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TOWARDS A THEORY FOR FUNCTIONAL REASONING IN DESIGN

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ABSTRACT

Engineering design can be considered a problem solving activity where a designer starts with functional descriptions of the problem (ie, what the intended product should do), and undergoes a reasoning process, co-evolving both the problem and its possible solutions, aimed at eventually producing a solution in terms of its realisable form (structural) descriptions. Reasoning about design problems and solutions in terms of their functionality, termed here as functional reasoning, is central to designing. Therefore, problem, solution, function and form are important concepts in design, and devising ways for supporting functional reasoning is important. Supports for functional reasoning should include supports for (i) representation and change of design problems and solutions, (ii) generation of problems that a given solution could solve, and (iii) generation of solutions to a given problem. As a prerequisite to supporting functional reasoning, an understanding of (i) the above concepts, and (ii) the processes for functional reasoning is required. How functional reasoning is done is largely dependent on (i) how the knowledge about functions, form and their relations are gathered represented, and (ii) how a design problem and its possible solutions are understood in terms of this knowledge of function and form, and are used in problem solving. All these could probably form part of a theory for functional reasoning. The feasibility and scope of such a theory would depend on whether we could find measurable criteria to define function, form, problems and solutions in the design context. This paper provides a survey of literature in design research to highlight the multiplicity of views about the above concepts, and examines the feasibility, scope, goals, possible approaches, and validation issues for producing a testable theory for functional reasoning.

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KEYWORDS

Engineering Design Theory, Functional Reasoning, Functional Synthesis, Design Automation, Function-Form Relationships in Design

1 INTRODUCTION

Engineering design can be considered a problem solving activity [1] where design problem and its solutions co-evolve. A designer starts with functional descriptions of the problem (ie, what the intended product should do), and undergoes a reasoning process aimed at eventually producing a solution in terms of its form (structural) descriptions from which the solution can be realised. Reasoning about design problems and solutions in terms of their functionality, termed here as functional reasoning, is central to designing. Therefore, problem, solution, function and form are important concepts in design, and devising ways for supporting functional reasoning is important. As a prerequisite to supporting functional reasoning, an understanding of (i) the above concepts, and (ii) the processes for functional reasoning is required. This article attempts to highlight the multiplicity of views about these issues, and examines the possibility, goals and possible approaches to produce a theory of *functional reasoning*. The next section provides a background to the present state of understanding of these issues; from this, the possible supports to, and as a pre-requisite to these, the goals and scope for a possible theory for functional reasoning are outlined in section three. Finally, the issue of validating any such theory is discussed in section four.

2 FUNCTION, FORM AND THEIR RELEVANCE IN DESIGN PROBLEM SOLVING

What is *function*? What is *form*? What are the *relations* between these two? How does this information affect design problem solving (ie, representation and evolution of design problems and solutions)? A first step to understand these is to look into the research, direct and indirect, involving function. In this section, some results and examples are used (which by no means is exhaustive) from areas of Design Theory and Qualitative Physics to make some observations about the state of understanding about these issues.

2.1 Results and Examples

Matousek [2] maintained that function is the *action required* by the design problem, such as electrical energy converted into mechanical power at a given torque and speed, or making a work-table reciprocate. Form, the structural description of the solution, includes *geometry, arrangement* and *material*; its determination is affected by the working principle, among other things such as cost, size, manufacturing, material and space considerations.

Hubka [3] proposes to use *process structure* and *function structure* to elaborate and solve design problems. For instance, let us take this problem statement: "A welding fixture is to be designed that is capable of bringing a workpiece into a desired position for welding, and to hold it in that position during work. A universally usable fixture is required for application to a wide range of tasks..."; the design problem is represented by a *process structure* which is a transformation between the *input* and *output situations* demanded by the problem (in this instance, from a situation where all workpieces are unwelded and unfastened, it must go to an output situation where all workpieces fastened and unwelded), and the function structure in terms of *verbs* (such as enable change in height, connect with the fixed frame, etc) enabling these processes to happen. Design solutions are represented, in conceptual design for instance, as schematic diagrams of abstract elements in action. Hubka [3] defines function as "..duty that the product must be capable of capturing, ie, the effects and actions, or the benefits or utility of the machine system. Can also be stated as functional purpose or aim." In another definition, he describes function "..as a general connection between input and output (analogous to a mathematical function) which is connected more with the act of functioning and the method of function performance." Note how widespread the scope of these definitions are. Form is defined as "..fundamental characteristic of each machine system that describes the geometry, proportions etc., of the items." Form determination, in his view, is affected by complicated interaction among other things "..between form and function.." In his opinion, various *principles* and *moderators* can be guiding factors in this process.

Pahl and Beitz [4] describe function on the basis of *inputs* and *outputs*, where inputs and outputs can be *materials, energy* or *signals*. Function is defined as "..the general I/O relationship of a system whose purpose it is to perform a task." Examples include "increase pressure", "transfer torque", "reduce speed" etc. A design problem is described in terms of an overall function. Design solutions, in conceptual design for instance, are represented as *solution principles*, which are partial structural descriptions in action. Similar is the case with Hubka's conceptual solutions, and it is noticeable that this description contains both functional and structural (or form) descriptions of the solution. Problem to solution transition in conceptual design is prescribed to be done, based on the *Morphological Approach* [5], in the following steps:

- ° Find the overall function of the problem
- ° Find sub-functions
- ° Find physical effects to each sub-function
- ° Find corresponding physical principles
- ° Combine these to produce solution principles for the overall function.
- ° Evaluate these principles to select the promising ones for detailing.

Similar steps are prescribed for the other design stages as well, to produce the more detailed forms of the solution. Guidelines form a central source of knowledge here for the development of form.

Roth [6] prescribes functions of various kinds. There are *cybernetical functions* (such as energy transformation, material storage, etc), *general physical function*, *function* with *physical effect*, and *function* with *effect-carrying element*. Note that these representations, of varying levels of coupling between function and form, provides a gradual transition from fairly abstract statements about the problem to less abstract ideas about the form of its solutions, functional representation acting as the common representation between the two.

In Pye's view [7], functional designs are those that are designed on "..measurable, quantifiable, testable criteria.." and excludes aesthetic / appearance / decoration / ornamentation and applied art aspects. In short, functional designs are "..things designed for use and not solely for contemplation such as pictures and statues." To him, designer's "..freedom in choosing the shape is an imposed freedom...the limitations arise only in small parts from the physical nature of the world, but in a very large measure from considerations of economy and style. Both are matters purely of choice." He, however, maintains a distinction between the purpose of a device and the result of a device being used. In his words, "the purposes of things are purposes of men, and change according to who entertains them. The fact that every device when used produces concrete, measurable, objective results is the only basis for the theory of design." He takes the example of a cargo liner whose purpose to the owner is to make money, to the captain is to ply seas, etc; the result however is "cargo transported overseas".

French [8] proposes functions of varying levels of abstraction, as is indicated in his various examples:

- Carrying sap; extracting water / mineral from soil; transmitting signals;
- Securing peg to line; disconnecting from line when required;
- Preventing bursting; preventing leaking;
- Withstand shear.

Note that "preventing bursting" is a function at a higher causal level of abstraction than "withstand shear".

In Chakrabarti & Bligh [9], function is viewed as a *transformation* between a set of (time-varying) *input characteristics* and a set of (time-varying) *output characteristics*. A design problem is then expressed in terms of the required function, such as the production of two output motions having defined directions, magnitudes and positions at specific time-instants from an input force of specified characteristics. Solution concepts are represented as combinations of functionally described simpler solution-elements. Problem-to-solution-concept conversion is facilitated by constrained search, leading to the generation of schematic solutions (ie, functionally represented solutions) to mechanical transmission problems describable in terms of upto multiple inputs and outputs.

Rinderle and his colleagues [10, 11] have been looking into form-function relations at the preliminary stages of design. They take, as functional requirements, parameters that describe performance (eg, positioning the paper, positioning the printhead, and printing, in a printer; spring stiffness k, or maximum spring spring deflection Δ_{max}]. Form of a design is described in terms of design parameters, examples of which include parameters describing a round way, a left bearing, or the weight w of a simple coil spring. Form-function relations in their view are many-to-many and complex; an example of such a relation would be: $w \propto k.\Delta_{max}^2$. Function is not isomorphic to form (one-to-one correspondence) in mechanical design (note that they take function and form, respectively, as synonymous to function and form) Form-function relations, in their view, can be identified from physical principles. Essentially they talk about parameters at various levels of abstraction. High-level parameters can be positioning speed, weight, etc; medium-level parameters include stress, aspect-ratio, current-density, etc; low-level parameters could be, among others, length, diameter and materials. The words function and behaviour, in their view, are synonymous. A device is represented in terms of a set of parameters (both behavioural as well as form parameters), and constraints among these parameters.

Suh [12] maintains that function is something "we want to achieve" in design (say, to go to the moon), and a physical solution is "how we want to achieve it" (eg, physical embodiments of rockets and space capsules). Functional requirements are described in terms of a set of *FR* (functional requirements) (such as: for birds, flying, vertical take-off, power for propulsion, etc), and these are satisfied by a set of design parameters DPs of the structure (in this case the wing structure of the bird). In Suh's view, reduction of the cost of a material, or maintenance of a material property such as toughness while the material cost is reduced are considered functional requirements. He does not believe that there is any method of function to form transition; however, his principles in his view decide whether or not a design, described in terms of a set of DP (design parameters), is a good one, against a set of FRs.

Ullman [13], in his O-RE-O model of mechanical design, describes three kinds of functions. *Operational function* is the transformation of *objects* or *relations* during an *operational step* or other life cycle phase, or constant object and relations *state* with differing operating conditions. *Relational functions* are relations between objects enabling operational function of the product. *Object behaviour* deals with the object attributes for *energy* or *information states*. Not much is said about the exact nature of form-function relations.
Yoshikawa [14] proposes functions as "a set of a sub-class of abstract concepts" in his General Design Theory. Function of a pencil, for instance, is that letters are written on papers with it. This function manifests itself as a result of the activation of a number of *attributes* of the *entities* constituting the design (eg, the total form, tip form, structure, length and section for writing letters). He describes *visible function* as a behaviour exhibited under a given circumstance; the total of the behaviours the design could potentially exhibit under various possible circumstances are called its *latent functions*. Problem-to-solution transition in real-world situations is seen as a sequence of patching operations on a promising provisional solution, until the whole problem specification is met. How exactly these operations have to be done is not clear, although he presumes some form of search might be involved.

Research into Qualitative Reasoning [15] has given rise to a host of research efforts into reasoning about behaviour of devices, and provides some treatment of functions. Function, behaviour and structure (form) are treated as distinct elements. Kuipers [16], for instance, adopts the following definitions:

<u>Structural Description:</u> Individual variables that characterise the system, and their interactions, derived from the components and physical connections of the device.

<u>Behavioural Description:</u> Potential behaviours of the system in terms of a network of qualitatively distinct states.

<u>Functional Description:</u> Description that reveals the purpose of a structural component or connection in providing the behaviour of the system.

To clarify the distinction between behaviour and function, Kuipers takes the case of a steam-release valve whose function, in his view, is to prevent an explosion, while its behaviour is simply that the pressure remains below a certain limit. Form to behaviour transition takes place by first forming the qualitative relations among the variables describing the structures, then propagating the various possible values of these variables through these relations, and finally identifying the *qualitatively distinct states* which these variables assume.

In Sembugamoorthy & Chandrasekaran's approach [17], function is the *intended response* of a device to *external* or *internal stimuli*. For instance, the function of a *Buzzer* is to make a buzzing sound, when signalled. Behaviour on the other hand is a description of *how* such a response is produced, described by a causal chain of states, where a state is an assertion about the state of some objects in the world. They maintain that the distinction between function and behaviour is only a matter of relative levels of abstraction, and therefore should be used interchangeably.

2.2 Observations

From the above literature survey, the following observations are made.

- There are multiple meanings and representations of function, ranging from purposes through effects to material properties, and even cost and spatial constraints.
- There are multiple representations of form.
- There are multiple meanings and representations of design problems and solutions; some of these overlap.

• These views are goal- specific, ie, serve specific purposes in design.
• Design solutions are represented in various blends of functional and structural (form) descriptions.
• All these can be at varying levels of abstraction.
• Function and behaviour are interchangeably used.
• There are different views about form-function relations. They rely on the existing knowledge which are available at various degrees of formalism (including design guidelines).
• There are different ways of problem-to-solution transition. Problems and solutions cannot necessarily be described in terms of functions and form respectively.

3 SUPPORTING FUNCTIONAL REASONING IN DESIGN

By functional reasoning is meant here reasoning about designs from the functional point of view. Supporting functional reasoning should include supports for:

-Representation and change of design problems and solutions;
-Generation of problems that a given solution could solve;
-Generation of solutions to a given problem.

A prerequisite to these is an understanding of the processes in functional reasoning. How functional reasoning is done is largely dependent on how the knowledge about functions, forms and their relations were gathered at the first place, and how they are represented, both internally and externally, by the designer. Finally, we need to know how a design problem, and possible solutions, are understood in terms of this knowledge of function and form, and are used for problem solving. All these could probably form a theory for problem solving from the functional point of view.

However, before the goals of research into functional reasoning could be laid out, the scope of such a theory for functional reasoning needs to be clarified. We need to clarify what we would, and perhaps more importantly, what we would *not,* consider as function and form. My view is that we take Pye's view, ie, we do not consider aesthetic / appearance / decoration / ornamentation and applied art aspects; these cannot be objectively quantified, measured and tested. Cost should also be left out, as in my view, though important, it does not constitute part of the function of the products of design. The proposal here is to keep the scope of investigation limited to function as intended and actual responses of design to external or internal stimuli, where the stimuli and responses are objective, measurable and testable, thereby providing a common means of agreement and perhaps a means for validation for any such theory. Form should also be describable in terms of observable attributes. The distinction between function and form is proposed to be such that while a form should be expressible in terms of an essentially static description of a connected set of physical or conceptual entities, function would be described in terms of changes in situations of these entities.

The prime goals of a theory for functional reasoning in design would be to provide mechanisms of:

-How the knowledge about function and form is understood or created;
-How this knowledge is represented;
-How design problems and solutions are represented in terms of this knowledge;
-How problems solvable by a solution, or solutions to a problem are produced.

Function and form, and design problems and solutions should be representable, and mechanisms for the above processes provided, at multiple levels of abstraction.

These theories would probably have a knowledge-based nature, having constructs and mechanisms with formalisms able to handle imprecise and incomplete knowledge.

Validation of any such theory eventually has to be in terms of applications in specific domains. Given the size of this task and the possibility of solving this in a reasonable time of research, it is reasonable to start from specific domains of applications, with the eventual aim of blending them into some common theory.

4 VALIDATION

Design rationale constitutes a chronological account of the outcomes, both intermediate and eventual, of the methods employed by designers during design. Design rationale capture systems [18] therefore are important in capturing / observing / explicating (some of) these outcomes. However, it cannot be overemphasized that they do not, and cannot, capture the methods that produce these various product (-related) information. Theories have to be produced for these methods. Rationales might be useful in testing these theories for how well these methods are understood, and whether there is scope for improving them. The characteristics of the rationale which seem to be of prime importance are (i) the outcomes, and (ii) their temporal ordering. Depending on the level of granularity required, the possible theories should be able to explain, along with the eventual outcomes, various numbers of intermediate outcomes as well. Validation should be done using statistical evidences in order to avoid effects on results arising from individuals' influences, and caution exercised in normalising the backgrounds of the subjects under observation, and the context under which they are to operate. Research into how these might be done, and a framework for capturing rationale at the EDC, Cambridge is in progress [19, 20].

5 SUMMARY AND CONCLUSIONS

- Function, form, and form-function evolution issues are important in design problem solving.
- Multiple views about function, form, and form-function relations is available.
- Multiple views about problem, solution, and problem-to-solution transition is available.
- Functional reasoning supports should include supporting representation and change of problems and solutions in terms of function and form, and generation of solutions from problems, and vice-versa, over the design process.
- Supporting functional reasoning would require understanding, possibly in terms of a theory for functional reasoning, about (1) how function and form are understood or created, (2) how these are used to represent design problems and solutions, and (3) how one is generated from the other.
- A definition of function and form, describing the scope of such a theory, is required. Function is proposed to be a relation (or relations) between at least two situations, describing the measurable responses of a device to measurable external stimuli. Aesthetic and cost aspects are not included in functions. Form is proposed to be one or several structural descriptions of a solution, and could be described by one or a set of situations.
- A theory for functional reasoning should provide representation and manipulation of design problems and solutions, in terms of function and form, at multiple levels of abstraction. They probably would be knowledge-based, and eventually domain-independent.
- Design rationale systems, though not directly relevant in identifying the methods for functional reasoning, could be useful in the identification of constructs for, and testing of, such theories.

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