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A NEW APPROACH TO MODELING OF THE DESIGN PROCESSES

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Abstract

The paper presents a new model of the design process. First the distinction is made between 'soft' and 'hard' system models. Then the design process is conceptually decomposed into the designing system, the system of design operations, and the model of designed object. The designing system performs design operations. The design operations determine features of the designed object. The design object model is being constructed of features in course of the designing. A basic invariant structure of the design process is identified, which is common to all engineering design processes.

Keywords: Design models, design process, design operations, features.

1. Introduction to theories and models in engineering design

Technical sciences are characterized by a systematized knowledge based upon laws and principles, as well as by methods of application of these laws and principles in order to anticipate the behavior of physical objects. Each domain of technique and technology has elaborated its own methods of predicting the operation of technical systems, so as to enable making correct decisions. For instance, engineering fluid mechanics utilizes the notion of control volume, the principles of mass, energy and momentum conservation, the law of entropy, as well as physical properties of the fluid, in order to anticipate performance characteristics of the fluid-flow machines or lift and drag forces of an airplane wing.

The knowledge of specific classes of machines and engineering systems, gathered in course of years of experience and based on physical principles has provided, in principle, a sufficient ground for the design and manufacturing of these machines and, to some extent, for their optimisation. So we have theory of gears, turbomachines, mechanisms, and so on. We have also methods of designing and investigating for them. The validity of those theories and methods is limited to a specific class of machines.

A scientific theory aims at an explanation of the causes of phenomena appearing in the nature or in the society. It does not concern exactly a real system but an idealised model of the system, which is abstracted from the reality. A theory contains statements and theorems concerning the behaviour of this system model. Thus one can expect that investigations concerning the generation of new artifacts in the human mind will lead to a theory of conceptual design. This theory could constitute a basis for a methodology that would improve the design process.

It is essential to distinguish the results of investigation and/or observations of a real system from the explanation why those data or observations are such and not other ones. Data on a real system and different forms of their description do not constitute a theory. Descriptions can establish a base to practising the designing but do not serve the theoretical foundation. A theory must be formulated on a higher level of abstraction than facts, which are explained by the theory. Theories result from the explanation of the hidden cause of the facts being observed. Generally, a theory is an inductive explanation of the knowledge acquired by observation, experiments and reflections, and is not a consequence of deduction based on other statements and theorems.

One should also distinguish explanatory theories from various kinds of prescriptions, claims, recommendations, etc. An explanatory theory defines the system and explains the reasons of its behaviour. Conversely, a prescription recommends a determined behaviour of the system or any of its parts. According to Tribus [1], a theory is constructed, not discovered. A general theory should have a broad field of applicability without necessity of becoming more and more complicated when new applications come into consideration. A good theory determines the field in which it holds. For example, hydrostatics is valid for the state of fluid equilibrium, and the state is defined solely by means of hydrostatics. Consequently, because the design theory concern is the design process then the design process should be defined on the ground of the design theory.

According to Popper [2] good scientific theory must be verifiable. A "theory" for which no test can be framed which could contradict the theory is not a scientific theory. As long as a correct verification of a theory have not been performed, the validity of the theory is questionable. The test should not have the purpose to confirm the theory but to contradict it. Only one contradiction falsifies the theory, no matter how many facts seem to confirm it.

Popper's postulate of the theory verifiability is too strong for empirical theories, especially for inhomogeneous systems within which people are subjects. Lakatos [3] argues, that every reasonable empirical theory is based on some, supporting it, empirical evidences, however - sooner or later - such theory meets facts that, at least apparently, do not match it. If a well-grounded empirical theory, which has been proved in numerous applications fails in an experiment it only means that the model built by means of the theory is not adequate. If it appeared impossible to build an adequate model, it would mean that the theory was inadequate for this case; thus it may be completed or extended but not necessarily rejected. Physicists know well that there are no theories explaining everything! The most important merit of the theory, Lakatos says, is its potential to formulate research programs, which are aimed at transformation and completion of scientific knowledge. Thus some imperfection of a theory does not disqualify it, it may be considered as a positive feature, provided it is an incentive to further research. This approach is encouraging for researchers attempting to set up theoretical backgrounds for such an important human activity as engineering design.

If an empirically proved theory nor can be falsified neither validated by further experiments, then what have experiments to do with the theory validity? The answer is that experiments are aimed at determining the range of the theory applicability.

Above mentioned arguments can be transposed to the issue of design process modeling. It is crucial to be aware that the designing systems are not 'hard systems' but 'soft systems' [4]. At least as long as we consider the designing as a genuine human activity. The fundamental difference consists in validation of the models. Models of soft systems can not and need not be validated in the same way as models of hard (i.e. physical) systems. The objective of the soft approach is not to represent a part of real world but to be helpful in understanding what and why a particular inquiry and action should be taken. In soft systems methodology developed by Checkland models do not have to map a real-world system; they are only relevant to debate about the real world and are used in a cycling learning process [4]. What we can rationally do is not to tend to make hard models for the soft systems but to set up inquiry models relevant to real situations that will help us to learn of and to tackle with the problem in question. Soft models should be just able to defend their relevance to the problem situation. This forms a common basis for evaluation descriptive, prescriptive and even computer-based models of the design processes.

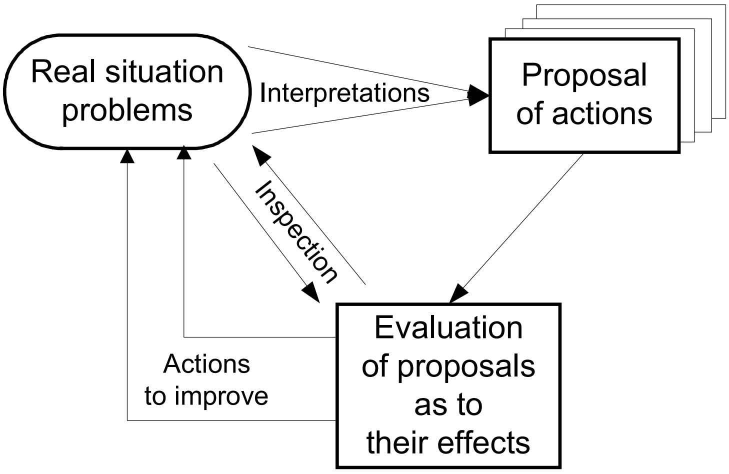

Fig. 1. A soft approach to the design methodology.

Figure 1 illustrates the whole cycle. After identification of a problem situation, for which methods of inquiry have been developed, a number of purposeful activities are put forward. Then people involved into the problem situation debate about actions to be taken to improve the problem situation. The system depicted in Fig. 1 is the learning system. It produces actions to improve the real problem situation. It is especially relevant for concurrent engineering because it makes possible to take into account different points of view.

2. Operational approach to the design process modeling

Thousands of papers and many books recommend various design methods and techniques as well as offer various structured approaches to the design process. Duffy [5] noted that in every hour of the working day one book and 11 articles are published with 'design' as keywords. He asks the rhetorical question: "…do we apply what we have learned to design the design process?". In fact, implementation of outcomes of the research on the design methodology has not been satisfactory as it is emphasized in numerous papers. It seems that no one knows panacea to this trouble, two symptoms are, however, salient. One is that procedural prescriptions are not flexible enough to fit real design process solving on the whole. Second is that descriptive and cognitive models can not be generalized so that to model wider class of design processes. It does not mean that these approaches do not make sense. In view of considerations of sec.1 these models do contribute to our knowledge. It is only the validity of these models that is limited and we should not expect to get more than they can offer.

For facilitating real designing there is rather a need to identify models of partial design activities than to prescribe the design process in general. Identification of generic activities which occur repeatedly should provide a framework for understanding similarities and differences between various design processes. These activities must be capable to form flexible structures to represent any design process that human designers carry out. Thus, instead of suggesting any top-down prescribed procedure for design we should look for invariant constituents of the design process and leave to the designer's experience how to built the problem solution process by means of these 'bricks'. Smithers compared the design process to puzzle design and to puzzle solving, simultaneously [6]. The analogy is very up to the point. The basic puzzle elements can be identified, I hope; we only can not (and must not) strictly prescribe the way designers use it in solving various design problems. Otherwise designer's creativity and individual way of problem solving would be seriously constrained.

Comprehensive investigations of real design processes and interviews with professional designers have shown that the designers see designing as a process of building a model of the designed object. Although the process is not linear it consists in providing more and more information about the object. When the body of the information is complete, i.e. satisfies design specification and manufacturing requirements then the design is finished.

Every design system can be decomposed into three sub-systems: the design problem to be solved (operand), the design process (operations), and the designing system (operator). Bearing this in mind the author devised a model of the design system [7,8] (Fig. 2).

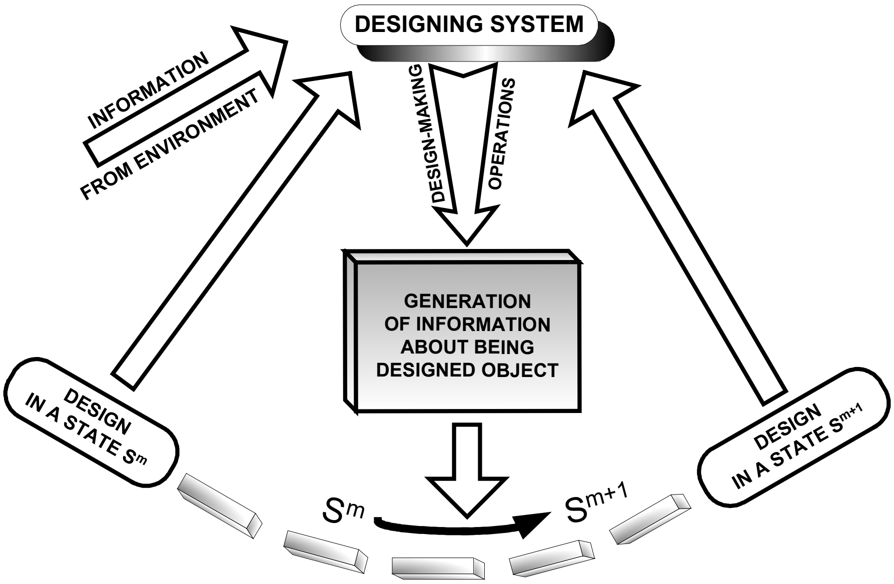

Fig. 2. Design generation in the design system.

The designed object is interpreted as a multi-layered, hierarchical model of a real object that does not exist yet is bound to be manufactured. Hence, it is an 'a priori' model established before the real object comes into existence [9]. Consequently, designing can be perceived as the construction of the 'a priori' model by features. A complete design comprises all features that are necessary to manufacture artifacts capable to perform prescribed functions within real-word constraints.

The design process is envisaged as a sequence of design operations that instantiate the designed object features. The concept of features is crucial for this model, see section 4. Assume that the design is complete when M of its features have been determined (instantiated). In a state S^m of the designed object m of M its features are identified, while (M-m) features have not yet been decided upon. The designer makes analysis of the current problem situation and takes a decision about next design operation. It attributes one more feature to the designed object, making it more complete. The object is in the state S^{m+1} now; then the cycle is repeated. Note, that now the problem situation has changed.

In an actual problem situation the designer have a possibility to choose a number of operations, each leading to instantiation of a different feature. For rational choice of the next design operation the experienced designer makes analysis of the global problem situation A^m, and decides which one of the features still to be determined will be the subject of the subsequent design operation. This is depicted in Fig.3 left. The distinguishing of the feature choice phase as a prerequisite of the subsequent operation is essential, as only trivial design tasks have the order of feature determination established in advance. Executing a design making operation is a tactical tasks, whereas setting up the sequence of operations is a strategic one.

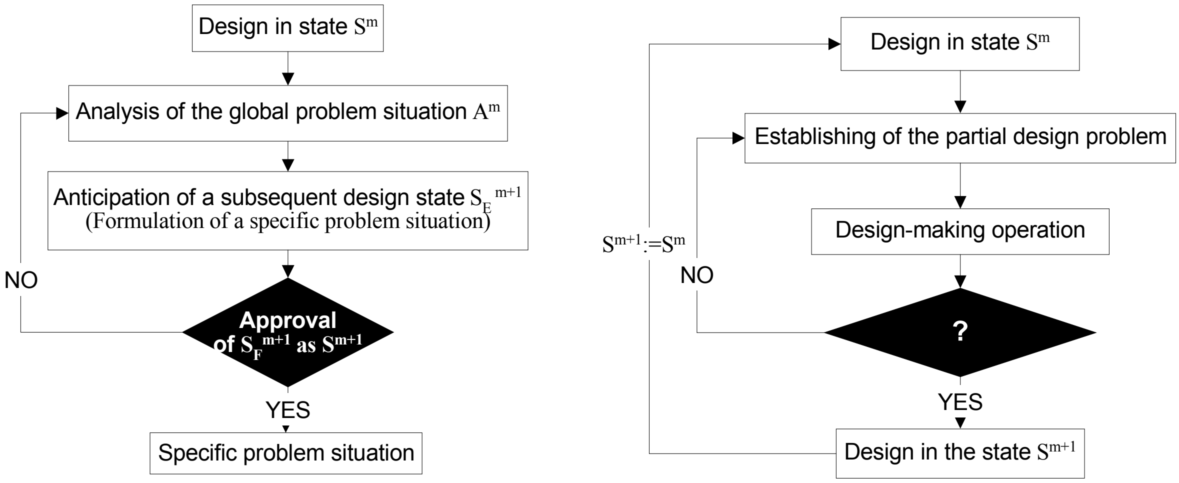

Fig. 3. Choice of a specific sub-problem (left), and basic structure of the design process (right).

Choice of a partial task and proceeding a design making operation form the cycle which represents basic elementary structure of the design problem process solving (Fig. 3 right). The structure depends neither on the kind of the task nor on the feature currently being determined. Neither does it depend on design advancement. It is object independent and invariant in course of the designing, hence it is a very useful notion while considering design processes. The design process can be represented as a sequence of the basic structures. If the completed design is supposed to contain M features, the basic structure must be applied minimum M times, but most often more since not all of the operations will be successful.

The design-making operations mean a purposeful actions of the designer (more precisely: of the designing system) that result in instantiation of the designed object features (Fig. 4). The complexity of the operation may vary considerably depending on the kind of the feature and actual problem situation. The intention of determining a chosen feature creates a specific problem situation. The designer is supposed to create a number of tentative solutions and to choose a feasible one, possibly the best. The design supplemented by a new feature may be accepted or not. In case the decision is positive, the new state is documented and the design passes on to the subsequent, more advanced state, S^{m+1}. If the new design state is not satisfactory, the designer may repeat the partial task or may formulate another partial task, that is another feature would be determined first.

The decisive element to acknowledge the result of a design-making operation is that a resulting feature must not violate constraints and has to ensure compatibility with the requirements. Not only internal compatibility of the feature, i.e. within the designed object, should be checked but also external ones, because a feature, even if it is placed inside the object, may influence it external attributes. In many cases, such a verification is possible only after a number of subsequent design operations is made. The situation is particularly difficult when relationships between features are nonlinear or implicit or vague. This brings about a substantial difficulty for the design process as a negative result of the verification invalidates results of a certain number of earlier operations and the designer must repeat them. In engineering design iterations should be avoided since they add to time and cost of the design process. Effective methods have currently been proposed to minimize iterations in scheduling design tasks [10].

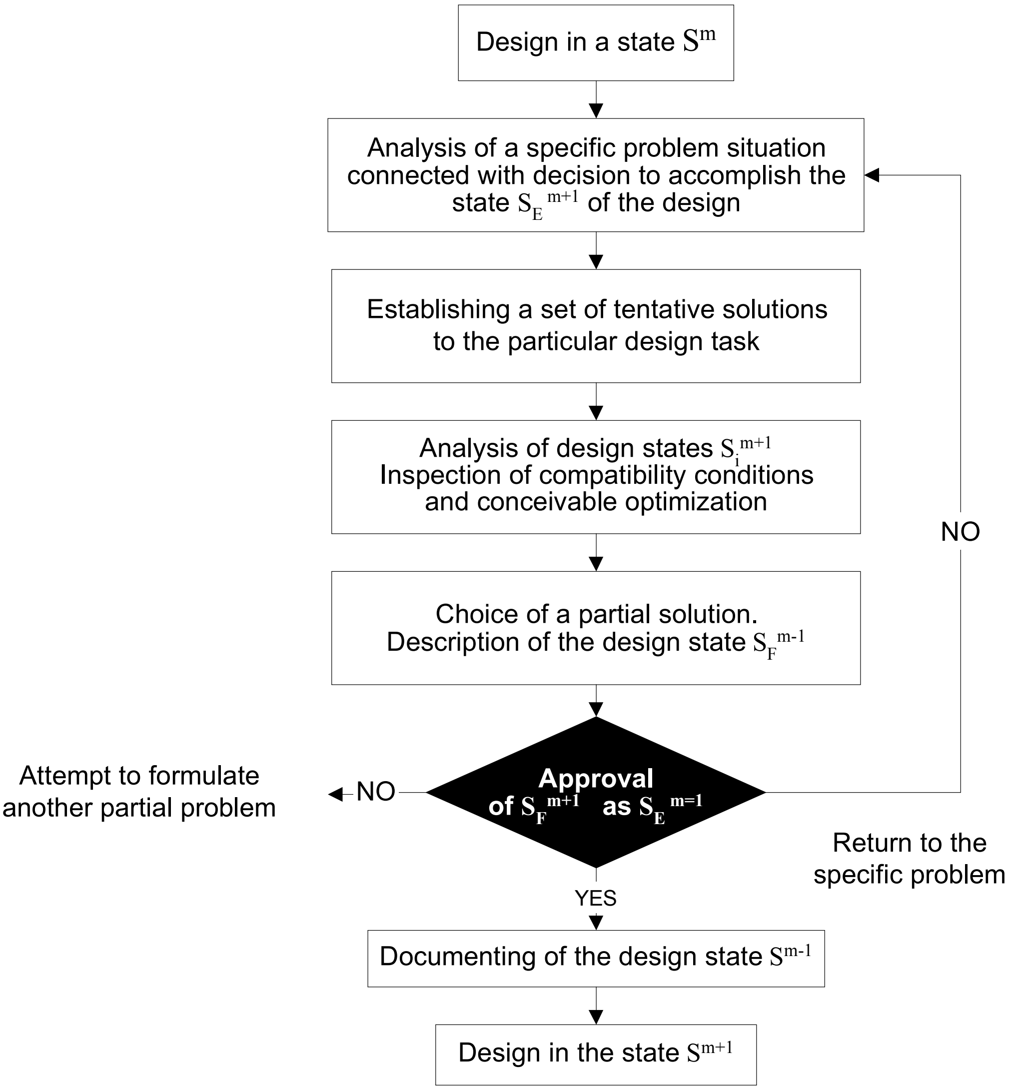

Fig. 4. Design-making operation.

The operational model, which has been shortly presented here bears an inhomogeneous structure; it compounds descriptive and prescriptive approaches. Elementary design operation is, in principle, prescribed; its structure is, however, supported by real design observations. The coordination of the operations during design is, on the contrary, left to the designer. The suggested model leaves room for investigation of how the designers ‘construct’ the designed object by means of basic operations. Statistically justified descriptions may then result in well grounded prescriptions for a class of problems and for a class of designers.

3. Abduction as one of the fundamental processes in designing

Gero [11] specified eight fundamental processes in designing: formulation, synthesis, analysis, evaluation, documentation, and three types of reformulation. Tomiyama [12], referring to his experimental investigation of design processes, formulated a ‘unit design cycle’, which consists of five subprocesses: awareness of the problem, suggestion, development, evaluation, and conclusion. His cognitive process model has two levels: the object level, where the designer thinks about the designed object, and the action level, where the designer thinks about how to proceed with his/her design, that is, what s/he should do next. The action level knowledge is general and applicable to any design. The designer seems to perform his/her design mutually using these two types of thinking.

Despite of some differences in terminology and ways of representation, the similarity between Gero's, Tomiyama's and Rohatyński's models is striking. Since these models were derived from different starting positions and by means of independent and different reasoning therefore credibility of the basic elementary (or invariant) design operation is high. Besides, there are also other enunciations supported this concept more or less distinctly.

From the logical point of view reasoning in design consists of deduction, induction and abduction. The latter term, although not new [13] has attracted attention of design researches not long ago. Peirce's abductive reasoning can be explained by comparing the following examples:

Example of inductive reasoning: Observation: "These gears are produced by X-company".

Assessment: "These gears are very good".

Conclusion: "All gears produced by X-company are very good".

Example of abductive reasoning: Observation: "All gears from X-company are very good".

Assessment: "These gears are very good".

Conclusion: "These gears are produced by X-company".

So abduction is opposite to induction. The result of abductive reasoning, 'conclusion', is rather a guess or hypothesis, than statement. Abduction is defined by Peirce as the process of forming an explanatory hypothesis from an observation requiring explanation. He describes abduction as a capacity of guessing right. Although this process is not algorithmic, it consists in a logical inference. The explanatory hypothesis is supposed to account for some facts. These are hypotheses that can explain and predict.

Besides being explanatory, Peirce mentions two more conditions to be fulfilled by abductive hypotheses: they should be capable of experimental verification, and they should be economic. A hypothesis should be experimentally verifiable, since otherwise it cannot be evaluated inductively. Economic factors include the cost of verifying the hypothesis, its intrinsic value, and its effect upon other projects. Economic factors should be taken into account when choosing the best explanation among the logically possible ones. Induction is identified by Peirce as the process of testing a hypothesis against reality through selected predictions, e.g. experiments.

The notion of abduction applies in problem solving, in artificial intelligence, knowledge-based design systems, and engineering design itself [14,15,16]. The relevance of Peirce's perspective to the design process is evident. It fits well in design-making operation depicted in Fig. 4.

Peirce clearly separates hypothesis generation from hypothesis evaluation. In practice, for creative design operations, the designer is interested in such creative hypotheses that have great plausibility and value. Generating low value and infeasible explanatory hypothesis would mean lost time and resources, hence it would not be clever. We need plausible explanatory hypothesis, relevant to the current problem. Yet pre-screening hypotheses to remove those that are implausible or irrelevant introduces a hierarchy in the two-stage generation-evaluation process. Furthermore, the prescreening needs mutual comparison between generated hypotheses or, alternatively, evaluation of the hypotheses against a common metric. It is not efficient procedure. Experimental investigation of the designer's behavior seem to show that they often implicitly use criticism at the hypotheses generation, and that they implicitly generate alternative hypotheses during evaluation. The more experienced designer the more coupled and efficient is the whole process. Thus in a good design process hypothesis generation and hypothesis evaluation can not be neatly separated, otherwise the process will not be streamlined. This conclusion brings about a new challenge for design teaching and methodology.

4. Features and design by features

For mechanical design defining geometry of the designed object is crucial since the geometry complemented by material properties, fits and tolerances, and surface properties determines internal and external properties of the designed object. There is a vast literature devoted to features and their implementation in manufacturing, design and elsewhere. So I only quote two pioneering authors [17, 18], and two latter ones [19, 20].

From among many ways of geometry representation in computer systems, features are most suitable for recording both syntax and semantics of the product geometry. On general it can be said that a feature is an abstraction of low-level design information to a high-level modelling primitive which encodes engineering significance of the primary property attributes. Thus, representation by features is especially promising tool for product geometry representation in the CAD/CAM environment.

There is sufficient evidence that experienced designers do not think by means of lines, circles, arches and so on. Conversely, they merge intended function or property with a geometric shape, which may be a part of a more complex element or the element itself. Thus viewing the design as construction by features is legitimated.

Features, however, are viewpoint dependent. One (e.g. designer, manufacturer, operator, etc) can have multiple feature models for a part or assembly. This arbitrariness in interpretation of features is a weakness of the concept but, on the other hand, it agrees well with the way engineers reason about the designed object. It also makes the concept of features very useful in concurrent engineering and design for life.

Although most of the research to date has been on geometric features for design and manufacturing, the concept is not limited to this application. For the design process model proposed in this paper it is useful to generalize the classical definition that a feature is 'an entity with both form and function'[18] to 'a feature is a relationship among a set of elements of a design'.

The designed object can be represented in different levels of abstraction and various levels of detailness [21, 22]. The three basic levels of representations are: functional, of physical processes, and material form. The most popular design operation is 'function – to – form', where physical process is skipped or considered only implicitly. Analogical to function-to-form operations one can use 'function-to-physical process' features and 'physical process-to-material shape' features.

In the creative design it is necessary to consider various parts of the designed object in different abstraction levels and different detailness. The granulation of the design process by the concept of design-making operations and visualization of the designed object as a composition of - more or less abstract – features naturally extends the matter of using manufacturing features in design to other types of design and is consistent with the operational model presented in this paper. The design process is sometimes compared to puzzle solving [6] or to wandering in a maze [23]. These models may be regarded as simplifications of the model presented here because they do not explicitly relate design operations with 'producing' the designed object model. Furthermore, such models are inherently two-dimensional whereas the operational model allows for different abstraction levels in the object modelling, thus adding the third, abstraction-concretisation axis of the design process route.

5. SUMMARY

There are several points which this paper has attempted to convey. The first of these is that design systems fall into category of soft systems. Theories and models of soft systems and hard systems are different. They can not and need not be validated in the same way.

The second important point is the operational one – systemic model of the design system, which encompasses three subsystems: the system that performs design operations, the system of design operations, and the systemic model of the designed artifact. The design is generated by means of the so-called design-making operations. Each operation adds one feature to the being designed object. Consequently, the design process is interpreted as constructing the design object of features. On this ground a basic elementary structure of the design process is identified, which is invariant and common to all engineering design processes.

Third, the well known notion of features is adapted in the proposed approach. Features are generic shapes with which engineers associate certain attributes and knowledge useful in reasoning about the designed product. Since it has been proved that designers think by means of features, then the designed object model is envisaged as a hierarchical, multi-layered system of features.

The fourth point is the interpretation of design process as modeling of designed object. The designer uses various partial models of different abstraction and detailness. Some of these models are based on well known real elements, others are hypothetical. They are called 'a posteriori' and 'a priori' models, respectively. This distinction is very important for understanding one of the most salient feature of creative design: in fact, the design documentation represents an a priori model.

To sum up, a new consistent– although by no means complete – model of the design process is proposed, which can be useful in further research on engineering design.

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