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Modeling and Reasoning Techniques for the Conceptual Design of Mechanical Products - Review

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Abstract

Decisions made at the conceptual design stage have significant influence on factors such as costs, performance, reliability, safety and environmental impact of a product. However, knowledge of all the design requirements and constraints during this early phase of a product's life cycle is usually imprecise, approximate or unknown. Faced with such complexity, individual designers have restricted themselves to narrow, well-defined sub-tasks and as a result, progress in this area has been patchy and spasmodic. The purpose of this review is to document the current state of research and development in this crucial design activity and in doing so, to identify avenues of fruitful exploration. In this paper, we provide a comparison of the advantages/disadvantages and limitations between the various techniques/tools and, where applicable, suggest possible future research directions.

Keywords: *conceptual design, reasoning techniques, representative schemes*

1. Introduction

Product design is an iterative, complex, decision-making engineering process. It usually starts with the identification of a need, proceeds through a sequence of activities to seek an optimal solution to the problem, and ends with a detailed description of the product. Generally, a design process consists of three phases. Phase 1 is product design specification where information about the product is collected and defined in precise yet neutral terms. Issues addressed in a typical product design specification are performance, quality, reliability, safety, product life span, aesthetics, and ergonomics. Phase 2 is the conceptual design whose primary concern is the generation of physical solutions to meet the design specification. The final phase is the detailed design. In this phase, final decisions on dimensions, arrangement and shapes of individual components and materials are made with due consideration given to the manufacturing function. *Fig 1* summarizes the three phases of the design process.

Conceptual-level design begins with the specification of goals/objectives of the product. Subsequently, all possible structural configurations that could achieve these goals/ objectives are generated. An evaluation process is then carried out to select the best candidate for further refinement in the detailed design phase. This process is complex because the design of a mechanical product is, in general, multifaceted. To describe a mechanical product, we need to express its function, its behavior, and its structure. Function is the perceived use of the device by the human being.

Behavior is the sequence of states in which the device goes through to achieve the function. Structure refers to the physical components or forms that are utilized to achieve the behavior. Kuiper [2] illustrates this distinction with the example of a steam valve in a boiler. The function of the steam valve is to prevent an explosion, its behavior is that it opens when a certain pressure difference is detected and its structure is the physical layout and connection between the various physical components. Having expressed the various aspects of a mechanical product, we need to be able to understand the interactions between these different facets so as to be able to generate and select some feasible solutions.

Hence to effectively support conceptual- level design activity, we need to resolve two inherent difficulties: (1) modeling the complex interactions between various facets of a product, and (2) reasoning about the generation and selection of feasible solutions. We refer to the former as the modeling problem while the latter is referred to as the reasoning problem.

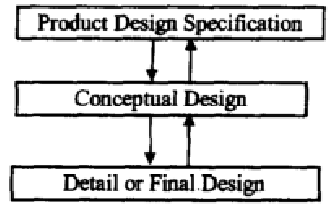

Fig 1: The Phases of Design

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A number of tools and techniques have been proposed in the literature to address the modeling and reasoning problems associated with the conceptual design of mechanical products. Many of these tools/techniques are tailored to specific products or to specific aspects of the design activity. Each of them has their advantages and disadvantages.

2. Classification Scheme

Due to the complex nature of design and the vast variety of mechanical products, the chance of being able to take existing tools/techniques off the shelf and directly applying it to a new problem is very slim. Thus the usual classification schemes, along the lines of the methodology tools spectrum or processes involved in conceptual design (user requirements, component selection, component synthesis, transformation), are not very useful. Neither scheme gives a comprehensive view of the underlying representation or reasoning techniques used to support conceptual design.

This is essential if the designer/researcher wants to customize some existing modeling and reasoning tools/techniques for their specific domains. In our review, we extract the modeling representations and the reasoning techniques separately to address the respective modeling problem and reasoning problem. The classification of the modeling representations is along the lines of computer needs versus human needs. The classification of the reasoning techniques is divided into the types of reasoning performed and whether the technique requires large amount of data or is more procedural-oriented.

3. Modeling Representations

One of the main difficulties in supporting conceptual design is the complexity involved in modeling the many facets of a mechanical product. We refer to this as the modeling problem. In this section, we will explore various representation schemes that attempt to address this problem. They range from the formal specification methods such as languages to the highly visual representations such as images as shown in *Fig 2.* Computer-oriented modeling techniques refer to those whose primary concern is to ensure that computational reasoning can be carried out efficiently. On the other hand, human-oriented modeling techniques focus on providing conducive modeling environments that aid the creativity of human designer.

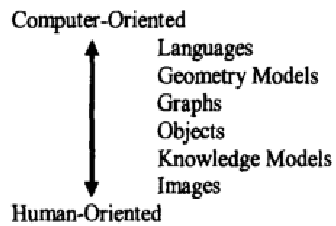

Fig 2: Specrum of modeling Representation

3.1 Language

Language represents an attempt at formalizing design. It is useful in expressing our understanding of designs unambiguously. In general, a language is defined by a grammar. A grammar is denoted by the quadruplet (T, N, S, and P) where T is the set of terminals, N is the set of non-terminals, S is the start symbol and P is the set of production rules.

For example, Rinderle and Finger [4] [5] used a graph-based language to describe behavioral specifications of design as well as the behavior of the components. Neville and Joskowicz [6] present a language for describing the behavior of fixed-axes mechanism, e.g. couplers, indexers and dwells. Predicates and algebraic relations are used to describe the positions and motions of each part. Vescovi et al. [7] developed a language, CFRL, for specifying the causal functionality of engineered devices.

A different approach taken is that instead of developing special-purpose languages for each application, effort is directed to developing shareable design ontology. Ontology is a useful set of terms/concepts that are general enough to describe different types of knowledge in different domains but specific enough to do, justice to the particular nature of the task at hand. Albert [8] proposed YMIR as engineering design ontology. The “How Things Work” project at Stanford University aims to build a large-scale ontology of engineering knowledge. By having a common set of ontology, knowledge can be reused and shared. This allows better integration between the different phases of the product’s life cycle.

3.2 Geometry Models

Geometry modeling focuses on representing the structural aspects of a product. The objective is to represent 2-dimensional or 3-dimensional geometric shapes in a computer.
Popular representations of geometric shapes include: B-rep (boundary representation), CSG (constructive solid

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geometry), and variational geometry and feature representations. Briefly, in a B-rep approach, a shape is represented by the boundary information such as faces, edges and vertices. The CSG approach models geometric shapes using a set of primitives such as a cube, cylinder or a prism. Complex shapes are built from the primitives through a set of operators (union, difference and intersection).

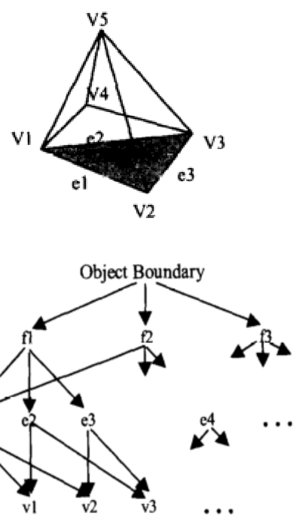

Fig 3: An example of boundary representation of a prism

Variational modeling allows a designer to use equations to model mechanical components analytically, while in feature representation approach, a part is built from a set of primitive building blocks with the guarantee that this set of building blocks are manufacturable.

B-rep represents geometry in terms of its boundaries and topological relations. For example, the B-rep of a prism is given in *Fig 3.* The transformation from one topology to another can be achieved using Euler operators. Since Euler operators are sound, the topological validity of the structure is guaranteed. The major limitation of B-rep is its inefficiency in performing geometric reasoning. Besides B-rep, CSG is another geometry modeling technique that was widely accepted by both the research community and industry. For example, the primitives given in *Fig 4* can be combined using set operations to form complex solids like that given in *Fig 5.*

In spite of its promising start, CSG modeling faces several inherent limitations. The most serious limitation, in our opinion, is the non-uniqueness of the CSG representations. This non-uniqueness of representations makes recognition of shapes from CSG representation extremely difficult. Hence, this tends to dissuade researchers from relying solely on CSG representations alone. In addition, CSG representation does not guarantee that the solid it models is always a valid object. It is possible in CSG representation to model an invalid solid.

Variational Modeling is gaining popularity because it allows the evaluation of competing alternatives. The concept of using variational geometry in computer-aided design started as early as 1981.

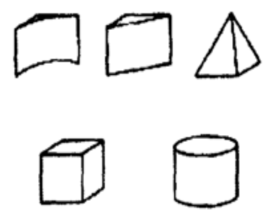

Fig 4: Some CGS Primitives

Instead of defining a geometric model with respect to a set of characteristics points in 3D space, dimensions are treated as constraints limiting the permissible locations of these points. For example, a rectangle with dimensions x1,x2,x3,x4 may have the following set of constraints on the dimensions: xi = x3, x2 = x4, x2 + x I = 5. A change in the constraint (e.g. the last constraint is changed to x1 = x2) may result in a new geometric shape, i.e. a square. Lin [9] in his thesis described the feasibility of using variational geometry to model geometric information. Light and Gossard [10] expanded upon his work to allow modification of geometric models through variational geometry.

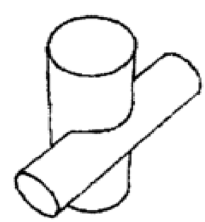

Fig 5: Complex Solid Example

3.2 Graphs

Graphs and trees are popular representations in the conceptual design stage. They have been used to model all aspects of a product-function, behavior, and structure.
Malmqvist demonstrates how graphs can be used to model the functions of structural systems in mechanics, electronics, hydraulics, e.g. hole punch, washing machine. Nodes of graphs are lumped elements which correspond to

the different physical properties (capacitance, transformers) and these nodes are connected by edges (bonds), e.g. force, velocity.
The power flow direction and causality of bonds are specified. Murthy and Addanki [11] manipulate a graph of models to modify a given prototype of some structural engineering system, e.g. the design of beams.

A model describes the behavior of the system under certain explicit assumptions. The models form the nodes in a graph and the edges represent sets of assumptions that must be added or relaxed to go between adjacent models. Graph/trees have also been used to model the physical representations of the design components and their layout.

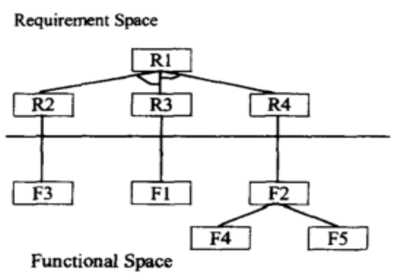

Fig 6: An example of a graph model

Besides modeling structural, behavioral and functional aspects of the product, graph and trees have also been used to model requirements and constraints. Kusiak and Szczerbicki [12] use tree models in the specification stage of conceptual design to represent the functions and requirements of mechanical systems, with an incidence matrix to represent the interaction between requirements and functions. *Fig 6* shows the requirement and functional tree for the design of a shaft coupling. An arc between the nodes of a tree represents a conjunction. A node without an arc represents a disjunction. One main advantage of using graphs to model different aspects of design is that graph theory is a developed field of study. By using the graph model, we are implicitly tapping into the rich resources of the many existing graph algorithms with well-founded theoretical bases. The drawback of using graph models is that they lack the concepts of classes and inheritance. Such concepts are useful in conceptual design.

3.2 Objects

An increasingly popular modeling representation is the object. An object is an entity that combines its data structure and its behavior into one. The characteristics of object representation are: abstraction (focus on what it does before deciding how to implement it), encapsulation (separating external aspects of an object which are accessible to other objects from the internal implementation details which are hidden from the other objects), polymorphism (do not consider how many implementations of the given operation exist) and inheritance (of both data structure and behavior which allows sharing without redundancy).*Fig 7* shows a component with two slots with its corresponding object representation given.

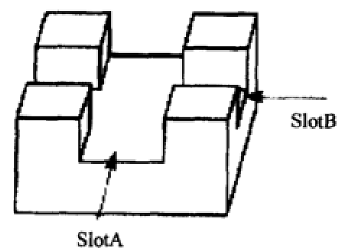

Fig 7 Component with two slots

Object-oriented techniques provide modeling flexibility needed for conceptual design. Physical elements of a design, its parameters and properties can be represented as objects and their attributes. Several objects can be combined to form an assembly. This ability to mix and combine different objects allows us to generate many design alternatives quickly.

4. Reasoning Techniques

The second difficulty in supporting conceptual design activity is the difficulty of generating and selecting appropriate means of mapping the user's requirements to some physical structures that can realize the given set of requirements. Many existing mechanical design systems derived this mapping based on a refinement approach.

The system starts with a rough design that is successively refined at each step. At each refinement stage, constraints that guide the design process are generated. Frequently, the constraints generated cannot be satisfied by existing prototypes in the library and modification of the prototypes is required.

However, such modification is impossible unless one is able to model the function, behavior, and the structure of the product and then apply suitable transformations from one plane of abstraction to another to arrive at candidate sets of solutions. Earlier in the paper, we introduced various ways of representing these models. Here, we focus on the transformation process.

Theoretically, there are three pairs of mappings to be considered in order to realize the transformation process. They are: function - structure, behavior structure, and

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function behavior mappings. Practically, it is hard to distinguish between the function and behavior of a product. For instance, in value engineering, there is no difference between function and behavior. Although some researchers[13][14] argue that knowledge of the function of the device is important as it allows focus on a particular subsystem, thus reducing the complexity of the model to be analyzed, other researchers[15-17] view function to mean the designer's intended purpose for the product and classify unintended uses for the product as behavior. Therefore, they concentrate on defining all the behaviors of the device, since one or more of these behaviors will represent the device function.

The reasoning techniques are, therefore, classified under the headings of realizing: function - structure, structure - function, behavior structure, or structure - behavior mappings. In addition, for practical reasons, it is helpful to know whether a particular reasoning technique requires large amounts of data (data driven) or whether it requires prior knowledge about the domain (knowledge driven). Knowing this fact can aid a designer/researcher in selecting the right reasoning technique for his/her chosen domain.

A method is deemed to be 'knowledge driven' if knowledge specific to the problem and the domain can be articulated and specified a ***priori*** before the method can be used as a reasoning technique. For example, using a rule-based system, we can reason about the functioning and problems of a switch from a set of principles about electricity or a set of cause-effect relationships. Thus, in 'knowledge driven' methods, knowledge is derived from a ***priori*** specified knowledge. In contrast, 'data driven' methods de-emphasize the use of general rules; they rely on a substantial base of data to perform inferencing. For example, in case-based reasoning systems, solutions to problems are stored in their original or slightly modified form. On addressing a new problem, the system retrieves a case it deems sufficiently similar and uses that case as a basis for solving the problem.

4.1 Neural networks

Artificial neural net models were first introduced in the hope of achieving human-like performance. Biological neurons transmit signals over neural pathways. Each neuron receives signals from other neurons through special connections called synapses. Some inputs tend to excite the neuron; others tend to inhibit it. When the cumulative effect exceeds a threshold, the neuron fires and a signal is sent to other neurons. The sum of all weighted inputs determines the degree of firing called the activation level. The input signal is further processed by an activation function to produce the output signal, which is transmitted along. A neural network is represented by a set of nodes and arrows. A node corresponds to a neuron, and an arrow corresponds to a connection between neurons. In general, neural networks are good for classification tasks and for performing associative memory retrieval. As a result, many neural networks applications in engineering design are geared towards either classifying the designs into families of design problems or to finding the nearest values for the design parameters.

4.2 Case-based reasoning

Much of design consists of re-design, in the adaptation of a previous design to a new context, or in the design iteration cycle. Case-based reasoning applies past experience stored in a computerized form towards solving problem in similar contexts. It involves three stages: the representation of cases, the matching and retrieval of similar cases, and the adaptation of the retrieved cases.

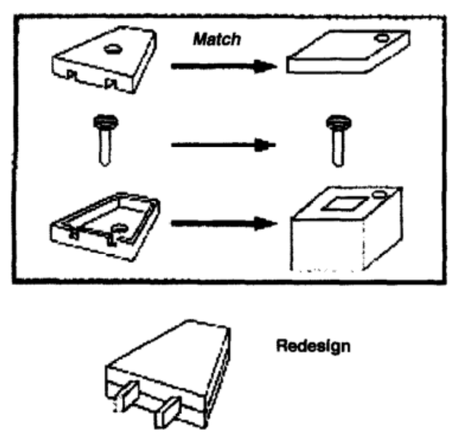

Fig 8: Three stages of case-based reasoning to design plans

Case-based reasoning techniques favor classes of domains where the number of primitive components are large, as is the number of possible interactions between them, because the computational cost of retrieval and adaptation would be less than generating the solution from primitive components.
On the other hand, case-based reasoning cases are stored over a long period of time and for that large number of cases, this may not be practical. Researchers like Mostow and Banares-Alcantara et dsO [18] are experimenting with applying case-based reasoning to design plans.

5. Knowledge-based reasoning techniques

Knowledge bases are used to capture procedural design knowledge as well as product or domain knowledge. We investigate types of reasoning techniques appropriate to interpretations of design descriptions: abductive, deductive, constraint-based, and non-monotonic reasoning.

5.1 Optimization

In conceptual design, optimization techniques have been used to derive an optimal trade-off between conflicting goals and criteria. Conceptual design problems can be viewed as deriving an optimal solution that satisfies some objective functions (such as cost, time to manufacture, reliability, etc.) within certain design constraints (such as maximum dimensions cannot exceed certain limits, maximum stress tolerance cannot exceed a given number). Thus, we can represent the design problem as follows.

Let the continuous variables be x and the discrete variables be y. The parameters which are normally specified as fixed values are represented by θ. The design goal (or goals) can be expressed as the objective function $F(x, y, \theta)$. This function is a scalar for a single criterion optimization, and a vector of functions for a multi-objective optimization.

5.2 Value engineering

Value Engineering is a process applied to achieve focused conceptual design goals. In Value Engineering, a designer begins with a description of the basic function of the design. The functions are then decomposed until each function can be mapped to a component that will accomplish it. By emphasizing different functions (for example, choosing to support the knee instead of the bottom) leads to different class of design *Fig 9.*

Fig 9: Two designs of a chair

5.3 Qualitative reasoning

Qualitative Reasoning (QR) is defined as the identification of feasible design spaces using symbols and intervals of continuous variables. This allows formal simplified representations about a domain that maintains enough resolution to distinguish and explain the important features of behavior while leaving out the irrelevant details. For example, we are interested in whether water in the pan is hot or cold rather than its exact numerical value. Qualitative reasoning is therefore particularly pertinent in early design phases when little quantitative information is available. The device- centered ontology proposed by De Kleer and Browndeals [17] with the problem of deriving function or behavior of a system given its structural descriptions and some initial conditions. All possible behaviors are determined by generate-and-test or constraint-satisfaction technique.

6. Conclusion

In this paper, we have performed a preliminary review of the tools and techniques that have been proposed to aid in the conceptual design of mechanical products.

In particular, we focus on the modeling and reasoning techniques underlying each proposed tools/methodology. The review results show that in spite of the great advances in both the modeling and reasoning techniques, much remains to be done. We hope this review will serve to motivate researchers to look closely at the underlying modeling and reasoning techniques for the conceptual design of mechanical products, and perhaps to derive an integrated framework for the next generation of computer-aided design tools.

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