. Stetter 2001]. Specific extensions of functions are known, e. g. operative, structural, ergonomic and communicative functions or

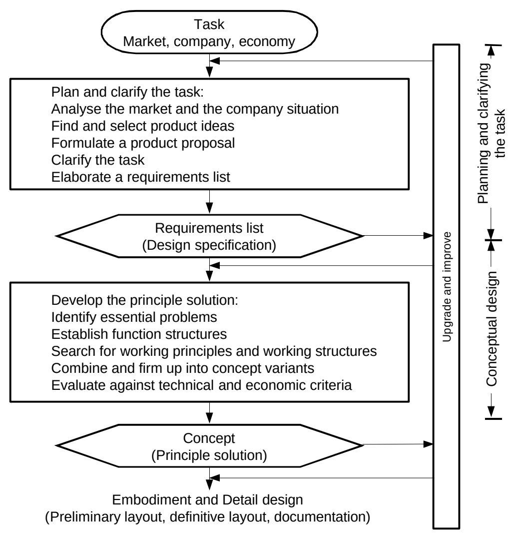

Figure 1. Conceptual design, excerpt of the planning and design process [Pahl; Beitz 1999]

recognition functions [Stetter 2001] communicating emotions, appearance, prestige, cost and product properties.

2.2 Function Structures

Function structures originating from systems theory describe technical artefacts as a network of interconnected elements. *Flow-based structures* use operands being transformed, e. g. the abstract function structure (AFS) [Roth 2001] containing standardised transformations (store, conduct, transform, sum, divide) operating on three *general quantities* (material, energy, information) or the special function structures (SFS) [Roth 2001] using *physical quantities* (e. g. force, electrical energy). Less formal models exist, e. g. the *technical process* [Hubka; Eder 1988] transforming *operands* regarding internal structure, external form, location or time under influence of effects received from technical means and humans in a preparing, executing and finishing time-sequence. *Hierarchical structures*, e. g. function structures [Pahl; Beitz 1999] or the Function Analysis System Technique (FAST) [Jensen 1999] connect functions in a hierarchy representing "why" in one direction and "how" in the opposite.

Functions and flows have been subject to creation of taxonomies [Hirtz et al. 2001], flows are grouped by material, signal or energy and several specific criteria, functions by verb (e. g. branch, channel, connect) and additional criteria.

2.3 Means

Different definitions of principle solution elements exist, e. g. *wirk principles* being basic principles, from which a certain physical, biological or chemical effect fulfilling a function can be deduced [Pahl; Beitz 1999] or *organs* or *function carriers* (e. g. "motion screw") being the system that realises a given internal function of a technical system [Hubka; Eder 1988]. Organs exert the main working effects on the operand, perform functions (e. g. "transform rotational into linear movement") and vary in complexity, degree of abstraction, category of purpose and placement relative to system boundary (internal, receptor, actuator). Design catalogues [Roth 2001] describe means using classifying criteria to obtain order and completeness. *Organ units* and a corresponding information model [Jensen 1999] have been suggested to facilitate design knowledge capture and reuse.

Classifications have been established for mechanisms, machine elements and supplier parts (e. g. [Meerkamm 1998]) and even for some specific products. These works, however, are more useful for embodiment and detail design than for describing the more abstract means in conceptual design.

2.4 Existing Modellers

Information models in existing implementations of tools covering conceptual design will be analysed on the example of three major modellers, for references see [Jensen 1999, app. D].

2.4.1 Schemebuilder

Schemebuilder, a computer aided knowledge based design tool for support during conceptual and embodiment design, focuses on mechatronic systems and simulation issues and aims at the automatic deduction of simulation models e. g. for precision motion controlled machines. Different from an expert system, the co-operation between designer and system and the generation of numerous alternative *schemes* (*concepts*) in a short time is supported. Schemes are visualised by hierarchical (function/means-tree) and flow models (bond graph). A knowledge base stores means, wirk principles and parametric components which embody the means.

Functions are described by name and purpose, a group (such as sensor, actuator, transmission, controller) and the input/output port-type (signal or energy) with connection, its type and purpose. Methods for functions are to find principles and find means. The *means* model contains the corresponding function type, input/output and link to simulation models. Methods address continuous or discontinuous analysis and component matching. For discontinuities, non-inherited specific methods are used. *Wirk principles* describe functions at non-lowest hierarchy level by a list of sub-functions and the corresponding segment of function/means-tree and flow structure. Methods

encompass analysis and simulation. *Components* are described by function type, input/output types, simulation model, producer reference and characteristics. Elements are connected at *ports* consisting of a port-type hierarchy (information, power, material) as first criteria. Connectors at ports are described by type and set of variables.
Retrieval is carried out by a multi-criteria hierarchical index applied on functions (e. g. sense – detect position – angular), components (e. g. component – engineering design – fluid system – hydraulic actuators – bidirectional hydraulic cylinder) or flows (e. g. power port – effort – electric – ac – 3~). Besides hierarchy browsing, even search by constraint-setting on function and port types is possible.

2.4.2 DIICAD

The DIICAD (Dialogue Oriented Integrated and Intelligent CAD) system aims to support every phase of the design process and incorporates methods for co-operative and distributed engineering. *Design working spaces* define the area enveloping an envisaged solution, which is gradually designed into the space. The concept product model consists of requirements, SFS functions, physical principle (with wirk principle, wirk geometry and physical equation) and shape. Means are described by input/ output, wirk principle (formulated as a function and design characteristics that determine the wirk principle) and form elements. *Solution patterns* (parametric application neutral solution elements) indexed by function structure and functional relations are applied. Search operates on input/output and function verb. The neutral solution is *instantiated* for a special case by setting or modifying its parameters.
The system has an orientation towards geometrical shapes. Due to the applied SFS-model, hierarchies are more difficult to model than in an integrated function/means model. Search is concentrated on lowest-level means.

2.4.3 KALEIT

The KALEIT system differentiates between organisational and functional information. The former identifies (e. g. id number), localises (e. g. author, date) or references (e. g. solved requirement), while the latter describes the function structure. Functions consist of input/output (including operand hierarchy, e. g. energy – mechanical – translation – force) and transformation performed in between (primary/secondary, verb/noun, modification (size, quantity, location or time) and a longer textual description). Requirements can be coupled to functions. Search is done by function recognition.

3. Demand for operative means models

Limitations of human short time memory require abstract representations [Franke; Lippardt 1997], especially during conceptual design. The hypothesis behind this work is that design support systems assisting in concept generation with abstract ”building blocks” of higher aggregation yield concepts of higher quality and help covering solution space better. The goal is at the same time not to find a complete algorithm, but to provide suitable support for the designer capable of intuitive steps.
To provide operative objects for conceptual design and operations on them, models have to become less vague [Hansen 1995]; the abstract information in conceptual design has to be defined more strictly. High abstraction and degree of aggregation, and ideally even storage of empirical data is necessary, in this way even facilitating collaborative design by giving a designer the chance to reuse “building blocks” from former projects or from specialists of other disciplines or departments.
Information is at present globally accessible and available. The new problem are search mechanisms to find in the vast amount of data. Many methods have been developed in the 1970s and are, being paper-based, not directly applicable in computers.
Functions of design methodology are often too vague to allow a transition to physical effects. Means are believed to be an important link for this transition. An important weak point of known process-oriented design models is that it is yet unsolved how to universally classify the manifold objects necessary for design from the aspect of aggregation and to establish a classification system or even metric – a generally valid classification might remain an unachievable dream [Franke 1999].
Well-defined means even provide a termination criteria about when to stop decomposition in the function/means-tree, a model which has means on its lowest level.

4. Method

The conceptual design in several projects, each a workload of six months with three 4th year mechanical engineering students per team, has been analysed retrospectively in a descriptive, empirical case study. The students were solving real design problems in cooperation with an industrial company and spanned different company types and branches, design types and problems, all having a creative design task in common. Work has been supervised and guided by a professor and two tutors from university and the company, the progress being assured by checkpoints during the project and the application of systematic design. The documentation by a written report contained extensive information on results and even to some extent the approach.

5. Results

5.1 Objects in Conceptual Design

Due to the steered approach, all projects used requirements list, function structure, function/means-tree and concept sketches. Several phenomenon models can be identified, see Table 1. The rightmost two columns give possible examples not necessarily found in the studied cases.

Table 1. Objects used during conceptual design

Phase	Product describing model	Object	Examples of methods	Knowledge sources
Task clarification	Requirements list	Requirement	Search matrix [Roth 2001]	Products, customers
Functional decomposition	Black box	Operand, overall function	Thesaurus	Verb lists
		Technological principle (effect on uppermost level)		Physics
	Technical process	(Transforming) functions, flows	Abstraction, SFS	Operations, quantities
	Transformation system	Technical system	Division into sub-modules	Req. list, interfaces
	Function	Verb/noun, flow, characteristics, properties	Search algorithms	Verb lists
	Means	Effects	Rough calculations	Solution catalogues
	Function/means-tree	Sub-functions, means	De-composition	Verb lists, functions
	Morphological matrix	Lowest-level sub-functions and corresponding effects	Evaluation methods	Score functions
Concept generation	Symbolic diagrams	Working structure		Arrangement principles
	Sketches showing arrangement	Spatial relation	Contact matrix [Roth 2001]	

5.2 Means

A model for means during conceptual design must provide coherent and exhaustive storage of all data relevant for the stage [Franke 1999], even capturing empirical experiences and physics, costs, etc. The studied cases allow some conclusions regarding a possible information model for means, relevant parts are shown in Table 2. A thought chain could be identified from requirements via functions to means (e. g. the requirement "communication by infrared light" implicating the function "transmit information" being solved by the means "cordless transmission" or "fibreoptic cable"). Means are strongly coupled to the function they fulfil, and a means model should therefore provide links to requirements as well as functions. This permits the common use of flows for classification and retrieval, namely the input and output flow of the corresponding function and their relation to the system border (internal, receiving, actuating). Means possess assigned requirements and give rise to

constraints, which in turn can be forwarded to become requirements for sub-functions.
Corresponding functions are described by verb/noun statements (e. g. “increase pressure”) and their input/output flows (e. g. “electrical energy” to “mechanical torque”). Functions determine a concept to different extent, indicated by main/auxiliary, and can be divided into intended (which contain no reference to the realisation yet) and achieved functions.

Table 2. Essential contents of information model for means

Scope	Entity	Remarks	Example
Generally valid	Name		Cordless transmission
	Constraints	Given by actual means	Requires electrical energy
	Effect	Physical basis	Light emission by diode
	Characteristics	Possible parameters	Current I = 0..100 mA
	Equations		a = f(I)
Instantiated	Requirements	Links to requirements	Communication: infrared light
	Function provided	Purpose	Steer vehicle
		Verb/object, transformation	Transmit information
		Corresponding flows	In: electrical signal, out: light
		Relation to system border	Internal
		Importance	Auxiliary
		Status	Achieved
		Verbal description	The vehicle has to be able …
	Properties	From characteristics	Visibility range a = 10 m
	Links	To external files and models	

A set of characteristics in connection with instantiated values can yield a set of properties indicating the behaviour of the means. In order to facilitate reuse of means, the model should contain generic data which is generally valid for a solution principle and data that is specific to a certain instantiation of the means (cf. [Jensen 1999]). Instantiation was found on means connected to machine elements, e. g. the setting of a bowden wire diameter depending on the transmitted force, and on more abstract means (e. g. calculation of force on a vacuum gripper).
Simple rough calculations on means, an important piece of engineering skills, were found on several occasions (e. g. for an early check if an envisaged battery could cover the power demand, at the same time estimating the resulting mass).
In all cases, non-aggregated means from the lowest decomposition level were combined. Some projects offered opportunities for building blocks, e. g. a flow-based aggregation of power supply, force generation and force transmission.
The level of abstraction affects the variability of means. The deduction of classifying criteria and subsequent variation is an example of this and allows even clustering of means into groups.
Sketches were used as graphic representations, partly for means in the morphological matrix and partly for concepts illustrating the organ structure and seem to support the mental thought process well. A means model should therefore support different symbolic sketch representations on means, symbolic diagram and concept level. The used sketches were mostly 3D views, sometimes shaded, showing the essential geometry and arrangement without shape details.
The suitable degree of formalisation strongly depends on the purpose. If creativity and finding a large number of alternative means is desired, qualitative information can suffice and emphasis is on description, ordering and retrieval of manifold data. For navigation purposes, focus is on clear and adaptive presentation of interrelations. For purposes of increased product understanding (e. g. breakdown of requirements and tracking to means), links between the objects are central. For prediction of properties, stringent data as in SFS, bond graphs or electrical circuit diagrams can be useful for conceptual design, especially in problems with a limited number of well-defined elements (e. g. electrical circuits or hydraulic and pneumatic systems). However, those models tend to be not

generally suitable for conceptual design (and were not used in the cases studied). For synthesis, relations between means are important, used by e. g. bond graph models. If the purpose is computer-based reasoning, means models have to comprise strictly formalised semantic information, which is likely to limit the application area.

5.3 Computer Support

Numerous attempts to create computer support for conceptual design have shown that operative models are important, yet difficult to obtain. In accordance to VDI 2222 [Pahl; Beitz 1999], the main objects during conceptual design can be grouped as in Figure 2, the lower half proposing possible interactions with a computer tool.

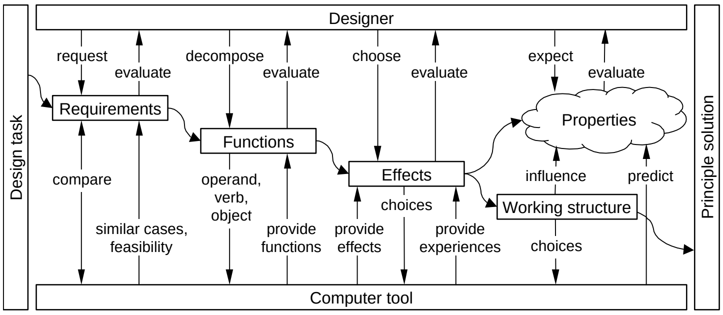

Figure 2. Interactions between computer and designer

6. Conclusions

Limitations arise as the project works were carried out by rather unexperienced students in a university environment. A retrospective study limits sources to the information in the final report, more models or methods might have been used without being presented in it.

In order to facilitate design reuse, "building blocks" of principle solution elements seem to be promising. A model for principle solution elements has to be sufficiently generic and abstract in order to be useful for reuse, at the same time allowing instantiation by setting specific parameters in order to allow modelling of concrete solutions.

Further questions arise when models have to capture simultaneous and distributed engineering work with issues as multi-department/-user access or model sharing.

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