Chapter Four

Design Process Models

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INTRODUCTION

A design model is defined as a theory-based set of descriptions about the object world, which is the object to be designed, and/or the design process itself [*Tomiyama et al., 1989*]. Mechanical design models presented in the engineering design literature therefore, can be classified into two main groups according to the type of the model as the ***design process models*** and ***design artifact models***. Various approaches based on these types of mechanical design models are explained briefly in the following sections.

MECHANICAL DESIGN PROCESS MODELS

There have been numerous efforts to place design on a higher intellectual level, and to develop design as a discipline with its own structure, methods and vocabulary. The detailed methodologies for design generated thereby are highly stimulating, but their inherent complexity would limit their wide spread utilisation in engineering education because of the scarcity of time. As a result, the design methodology, which has been adapted, is rudimentary and highly utilitarian (Dieter, 1993).

Design process models aim at reflecting the methodology and characteristics of the engineering design process and propose strategies for the designers about how to proceed in the design procedure. Existing design process models presented in this section are classified according to their modeling approaches. In the first approach, authors attempt to determine the flow of work during the design procedure. One of the most important models in the engineering design process in this category is the systematic approach (Pahl and Beitz, 1988) in which the flow of work during the design process is divided into four main steps as follows;

1. **Clarification of the task** (collection of information about the requirements and about the constraints),
2. **Conceptual design** (establishment of functional structures, the search for suitable solution principles and their combinations into concept variants/design alternatives),
3. **Embodiment design** (development of layouts and forms for the concepts, evaluation of them, determination of a preliminary layout, optimization, definite layout, determination of production procedures),
4. **Detail design** (finalization of design).

The starting point of any design activity is a need or an idea, and the end point is a product that fills the need and embodies the idea. The first step of design is called conceptualisation. At this stage designer considers the alternative concepts to find the best design to solution problem.

The selection of concepts is a decision making process which is carried out in terms of trade–offs. The success of designer at this stage depends largely on selection of evaluation criteria that must be relevant to performance specifications of product including also the cost.

Embodiment design concentrates on the function structure of technical system to be designed, and aims to analyse and optimise its operation at an approximate level. The operation conditions (stress, temperature and environment) that are deduced from above analyses enable designer to generate an approximate layout including sizes of components and types of materials.

The next stage is the detail design. Here, the major concern is to maximise the performance of components and groups of components through precise mechanical, thermal and economic analyses. Selection of materials and production techniques are finalised and the design is coasted. The design is completed with development of detailed production specifications.

An operational model for the design process describes the design activities into two phases (Lewis and Samuel, 1989):

a. **Divergent Phase**: Recognition and definition of the problem, search for alternative solutions.

b. **Convergent Phase**: Feasibility study, selecting one from alternatives (decision-making), specification of the solution.

Another overview of the design process is given by Ullman (Ullman, 1992a) and a generic diagram of the product design process is constructed. According to this diagram, a product's life cycle is divided into six stages as;

1. Specification development/planning,
2. Conceptual design,
3. Product design,
4. Production,
5. Service,
6. Retirement.

It is also stated that, first three stages are of major concern during the design of a product. Among them, the goal of specification development/planning stage is to understand the problem and lay the foundation for the remainder of the design project. In the conceptual design, concepts for the product are generated and evaluated. Product design concerns with refining the concepts into quality products.

The design activity is observed from a broader and interdisciplinary point of view and the "total design" concept is introduced by Pugh (Pugh, 1991). According to the Pugh's definition, the total design is the necessary systematic activity, from the identification of the market/user need, to the selling of the successful product that satisfies the need-an activity that encompasses product, process, people and organization. A total design activity model is proposed such that it has a central core of activities all of, which are imperative for any design regardless of the domain. This core is called the design core and consists of market/user need, product design specification, conceptual design, detail design, manufacture and sales.

Every product must be developed according to a set of specifications. The starting point of any design activity is therefore market research, competition analyses, literature searching, and patent extracting etc. from which a detailed Product Design Specification (PDS) must be worked out. The PDS is the interface between consumer and producer and plays a significant role as a means of communication between these parties. The PDS must be considered as an evolutionary document which, upon the completion of design, has itself changed to match the characteristics of final product. Figure 3 shows the most significant elements that go into PDS. For the guidelines for preparation of PDS the reader is referred to original literature (Pugh 1990).

The conceptual design is the most inventive and creative stage of design work, and almost always the weighty part of teaching design. In his book on "Total Design" Pugh (1990) analyzed the environment in which this part of design activity should be carried out. He emphasizes the merit of making a distinction between the simulating of ideas and getting of ideas, and comes to the conclusion that;

— Concepts are often best generated by individuals, and

— Concept selection and enhancement is often best formed in groups.

Concepts must be evaluated against a set of criteria, which are extracted from the PDS, again as a group activity; Pugh proposes the following scheme for the conceptual phase of design:

1) Concept generation and expression by individuals, based on PDS,
2) Criteria generation in groups,
3) Evaluation of concepts as a group activity.

The generation and selection of concepts are interlinked in a dynamic manner. "The method of controlled convergence" suggested by Pugh appears highly relevant to this chief feature of conceptual design, and will be described briefly. As illustrated in Figure 4, the selection of concept is not a straight–forward process. Instead, it is cumulative in the sense, that any step toward the reduction of number of alternatives is followed by the addition of new ones, which can be entirely new of the improved version of former ones. The reduction of alternatives requires establishment of an evaluation matrix, which compares the generated concepts, one with the other, against the criteria of evaluation. For the purposes of illustration we examine an example of this kind of tool (Figure 5), devised to evaluate 14 different concepts generated for a car horn. The first step in evaluation is to choose a datum with which all other concepts are to be compared. A design, which has been in use over many years, if available, should be considered as a suitable candidate for datum. Comparing each concept/criterion against the selected datum;

\+ "Plus" is used to mean better than, less prone to, easier than, etc. relative to the datum,

- "Minus" is used to mean worse than, more complex than, more prone to the datum,

S "Same" is used to mean same as datum.

Thus, we establish a score pattern in terms of the total numbers of +'s, -'s, and S's relative to datum. Next, we can attract the negatives of weak concept. Their viability will depend on the extent to which they can be improved without causing a reversal in the positives. Having repeated his procedure, the truly weak concepts can be eliminated, and there will be a stepwise reduction in the matrix size. This evaluation should be refined undertaking an additional phase toward developing the strongest concepts. This may be helpful in improving the understanding of the PDS and its projected solutions and adopting additional criteria for evaluation (Pugh 1990).

The design process is also modeled by a constraint satisfaction approach and one of the important studies in this category was performed by Serrano (Serrano, 1987) who states that much of the design process involves recognition, formulation and satisfaction of constraints. The constraint-based nature of the engineering design is also considered in an intelligent real-time problem solving methodology (Bradley and Agogino, 1991). This methodology models the design procedure as a constraint-driven search process.

One of the important approaches in the modeling of the design process is the axiomatic approach (Suh et al., 1978). This approach is based on developing a set of global principles, or axioms, which can be applied in making decisions during the design process. These axioms are considered as general truths such that no violations or counter-examples can be observed. However, they can not be proven, therefore development of axioms is mainly a heuristic approach. The creative processes in 4 different design steps based on the axiomatic design theory are discussed in (Sekimoto and Ukai, 1994). These design steps are the definition of functional requirements , the identification of design parameters, the analysis of the proposed solutions in order to choose the best solution and check the final solution. The mapping from functional domain to physical domain is explained and the properties of design matrix, which is responsible for this mapping, are given. The axiomatic theory is also discussed by Dimarogonas (Dimarogonas, 1993) and implication of these rules on the design and manufacturing methodology is presented.

Some of the existing models use a task decomposition approach. Among these models, Kusiak (Kusiak and Park, 1990; Kusiak and Wang, 1993a) presents a methodology for the decomposition of the design task into activities and modules. This methodology is based on clustering design activities into groups that allow an effective organization of resources required in the design process. The product or system to be designed is decomposed into subsystems and these in turn into modules. A set of design activities is determined for the design of each module. Similar or identical activities may be performed in the design of different modules. Then, interactions between modules and activities are represented as a module-activity incidence matrix. The number of mutually separable clusters of design activities in this matrix is maximized. Then, a knowledge-based approach is used for managing these design activities.

Graphical representation of design activities provides identification and analysis of coupled activities (Kusiak and Wang, 1993b). A triangularization algorithm is also presented to generate a sequence of design activities such that the number of activity cycles is minimized during the design procedure.

Another important aspect in modeling the design process is the experimental approach, which involves examining the real design processes. An important example for the experimental approach is a framework, presented in (Takeda et al., 1990), for logical formalization of design processes as a basis for developing a design knowledge representation language for intelligent CAD systems. The development of this framework is based on an experimental data obtained by examining design processes. A deductive formalization is introduced based on two kinds of non-standard logic; modal logic and non-monotonic logic. An examination of design processes is also performed in another study (Baya and Leifer, 1994) and it is stated that there is a need to understand and formalize the information generating, accessing and analyzing behavior of designers in building design tools and methods. They present a framework to analyze the information-handling behavior of designers based on an experimental study. Another experimental research on the design process includes the development of a design process recorder and its prototype implementation (Hirose et al., 1994). The framework for this record is called a hypergraph, because of its node-arc structure ("graph") and because it spans several types of information created during the design work ("hyper").

A few researchers consider the design process as a stepwise refinement from general to specific aspects. For example, a design problem-solver composed of hierarchical collection of design specialists has been developed (Brown and Chandrasekaran, 1985). The upper levels of the hierarchy are specialists responsible for the more general aspects of the product to be designed while the lower levels deal with more specific subsystems or components. The design refinement is performed by distributed, top-down interactions between these specialists.

Other design process models do not use the above mentioned approaches explicitly. For example, Mayer and Lu propose a conceptual model for integrating multiple sources of knowledge within engineering expert systems and its implementation in the engineering design domain (Mayer and Lu, 1988). This model allows resolutions to be dynamically accomplished by the knowledge sources themselves.

Roles of features and abstraction in mechanical engineering design are emphasized in (Taylor and Henderson, 1994). A 3-D abstraction space is presented to compare mechanical design process models, mechanical product models and mechanical design research efforts.

A learning shell is developed for iterative design to enable the extraction and use of information from an analysis package during the iterative design process (Jamalabad and Langrana, 1993).

Design process models explained briefly in this section illustrate that, main strategies in modeling the design process should be the following:

1. Division of the complete design process into meaningful and separable stages.

2. Determination of the sequence and interaction of design activities in these stages.
3. Management of these activities in an optimum way such that a satisfactory product with a maximum performance is designed, in a minimum possible time and with a minimum possible cost.
4. Modeling the behavior of human designers in generating design alternatives, evaluating them and selecting (making decisions) among many alternatives. This strategy generally requires experimental study on real design processes.

PRODUCT DEVELOPMENT PROCESS

Needs, whether factual or fancied, moral or amoral, present or future, important or unimportant, have been starting points in development of the engineering design products, and they will be initiative in future engineering design products as well. Needs are initiated by the people, society, and nature. Once the need is recognized by the designer, it needs to be defined formally. This is the first step in any design process (Figure 4.1). The next step in the product development process is the feasibility study. The feasibility study is a series of steps in the

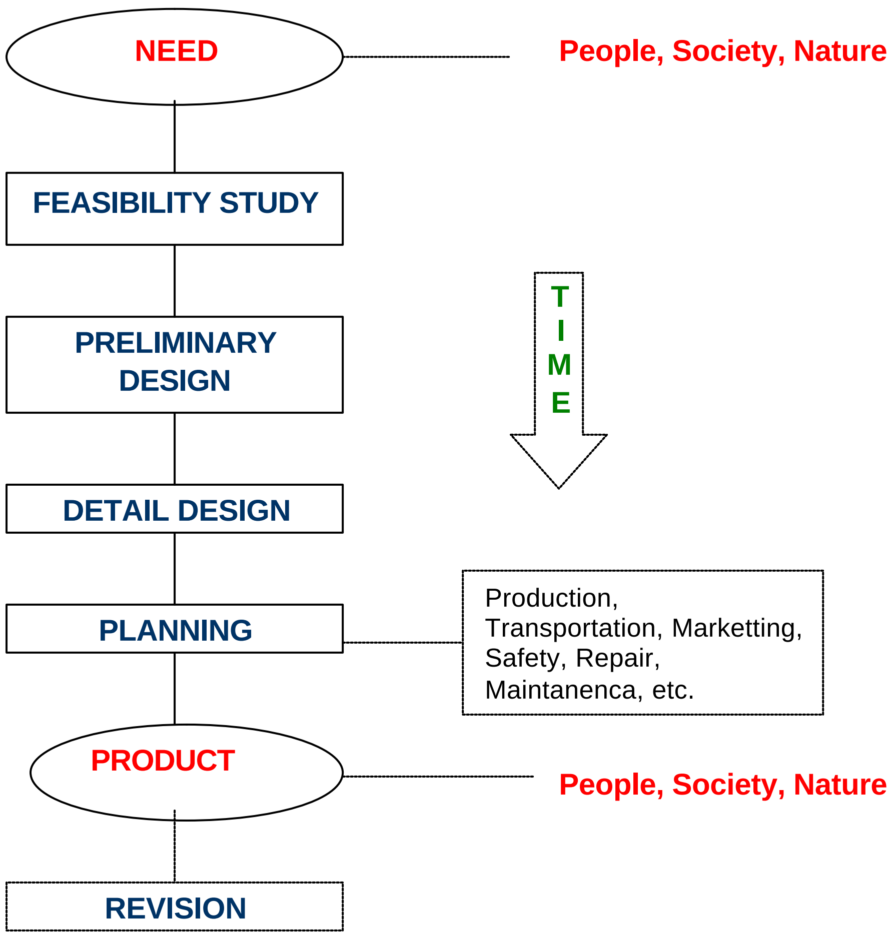


Figure 4.1 Product Development Process

product development process to explore and identify the possible and economical design alternatives. The details of the process is given in the next section. The feasibility study ends with a written “feasibility study report”. The report should start with the formal definition of the need, and it should end with one or more design alternatives, with an order of preference. The conclusion of the feasibility report must be a clear statement about whether the design process should continue with the other steps, or if it should be stopped because the possible alternative solution cannot be recognized for a technologically possible, economical, and worthwhile design. The feasibility study should be complete in itself with no possible return from the later phases of the design process.

Product development process has four main phases as it is illustrated in the Figure 4.1. These are;

- **Feasibility phase**
- **Preliminary design phase**
- **Detail design phase**
- **Planning (Design review) phase**

Probable work for each of these phases is illustrated in the Figure 4.2. It is important that each phase in the product development process must be clearly identified and separated from the other phases and a report should be prepared at the end of any phase. The report should have clear statements whether to continue or not. This is necessary for two reasons;

1- If the conclusion of the report has positive comments for the design process, then the report is a concluding summary of the design process up to that point. The report should be used as a reference work by the designers who are participating in the succeeding phase. No return to the previous phase should be allowed.

2- If the conclusion of the report has negative comments for the design process (stop the design process comment), then the design process should not continue. By this way, the effort and money to be spent in the following phases are saved. The next phase should be never started unless the factors effecting the design are changed completely for a new conclusion.

Generally, one may assume that probability of positive or negative conclusion in a feasibility report is 50%, however this ratio for positive comment for a preliminary design phase is 90%.

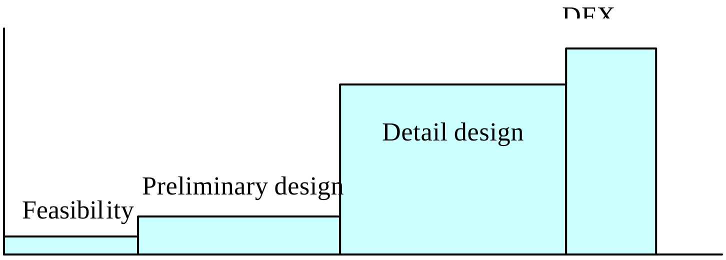


Figure 4.2 Manpower vs. time for design phases.

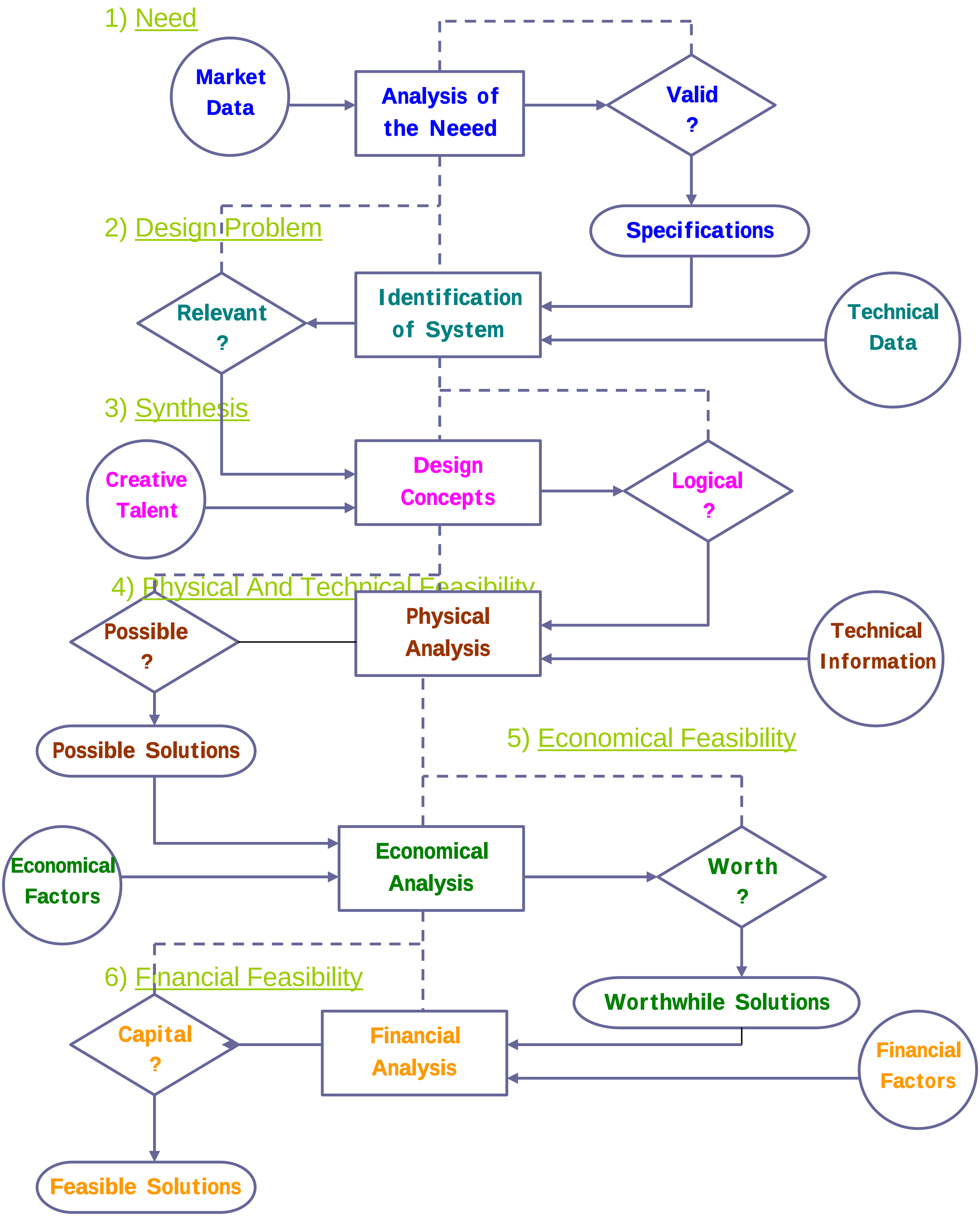


Figure 4.3 Flowchart for a feasibility study.

STAGES of DESIGN

Another representation of design includes 8 stages of any design activity. These are illustrated in Figure 4.4.

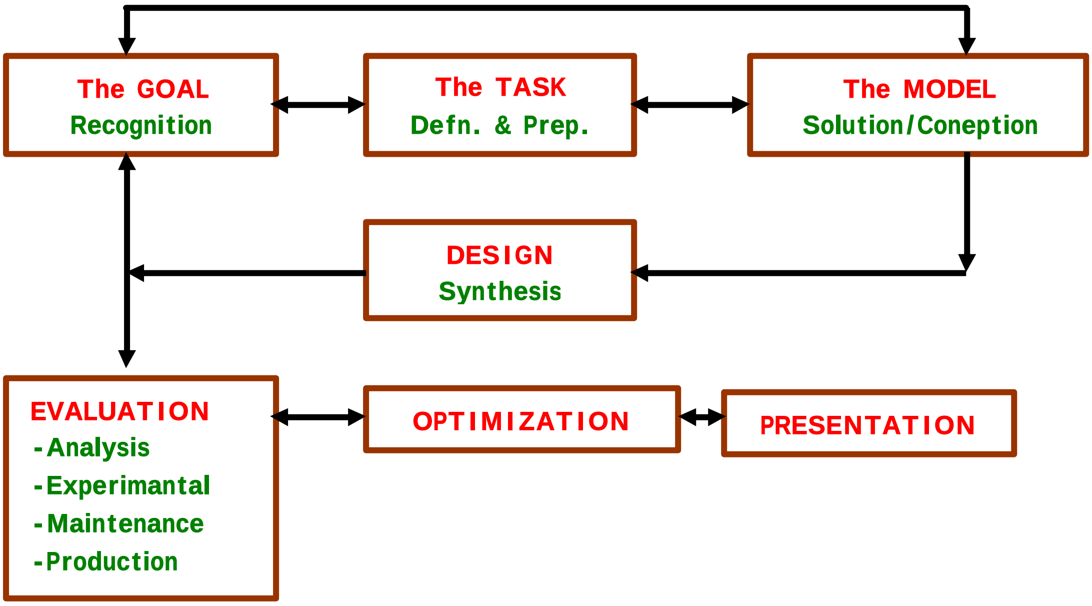
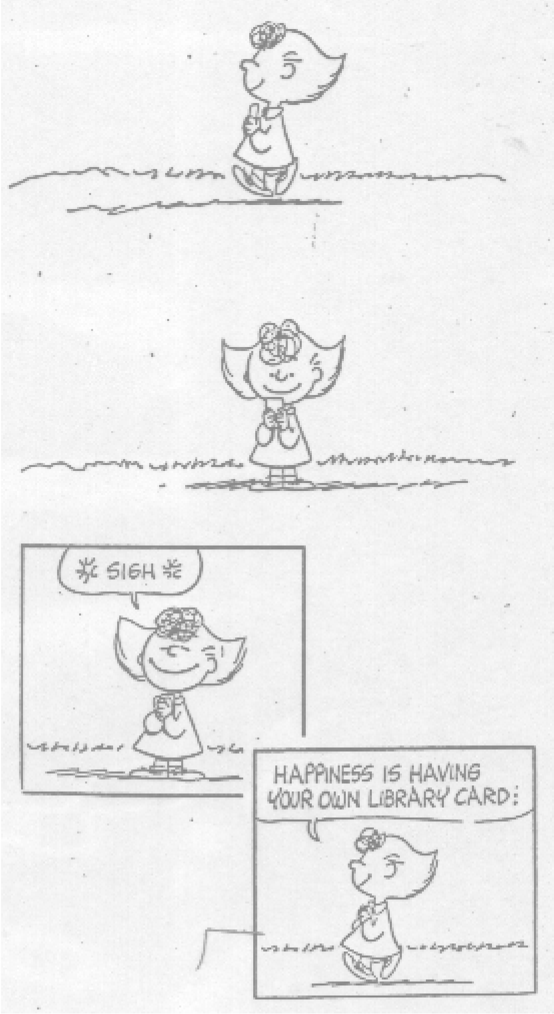


Figure 4.4 Stages of engineering design.



Library is the main source of engineers and designers. Conventional libraries with huge amounts of books and periodicals serve the designers as an archive of all sorts of previous design ideas. The internet is better in many respects then the conventional libraries since the information in the internet is more update. It is strongly advised to start any design (or engineering problem) by making a detailed library search. This saves a lot of time and effort, since many engineers and designers have already probably studied the same or a similar problem. Success and failure of these previous work are extremely valuable, and may solely direct the designer towards a better success.