An Approach to Configuring Mechanical Systems

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Summary

In order to be able to develop computer tools to support the engineering designer it seems that the existing phenomenon models of the design process are too vague. The problem is that it is not possible to perform an unambiguous translation of phenomenon models into computer models, because the phenomenon models does not explicitly define design activities and results in the stages of the design process. This paper presents a phenomenon model of the design task execution. The activities to perform the design task execution are set up, and some of the activities are described using IDEF0 modelling technique. The utilization of the results of this research will lead to computer tools to support the synthesis activities, which are characteristic for mechanical design.

1. Introduction

During the last decades a number of computer aided design systems have been developed, e.g. systems for aid of drafting, calculation of properties and retrieval of design solutions. However, various activities in design, e.g. synthesis of solutions and decision making, are hardly supported. The entities of geometric models in CAD systems (points, surfaces, volumes, features,...) do not have semantics with respect to designing, i.e. a geometric model cannot "carry" the designers decisions. Our long term research goal is to develop a computer based system capable of supporting synthesis activities in design. Such a system must allow creation of alternative solutions, systematic variation of product characteristics and maintain the designer's arguments and decisions.
In order to be able to develop such a computer based system to support the engineering designer it seems that the existing phenomenon models of the design process, e.g. Pahl & Beitz [1] and Hubka [2], are too vague. These models do not explicitly define the design activities and results in the different stages of the design process. This have been realised by several authors, e.g. Andersson [3], Stürmer [4], and Schmekel [5], and their approach is to apply information modelling techniques

as a means to formalize and extend design theories. Subsequently, the information models can be translated into computer models. This paper focuses on a phenomenon model of the design task, and the translation of this model to information models. In the domain of phenomenon models the work is based on the WDK design theory, Hubka & Eder [7] and Andreasen [8], and in the domain of information models, IDEF0-modelling is used.

In section 2 we set up the characteristics of the design task, and based on these characteristics we establish a phenomenon model, and set up the activities to perform the design task execution. Some of the activities are described using IDEF0-modelling. In section 3 we treat a function oriented decomposition, in section 4 we treat configuring, and in section 5 we conclude.

2. Designing Composite Mechanical Systems

The design of a product is a complex task where the engineering designer has to create a solution which best fulfils or optimizes the given goals. In principle an infinite number of solutions exist. However, in practice the designer normally knows a few solutions, and there is no guarantee that efforts to find more solutions will be worthwhile. The design task has the following characteristics:

- The wanted product is formulated as a goal, reflected in various and often conflicting criteria. The criteria are associated to the properties of the product, e.g. function, costs, lifetime and weight.

- There exist many solutions to the design problem. The solutions can be based on different physical principles, and for any physical principle parameters can be varied. Therefore the search for solutions takes place in solution spaces of different types. Firstly in solution spaces where the objects are structures and elements, and secondly in solution spaces where the objects are values of parameters. The many levels of searches for solutions may be seen as the determination of the characteristics of the product, e.g. physical principle, configuration, and material, form, dimensions, and surface quality of the parts.

- The properties of the modules in a product contribute in a complex way to the properties of the total product.

- Normally, only one or a few solutions are known in advance, in some cases no solutions are known.

- The resources available for the design task, e.g. time and money, are limited.

As a consequence of these characteristics of the design task it is generally accepted that there exists a need to develop computer tools to support the engineering designer. However, the development of such computer tools implies an operational phenomenon model of the design task. In the following we establish a phenomenon model of the design task. We choose to describe the product to be designed using systems modelling, and we focus on mechanical systems. Thereby the product is modelled as a composite mechanical system, and the modules of the product are modelled as subsystems of the mechanical system. The discrete optimization model becomes:

> Determine the composite mechanical system which realises the purpose function
> and optimizes the properties
> subject to:
> the specifications,
> and the available resources.

As a consequence of the aforementioned characteristics of the design task we have for the discrete optimization model:

- Multiple criteria, where the criteria are in potential conflict.

- Solution spaces of various types. Firstly, solution spaces where the object are system structures and subsystems. Secondly, solution spaces of subsystems, where the objects are subsystem structures and subsystem elements. This continues recursively until a level, where the nature of the subsystems change in type, from organisms to single organs, characterized by form, material, surface quality, and dimensions, i.e. the solution space becomes one of single organs seen as systems and later one of parameter values of these system elements.

- The solution spaces are not known in advance, i.e. the relations between the characteristics of a system and the properties of a system are unknown.

- Some of the criteria are associated with properties, which are difficult to quantify or cannot be quantified, e.g. aesthetics.

Obviously, the discrete optimization model cannot be solved by mathematical optimization techniques, firstly because in general the relations between the characteristics and the properties of the mechanical system are not known, and some criteria cannot be quantified, secondly because we are not able to model all solutions and control and foresee which solutions we have to consider as a result of choice of a specific solution on higher level. Therefore, we propose an approach to go "into the system" in a top-down manner, where at each system level the engineering designer searches for solutions and ideally selects a solution before proceeding to the next lower level. In order to perform this approach the engineering designer must be able to carry out the following operations:

- Synthesis, i.e. the creation of a system solution which implements the purpose function of the mechanical system.

- Decomposition, i.e. the identification of subsystems necessary for supplementing the higher level system solution in fulfilling its task.

- Configuring, i.e. the activity to create or identify the relations between subsystems to ensure that the composite mechanical system realises its purpose function.

- Breakdown of specifications, i.e. identification of the specifications for a subsystem to ensure that the subsystem contributes in the right manner to the composite system.

- Modelling of properties, i.e. the creation of models which permit determination of the properties on the basis of the characteristics.

- Make result assessment, i.e. calculation of the properties of the composite mechanical system from the characteristics and property values of the subsystems.

- Navigation, i.e. searching through the solution spaces to identify the best route and best compromise solution.

In the following sections the activities decomposition of a mechanical system, and configuring are described. The description will be based on the discrete optimization model and IDEF0 modelling technique will be used.

3. Function Oriented Decomposition

The decomposition of a product into modules is a very common activity in design work for at least two reasons. Firstly, modules are more easily designed than the product because of their lower complexity. Secondly, the decomposition makes it possibly for teams of designers to work in parallel on different modules to reduce the product development time. Although decomposition is a very frequent performed activity there does not, to the author's knowledge, exist a theory explaining decomposition and the laws on which it is based. According to the literature decomposition is done in a pragmatic and component oriented manner.

Several authors have described and discussed aspects regarding a component oriented decomposition. Parkinson et. al. [9] set up a mathematical model describing the relations between the characteristics and the structural properties, e.g. strength and stiffness, for the system, and this model is decomposed into mathematical models for the component level. Azarm & Li [10] describe mathematical methods to solve a decomposed mathematical model. They describe a method to solve a multi level model, i.e. a model containing a system, various subsystem, and a component level. The purpose of this component oriented decomposition is to determine the optimal values for the characteristics of the components with respect to the structural properties of the system. Himmelblau [11] focuses on the decomposition of large mathematical models.

Buur's thesis [12] is concerned with the development of mechatronics products. In this area a discipline oriented decomposition is applied in practice to facilitate a parallel development of the mechanics, electronics, and software of the product. However, the discipline oriented decomposition does not necessary mirror a functional decomposition.

The function oriented decomposition of a mechanical system is an identification of the functional elements in the system. The purpose of this decomposition is to identify the necessary supplementary functions to be realised for obtaining functionality for the composite system. The decomposition also leads to a reduction of the complexity of the solution spaces, and thereby facilitates the search for solutions. The function oriented decomposition is based on the law of Hubka [8], which provides a formal approach to the synthesis of mechanical systems. The law states that there exist causal relations between functions and means of a mechanical system. The functions are purpose functions (Buur [12]), which are expressed as verb/noun pairs. A function is realised by a means. A means may be of the type organ (function carrier), where an organ is a set of materialised entities and their relations which create effects and in this way "solve" a function.

A means will in general require one or more subordinate functions in order to be able to operate within a mechanical system. There are four types of subordinate functions (Hubka & Eder [7]): 1) Control/regulate functions, 2) drive functions, 3) connect/support functions, and 4) auxiliary functions.

Based on the law of Hubka a mechanical system can be modelled by the function/means tree (Andreasen [8]). The principle in the set up of the function/means tree is a hierarchical arrangement of function levels and means levels connected with lines corresponding to the causal relations between functions and means. The function/means tree is also able to express alternative solutions.

A function oriented decomposition based on the law of Hubka, illustrated by the function/means tree and following the introduced system modelling can now be established. A composite mechanical system realises an overall purpose function, and any subsystem realises a subordinate function. A decomposition procedure will contain three types of steps:

1. A search for means to realise a function, i.e. a synthesis step.
2. Selection of "the best" means, i.e. a decision making step.
3. Identification of functions to realise the chosen means, i.e. a decomposition step.

However, for performing the decomposition applying the function/means tree as a model, the tree has a number of drawbacks. Firstly, the configuration of the means is absent. This configuration is necessary because it defines the relations between the means, and must be known in order to identify the functions that realise those means, i.e. to carry out the decomposition step. Secondly, the function/means tree with its alternative means becomes extremely large. Thirdly, in practice it is not always expedient to express a function only as a verb/noun pair.

The configuration of a means describes the relations between the entities of the means which realise the function. The configuration can be expressed in a graphical model. To any means a configuration is set up. The configuration of a means shows which lower lever means exist to realise that means, and it shows the relations of these lower level means. As the design process proceeds more function/means levels are set up, and the configurations of the means expand to reflect this. Therefore, for any means there exist a sequence of configurations mirroring the gradual determination of the characteristics of the mechanical system. As a consequence of the nature of synthesis, the means in the function/means tree can vary from being abstract to concrete and from being undetailed to detailed. Therefore, also the configurations of a means can vary from being abstract to concrete and from being undetailed to detailed, i.e. the configurations will change from being a sketch showing the concept of the means, via configurations with information content and expression, like a lay out drawing, to the final configuration being a detailed drawing.

The problem with the size of a function/means tree showing alternative solutions is solved by listing the alternative means to a function below one another in the means box, and the chosen solution for the means is then rewritten in a field at the bottom of the box.

In order to clarify the effect created by a function, the function expression is extended from a verb/noun pair to include a description of the object or the environment, e.g. for an aircraft the functions "give steering on the ground" and "give steering in the air" create different effects and are realised by different means.

The decomposition procedure

When the overall purpose function of the composite mechanical system has been defined the following steps are performed recursively until no more functions arise:

While there is at least one function without means do:
Begin:
1. Search alternative means to realise the function (Synthesis step)
2. Select "the best" means between the alternatives (Decision making step)
3. Adjust the configurations on all levels above the current means level by adding this new insight (Composition step)
4. Set up subordinate function to realise the selected means (Decomposition step)

End.

In accordance with Andreasen [8], the function oriented decomposition procedure will in principle end up with functional surfaces at the bottom of the function/means tree which afterwards have to be integrated to components to finalize the design process.

4. Configuring Mechanical Systems

In accordance with the description in the previous section of the configuration of a means or subsystem the activity to configure a subsystem can be seen as the activity to set up the configuration for the subsystem. Thereby, to configure is to create or identify the relations between the elements to ensure that the subsystem realises its function and contributes to the overall purpose function of the composite mechanical system in the right manner. The acticity to configure a mechanical system is performed at each system level, and the configuration activity can be seen as a sequence of configuring steps mirroring that for any means or subsystem there exist a sequence of configurations. An IDEF0-model of a configuring step has been set up.

The configuring described here is a functional configuring of the sytem in the sense that it is focussed on establishing the relations between the elements to ensure functionality of the system. Two types of relations have been identified, namely spatial and temporal relations:

- spatial relations, e.g. parallellity, and orthogonality.
- temporal relations, e.g. sequence of processes or operations.

All rules for elements and relations of a subsystem can be represented as a mode of action model for the subsystem. Such a mode of action model could look like:

- **when**

  e1: wing profile is of type...
  e2: wing dimensions are...
  e3: tail plane dimensions are...

  r1: distance between wing and tail plane is...

  then

  the wing system realises its function "give lift".

The IDEF0-models of the decomposition procedure and the configuring shows that the design of a composite mechanical system can be seen as a sequence of design steps. In each design step the function oriented decomposition of the system identifies the subsystems necessary for supplementing the higher level system solution in fulfilling its task, and the configuring of the system creates or identifies the relations within and between sybsystems to ensure that they realise their functions and contribute to the composite system in the right manner. In each design step one or more characteristics of the mechanical system is determined. The means to determine the characteristics is models, Roth [13], where each model is used to determine a certain set of characteristics.

5. Conclusion

In this paper we have defined a phenomenon model of the design task execution as a means to be able to develop computer tools to support the engineering designer. The model is formal in the sense that it is formulated analogous to a mathematical optimization problem and it is based on the theory of technical systems and on the domain theory. The activities to perform the design task execution have been set up. These activities are synthesis, function oriented decomposition, configuring, break down of specifications, modelling of properties, result assessment, and navigation. For the activities function oriented decomposition, and configuring we have set up information models using IDEF0 modelling technique.

Our long term research goal is to develop a computer based system capable of supporting synthesis activities in design. Such a system must allow creation of alternative solutions, systematic variation of product characteristics and maintain the designer's arguments and decisions. The phenomenon model of the design task execution forms and sound basis for developing computer tools to support the engineering designer, because the model includes both an understanding of the product to be designed and an understanding of the process to design the product. The understanding of the product to be designed is based on the domain theory, Andreasen [8], which is valid for mechanical and mechatronics products. The design of the product is seen as a sequence of design steps, where each design step contains both synthesis and analysis.

It is difficult to verify the phenomenon model as a valid model of the design task execution. However, it is important to note, that the model explains the synthesis of design solutions in accordance with the work of Roth [13], namely that the characteristics of the product are determined using various types of models.

I believe that the work presented have forms a sound basis for the future development of computer tools to support the synthesis activities, which are characteristic for mechanical design, and is a contribution to the sharpening of the design theories of the WDK school.

References

A major part of this text originates from an article "An Approach to Simultaneous Synthesis and Optimization of Composite Mechanical Systems" which will be published in Journal of Engineering Design, September 1995.

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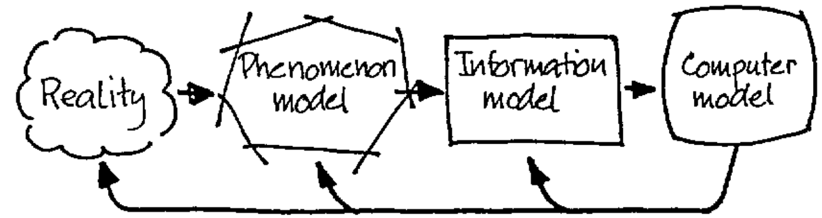
1. Introduction
2. Designing Composite Mechanical Systems
3. Function Oriented Decomposition
4. Configuring Mechanical Systems
5. Conclusion

1. Introduction

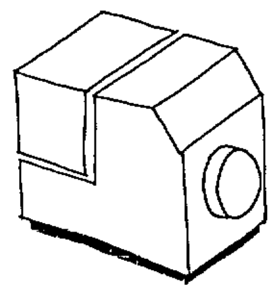


2. Designing Composite Mechanical Systems

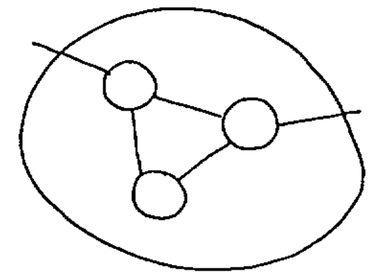
The design task has the following characteristics:

- multiple criteria
- there exist many solutions
- the properties of the modules contribute in a complex way to the properties of the total product
- only one or a few solutions are known in advance
- the resources available are limited.

The product is modelled by using system modelling



The product



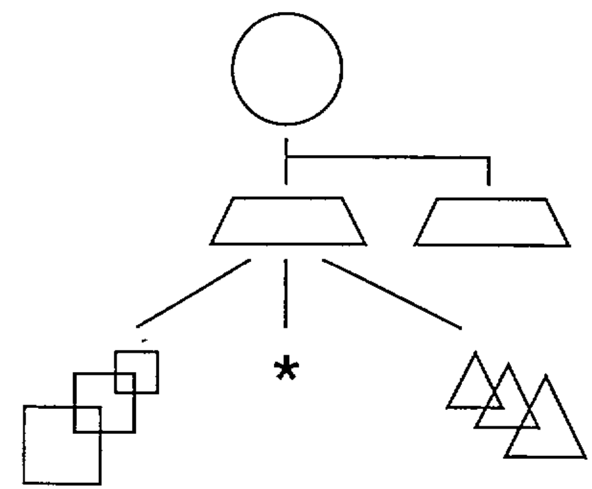
A system model of the product

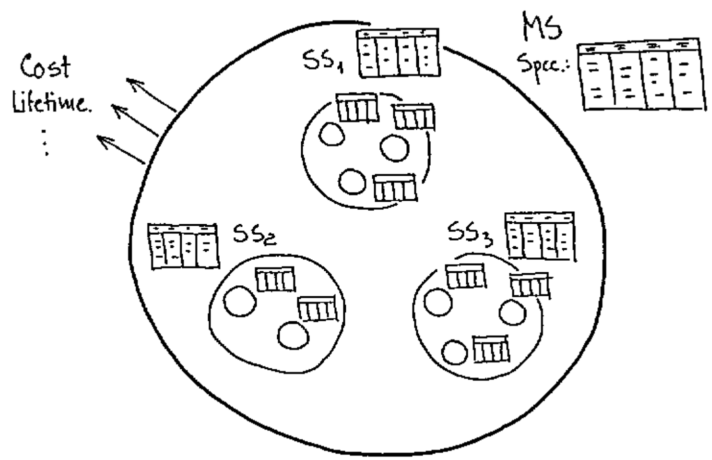
The discrete optimization model:

Determine the composite mechanical system which realises the purpose function and optimizes the properties subject to:

the specifications,
and the available resources.

An approach to solve the discrete optimization task:



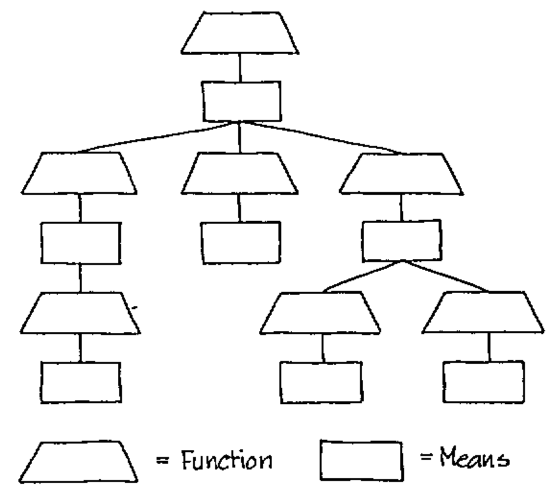


To perform this approach the engineering designer must be able to carry out the following operations: any orders ?

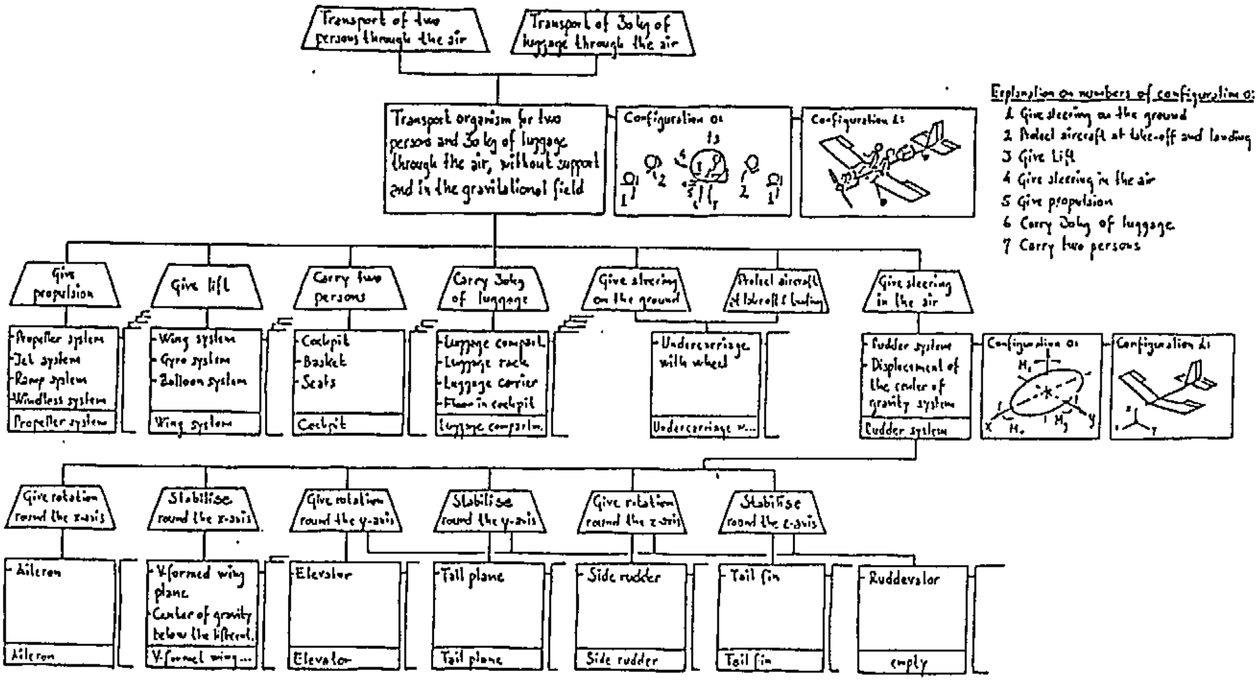
- synthesis
- decomposition
- configuring
- breakdown of specifications
- modelling of properties
- make result assessment
- navigation

3. Function Oriented Decomposition

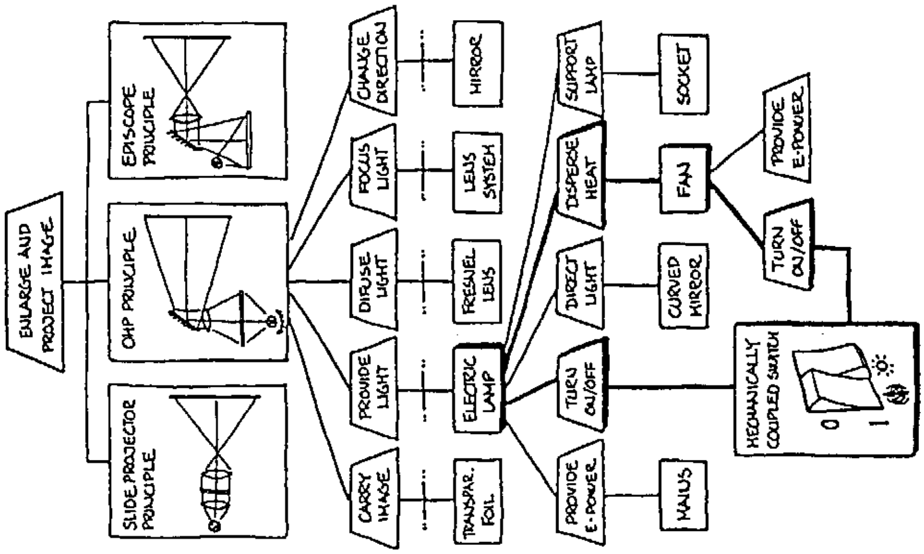
The principle structure of the function/-means tree:



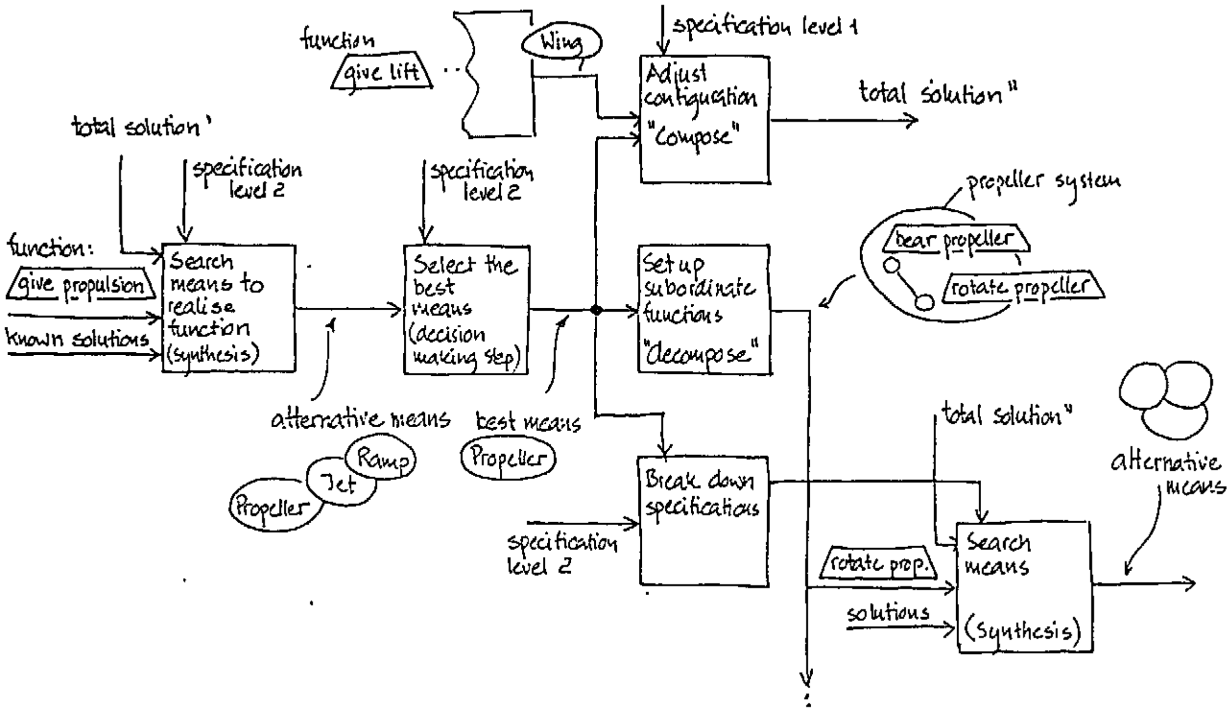
The functions are purpose functions, which are realised by a means at the level below.



A function/means tree for an overhead projector:



IDEF0-model of the decomposition procedure



The decomposition procedure

While there is at least one function without means do:

Begin:

1. Search alternative means to realise the function (Synthesis step)

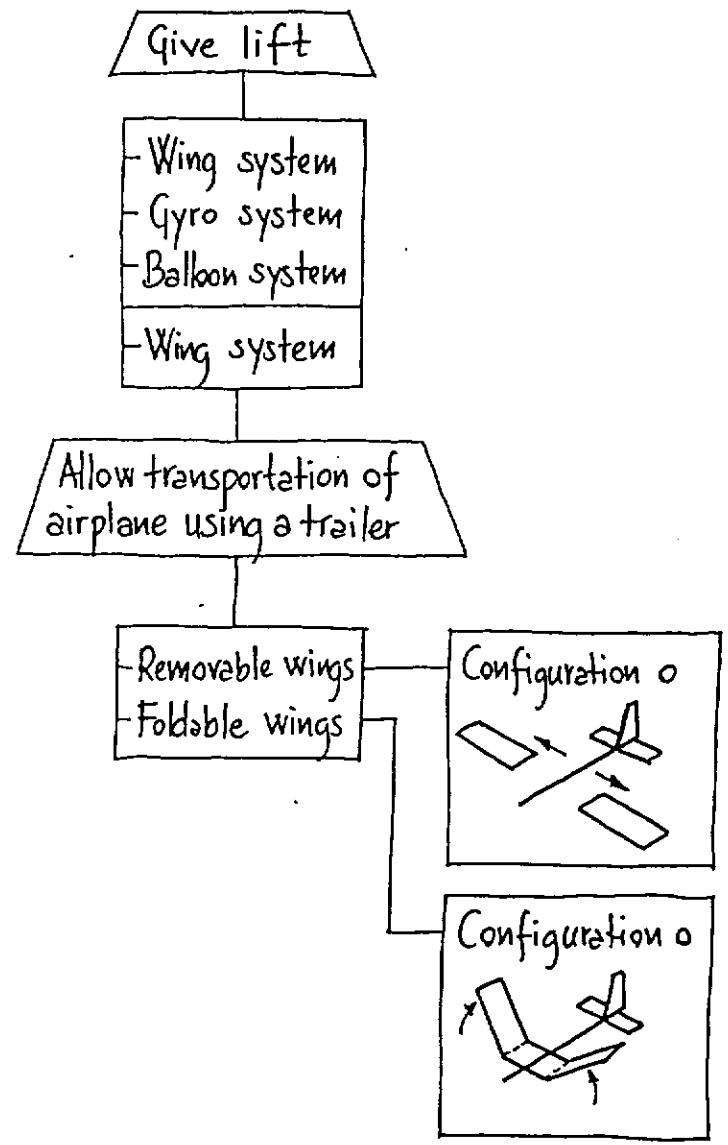
2. Select "the best" means between the alternatives (Decision making step)

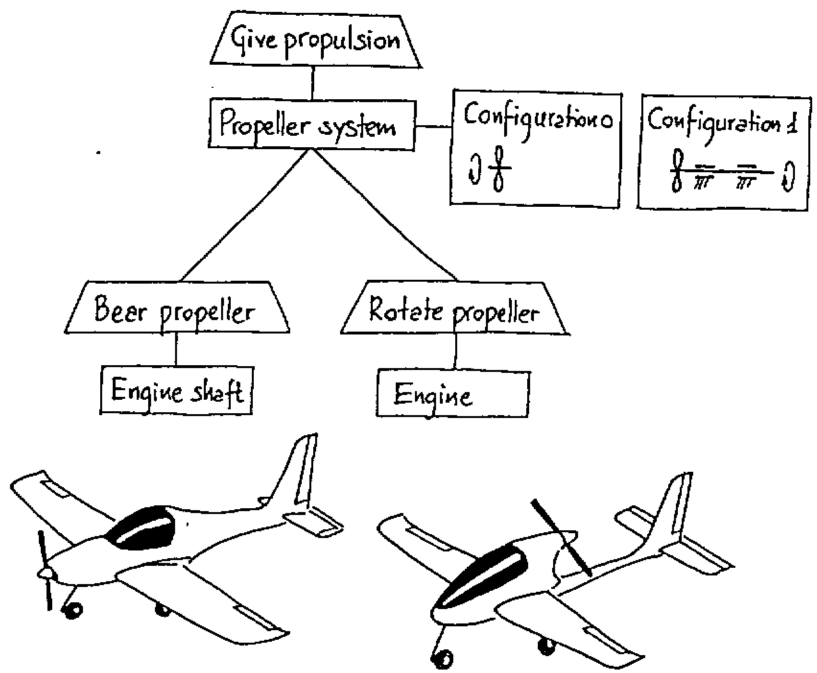
3. Adjust the configurations on all levels above the current means level (Composition step)

4. Set up subordinate function to realise the selected means (Decomposition step)

End.

Identification of an X-function:





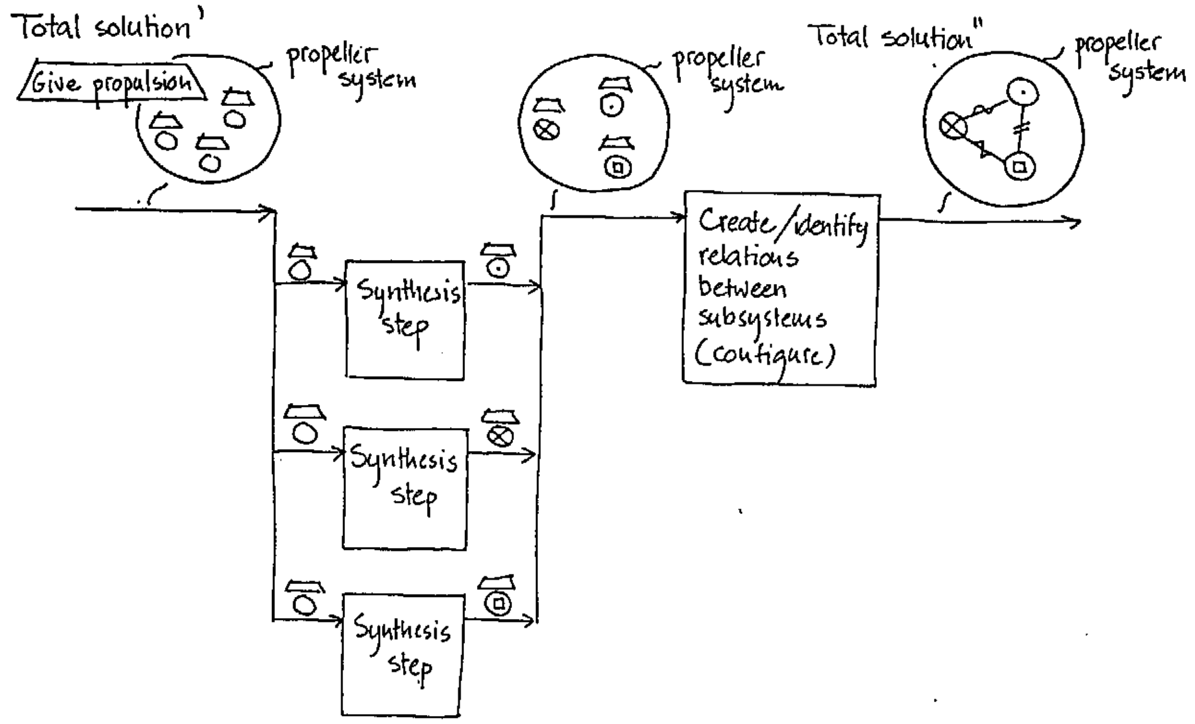
4. Configuring Mechanical Systems

Configuring is the activity to create or identify the relations between the elements to ensure that the subsystem realises its function and contributes to the composite system in the right manner.

What types of relations?

- Spatial relations
  - parallellity
  - orthogonality
  - plane to plane contact
- Temporal relations
  - sequence of processes
  - sequence of operations

IDEF0-model of configuring



Mode of action model for wing system

when

e1: wing profile is of type...
e2: wing dimensions are...
e3: tail plane dimensions are ...

r1: distance between wing and tail plane is...

then

the wing system realises its function "give lift".

5. Conclusion

- An operational model of the design task execution
- IDEF0-models of design activities
- Verification of the phenomenon model
- The work presented forms a sound basis for development of computer tools to support synthesis activities and is a contribution to the sharpening of the design theories of the WDK school.