METHODS ALLOCATED TO DESIGN STAGES

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Abstract

Engineering design takes place within a societal culture, a company. Designing involves finding the nature of the problem and what makes a solution acceptable, and then generates a solution. Designing is ended when the manufacturing and/or implementation instructions are completed. Designing can proceed either by abstracting, investigating and re-concretizing from an existing solution, or by treating the problem as novel.

The development stages of designing have been classified into clarif ying the task, conceptualizing, embodying, and detailing. These stages have been expanded and brought into a logical sequence, but theory-based procedures must be adapted to the particular problem situation,

Many methods have been proposed to help with parts of designing. Several published methods are named, and allocated to those design stages where they can be of benefit. Some of these methods have only recently been introduced under the title of "industry best practices."

For best effect, methods should be one of the subjects of teaching in engineering curricula. Methods, reasonably and well applied, can enhance creativity.

Introduction

Engineering design takes place within a societal culture, and especially within a company. Its main purpose is to generate the details that should be manufactured, assembled, tested, and delivered in the form of a product, or providing instructions for implementing a process, to satisfy a perceived need. Such a process usually needs some (technical) products to help in its implementation -- and they have to be selected and/or designed. Designing involves generating an agreed statement about the nature of the problem, and the performance (values) that would make a solution acceptable. Designing then proceeds to generate such a solution in progressive stages, with iteration (go back, review, modify previous steps and their results) and recursive decomposition into smaller problems, which are themselves regarded as design problems[1].

Designing is normally considered to be ended when the manufacturing and/or implementation instructions for a solution are completed. A decision can then be made, usually by management, whether making or implementing should actually take place. The recent trend towards re-introducing considerations about simultaneous development of the product and its manufacturing methods, under the catch-phrase of concurrent engineering, does not invalidate this description.

During designing, all life processes that the product will pass through, and their operators must be considered, and their needs fulfilled. The product must withstand all loads and conditions imposed on it during the life processes, i.e. whilst it is being made, assembled, tested, packaged, shipped, installed, used, and disposed of. The effects of the operators (humans, technical systems (tools), information, management, and the immediate environment) on the product must be considered, and they must normally also be protected from danger.

Designing can be divided into *re-designing*, where a prior product exists, and ***novel designing*** without

precedents, a minority of cases. Re-designing proceeds by abstracting from an existing solution, modifying, and re-concretizing.

By convention, the development stages and tasks of designing have been classified into four main steps[2,3]. *Clarifying the task* leads to a design specification. This document (whether formal or informal) records the requirements and, where applicable, their acceptable ranges of values for the product to be designed. It provides the target set of properties that should be fulfilled. *Conceptualizing uses* abstract models of the system to be designed, to generate a framework and outline of the product and its ways of functioning and behaving. ***Embodying*** places material where needed around the outline, as a preliminary and/or dimensional layout -- a *configuration* and *its parametrization*, which includes *form-giving* -- establishing the possible and necessary forms (and sizes) for the assembly, sub-assemblies and components. The final stage of *detailing* produces the manufacturing information, typically detail drawings, parts lists, and instructions for production, assembly, testing, adjustment, maintenance, etc.

These steps have been expanded and brought into a logical sequence[1,3,4,5]. A brief summary and outline of this expansion appears on figure 1, the upper section. The first column shows the four main steps of design as listed in the last paragraph. They are augmented by product planning as the preceding step (which should be performed by management with cooperation from design) and by preparation for production as the following step. The second column shows the major models and design documents that may be generated in a novel design problem. The third column lists typical characteristics in the progress of designing. The fourth column shows the steps of problem solving, which are repeated many times for each design process step.

This theory-based procedure must be adapted (by designers) to the particular problem situation and circumstances. One typical adaptation is that the planning and design work (e.g. jigs, tools, fixtures, etc.) for the production processes should take place as concurrently as possible with designing the product itself. A time shift, preferably short, is inevitable, changes in the documentation on the product must be *frozen*, before the production preparation can be completed.

Discussion of Methods

Many methods have been proposed to help with parts of designing. Other methods exist for assisting in managing a company, its product mix and market niche, and its sub-divisions such as designing, manufacturing, marketing, maintenance, customer service, etc., and for transmitting information, agreements and opinions from one area to others.

The methods best known for engineering are, of course, the analytical and mathematical methods based on the engineering sciences. These are applicable to the object of designing, the system. Analysis can take place once we know (more or less concretely) what the system will consist of, how it will look and act, how it receives power and control inputs, etc. This means that a proposal (and preferably several) for these features must have been generated -- by designing, i.e. anticipating and preparing for the future.

Methods can also be used for other purposes, especially tasks related to the processes of designing and its industrial context, e.g. communicating, negotiating, generating ideas, problem solving, evaluating (in part helped by analytical investigations), deciding, representing, modeling, etc.

The aim must be goal-directed ***searching*** for optimal ***solutions*** to a (design) problem. At any suitable level of abstraction of a TS-model, this search can be assisted by the use of appropriate (problem solving) methods. The word "method" can be defined as a prescription for a procedure that can be used to help accomplish this search. According to the type of procedure, we distinguish two groups of methods:

-- A *discursive* method recommends a stepwise procedure that builds systematically towards a solution or set of solutions. Using discursive methods, a previously defined goal can be approached according to a plan. By different combinations of known elementary solutions, new relationships can be discovered, and therefore new solutions can be found. Such a method tends to be transparent and explainable, and the results are traceable to prior knowledge, even though the final results were probably not predictable. Even discursive methods can produce idiosyncratic results.

-- Solutions may also be found with the help of ***intuitive*** (problem solving) methods. These are methods that

lead to finding new solutions by employing intuition (internalized prior knowledge) and spontaneity. For the problem solver, approaches to solutions come suddenly into consciousness. Such a method tends to be non-transparent and unexplainable, bordering on the mystic, it depends critically on the personal experience of the problem-solver -- intuitive feel for design must be learned by long practice. A statement that someone "never uses any methods" implies that this person uses an intuitive method.

Both groups of methods can and should be used together. They complement each other[6,7] by generating a natural tension between an ***intellectual thinking mode*** (systematic, methodical, structured, analytical) and an ***intuitive thinking mode*** (erratic, inconstant, non-calculable, playful). This can trigger and motivate the mental interactions with the intellect to attempt to solve the problem. The oscillatory interplay between intuitive and intellectual thinking, and related procedures, can result in creative proposals for solutions. Sufficient oscillatory ***tension*** must exist between the intellectual and the intuitive mental modes for creativity to occur.

An example of a method is the set of ***heuristic principles,*** which characterize a problem solving procedure as a battle with a problem that is fought under strict rules of play (tactics). These tactics cannot be of general validity, they depend on the subject. In order to learn them, each person must work through examples individually (and in groups or teams of individuals), then abstract the successful heuristic principles, and re-use them in adapted and modified form for later problems. Principles include, according to Polya[10]:

-- introduce and solve an auxiliary problem -- auxiliary problems are problems that we do not approach for themselves, but only because we hope that considering them can help towards solving the original and important problem. The solution of the original problem is the goal, the auxiliary problem is a means by which we attempt to reach the goal.

-- search for analogies -- analogies are present in all our thoughts, daily conversations, and even trivial conclusions. They also appear in all artistic expression and high scientific achievement, whereby all kinds of analogies may play a role in discovering a solution.

-- generalize the problem -- generalizing leads from considering an objector process (or a smaller set) to considering a larger set (collective) of objects or processes that contain the goal object(s).

-- specializing, particularizing the problem -- specializing leads from considering a given set of objects or processes to considering a smaller sub-set.

-- induction -- induction is a method whereby general laws can be discovered by observing and combining particular cases.

Application of Methods

Each of the many methods related to engineering design can usefully be applied in certain contexts and stages of designing. An overview is shown in the lower part of figure 1 of 35 known methods and their forms of representation and possible (computer) tools. My assessment of their strength of use and allocation to those design stages where they can be of greatest benefit is indicated in the matrix. Some of these methods have only recently been introduced under the title of "industry best practices, " e.g. QFD, TQM, Taguchi, etc. Others are more traditional. Some of these methods need additional comments with respect to placement in figure 1.

Quality Function Deployment (QFD) is shown with the four recommended "houses of quality" placed between the lines. This is not directly a design method, it serves particularly to capture information about customer wishes, transmit it from one essential stage in product development to another, and audit the results of the previous stages.

Mathematical analysis, based on engineering sciences, can be used to predict the behavior of a system (for instance as order-of-magnitude feasibility studies), or to analyze various system proposals to select the most appropriate.

Interpreting mathematical functions can be a powerful tool to select among operating principles and to establish reasonable starting values[11].

Contradiction-oriented procedure, the Theory of Inventive Problem Solving (TIPS), with the expert systems named *TRZZ* or ***Invention Machine, can*** assist in obtaining suggestions for innovative solutions (especially principles) to a problem, by offering patented solutions from other fields as analogies. After finding such

principles, the product must still be designed.

Axiomatic design is a method of evaluation and comparison of proposed solutions. It is based on mathematical decision theory which recommends formulating a small selection of objective design requirements (functional requirements -- FRs) and solution principles (design parameters -- DPs), preferably as mathematical functions, in such a way that (a) they are of equal number, and (b) Cartesian independent of one another. Decision theory can then solve the relationships to select the "best" solution. There is an obvious danger that the FRs and DPs are formulated in too simplistic terms, and that non-measurable (subjective) factors are suppressed.

Suh[12] defined design as "the creation of a synthesized solution in the form of products, processes or systems that satisfy perceived needs through mapping between the functional requirements (FRs) in the functional domain and the design parameters (DPs) of the physical domain, through proper selection of the DPs that satisfy the FRs. " Yet he states in his chapter 1 that "design is creative," and that nothing more can be said about design processes and methods to assist designing (perform the mapping, search for solutions). In consequence, I placed *axiomatic design* as part of the third step in problem solving -- evaluating and deciding -- and indicated it between design step lines.

In contrast, the systematic design procedure based on the given references[1,3,4,5] that is outlined in figure 1, uses at least five mappings, the modeling levels shown in the second column. This should make designing more rational and controllable.

Pugh's of concept selection is essentially an evaluation method to compare several proposed solutions among each other (and possibly with an ideal solution). It is performed in a discussion-group (team) setting, and therefore allows participants to suggest improvements and alternatives whilst evaluating. Some aspects of Brainstorming operate during the sessions. Nevertheless, I have indicated the method as an evaluation, placed between the horizontal lines.

Closure

Formalized methods can be useful tools to support engineering design. They should always be used in conjunction with intuition. In particular, intuitive results should be explained (after reaching them) within systematic procedures so that full records of design alternatives and decisions can be generated. These records can be vital in case of failures, and possible legal liability.

Engineering sciences are necessary, but not nearly sufficient, as foundations for designing. Procedural knowledge and methods must also be learned and applied. For best effect[6], methods should be one of the vital objectives and subjects of teaching in engineering curricula[7,8]. Methods, reasonably and well applied, can enhance creativity[9].

Endnote: A bibliography of the named methods is available from the author on request.

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Educated in England and Austria, with ten years of industrial experience, his academic appointments cover the University Conege of Swansea (1961-67), The University of Calgary (1968-77), Loughborough University of Technology (1977-81) and the Royal Military College of Canada, Kingston, Ontario. Ernst Eder has attained an international reputation in systematic design, theory, methodology and teaching.

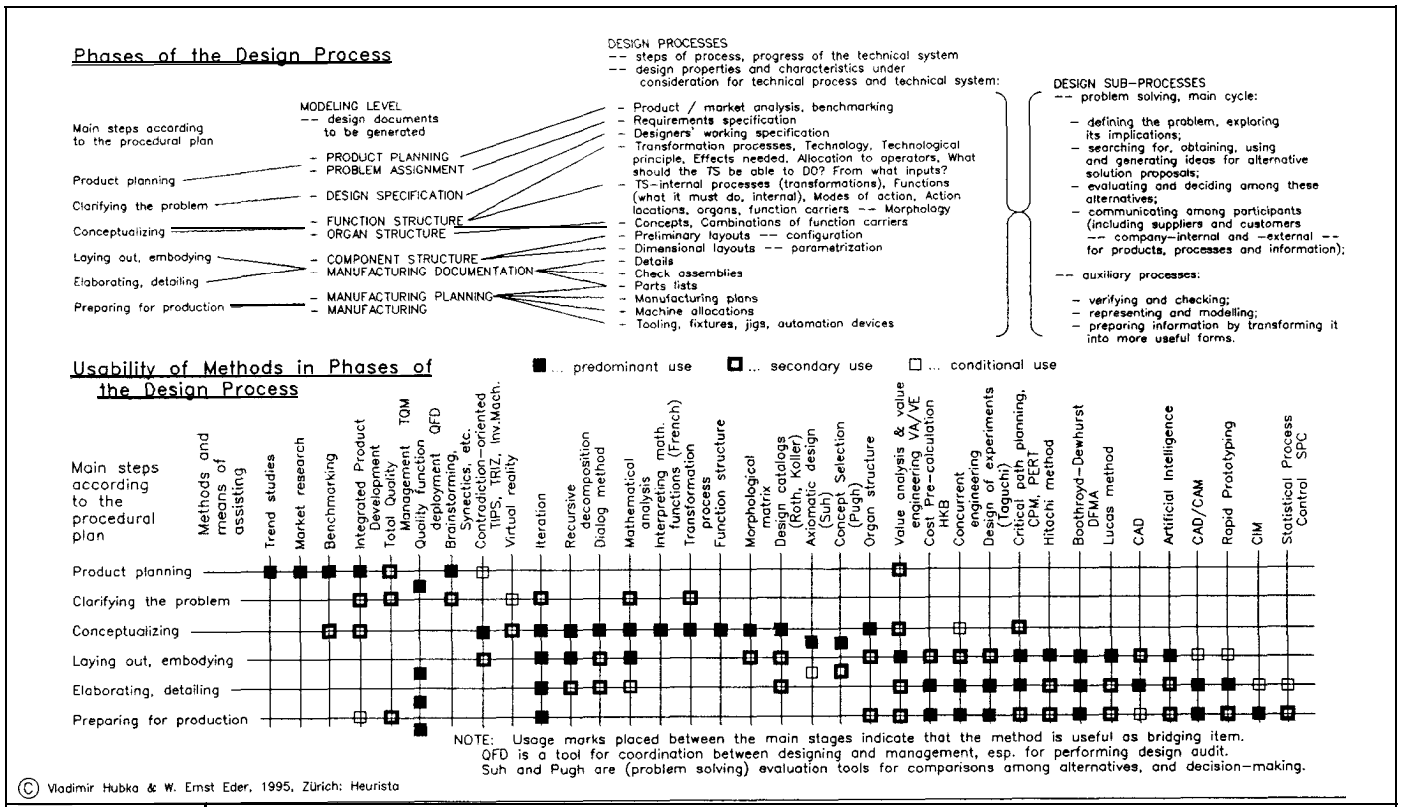

Figure 1 | Design Tactics: Phases of Designing and Usage of Methods