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Everything you wanted to know about **Design Methodology,** *but you were afraid to ask*

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Lecture on Engineering Design Methods

-Student's Handout-

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Excerpts from *Total Design* by S. Pugh and *Engineering Design Methods* by N. Cross

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Abstract

Design is vital to a manufacturing company's goal of creating successful products and processes. This lecture attempts to provide a framework for design whose purpose is to create innovative products that satisfy the needs of the customer. Based on a core of design activities, design is presented as a systematic and disciplined process. This is accomplished through a design methodology known as ***Total Design****, which has been developed by Professor Stuard Pugh of University of Strathclyde. The idea of developing a Product Design Specification or functional requirement list prior to the generation of conceptual ideas is emphasized in this lecture as well as the use of Idea selection techniques to avoid arbitrary concept selection.*

1. Introduction

Total design is distinguish from "partial design" in which total design requires the input from people of many disciplines, both engineering and non-engineering, in a mix that is almost unique to the product under consideration. See Figure 1.

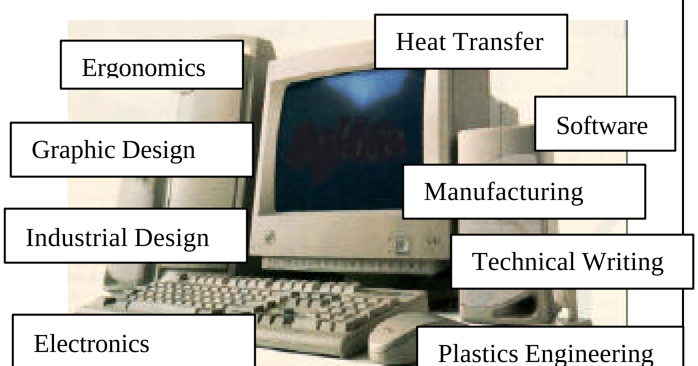

Figure 1. Typical Skills used in new Electronic Product Development

Total design is a systematic activity necessary, from the identification of the market/user need, to the selling of the successful product to satisfy the need - an activity that encompasses product, process, people and organization.

2. Components of Total Design

Total design may be constructed as having a central core of activities, all of which are imperative for any design, irrespective of the domain. This **design core**, as is known, consist of

- market/user need
- product design specification
- conceptual design
- detail design
- manufacture
- sales

2.1 Marker/Used Need

The 'front-end' of the design process is called marketing of the market research. This initial stage of the design process is one of the most important stages of the design process since this is the stage in which the user needs are identifies. Unfortunately, most engineers and scientist overlook this aspect of the design process since their education focuses mostly on the solution of highly technical problem which solution is assumed satisfy an already established market. Getting to grip with the user need situation requires the investigation of many avenues relating to your product area. Sooner or later, your design will be subject to the competition from either competing product manufacturer. A complete discussion on techniques for market research are beyond the scope of this lecture but techniques such as competition analysis, cost patters, market trends analysis and others are some of the tools of the market research expert. The outcome of the marker/user need stage of the design process is what is usually called a **brief**. A brief is a document, which can vary from the simplest statement of a requirement - for example, design a mean of transportation for a small city - to a comprehensive document that aptly describes the true user need.

Presently the designer is not involved in the "front-end" of the design form the total design point of view. That is the market research and investigation. Others presently do this.

Front-end people, market researchers, information scientist and the alike - must become part of and be involved with the design team of the future. They become designers since they contribute to the design activities.

For product success today, design must be, above all else, a ***team activity****.*

2.2 The Product Design Specification

From the statement of need, a document called the **Product Design Specification** or **PDS** must be formulated. This control document embodies the voice of the costumer; its specifies the product to be designed. Once this document is established, it acts as the mantle that envelopes all the subsequent stages in the design core. The PDS thus acts as the control for the total design activity, because it places the boundaries on the subsequent designs. Conceptual design is carried out within the envelope of PDS, and this applies to all succeeding stages until the end of the core activity.

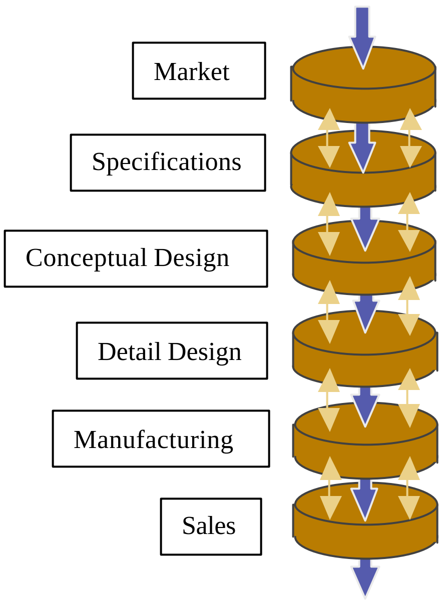

Figure 2. Design Core

An analysis of any existing product will reveal that the main design flow is from market (user need) to sales. This is shown in Figure 2. However the main design flow is itself an iterative process. For example, you may have reached as far as the detail design of a product when a new concept emerges (one that can be engineered to meet the PDS).

Iterations can occur because of changed circumstances or change of objectives. This interaction between the design core and the enveloping PDS, leads to the evolution of the PDS. Therefore we must thing of think of the PDS as a dynamic, rather than a static document. The interactivity of the design process is depicted by the vertical double-headed arrows in Figure 2.

. The PDS is an evolutionary, comprehensive written document, which must evolved to match the characteristics of the final product. In some cases the PDS is a contractual document, thus the implications of proposed changes upon the contract should be considered.

It must be pointed out that product based on a "blank sheet of paper" design - single ideas (Eureka's) - are unlikely to compete with, say Japanese products, unless you are extremely fortunate and luck. Japanese products pay great attention to detail and the voice of the costumer is embodied in the PDS.

To be successful, you have to be systematic and thorough, paying meticulous attention to detail from the beginning to the end of the design activity.

The PDS is the fundamental control mechanism that allows this success to manifest itself. The PDS must be comprehensive and unambiguous. At the end of the design process the product must *balanced* with the PDS. Poor PDS leads to poor design that will fail in the market. Good PDS does not guarantee good design but make the goal more attainable. PDS set the design in context, which is a comprehensive set of constrains.

2.3 The Contents of a Product Design Specification

2.3.1 Performance

Performance should be fully defined, e.g., how fast, how slow, how often, continuously vs. discontinuous, energy requirements- electrical, hydraulic, pneumatic, tolerances, etc.

A common failing in specifying performance is to ask for the ultimate, rather than which is obtainable from economical point of view.

In practice the client is amazed that the product emerging from their specifications cost too much. It takes litter effort or thought to specify ±zero tolerances for any parameter, which in reality translates into infinite cost.

$$\pm 0 \text{ tolerance} \rightarrow 8 \ \$$$

Beware of "over-specification" of performance, and also remember that performance is but one component of the Product Design Specification.

Example: It is not uncommon, say , with hydraulic pumps, for manufacturers to specify performance parameters that are not attainable coincidentally, but independently with reductions in the other parameters -for example pressure and flow for variable delivery pump. Maxima do not always occurs together.

2.3.2 Envi ronment

All aspects of the product's likely environment should be considered and investigated. For example:

- temperature range
- pressure range (altitude)
- humidity
- shock loading (gravity forces)
- dirt or dust - how dirty? - how clean?
- corrosion from fluids - type of fluid or chemical
- noise levers

- insects
- vibration
- type of labor or person who will use the equipment - likely degree of abuse?
- any unforeseen hazards to customer, user or the environment - for example inclusion of CFCs?

All manufactured items experience a number of these environmental changes in any or all of the areas before being called on to function for the user. These may occur at the following stages:

- During manufacturing - exposure to cutting fluid, solvents, fluxes, acids, etc.
- During storage - in the plant.
- During assembly - assembly forces, contamination from sweating hands?
- During packaging
- During transportation
- During storage - at a wholesale's warehouse.
- During display
- During use

2.3.3 Life in Service (performance)

Should service life be short or long and against which criteria should this be applied? Against which part of the PDS is (or should) the product life be asserted? One year on full performance, 24 hours a day, seven days a week or what?

2.3.4 Maintenance

Is regular maintenance available or desirable? Will designing for maintenance-free operation prejudice the design to such an extent that the product will become too expensive to buy in the first place? Does the company, or indeed the market into which the product will ultimately go, have a definitive maintenance policy? Is the market used to maintaining equipment once it purchased? The following points are relevant:

- Specify easy access to the parts that are likely to require maintenance. It is no good calling for regular maintenance if it takes 10 days to reach the part.
- What is the maintenance and spares philosophy of the company and market?
- What is the likely need and desirability of special tools for maintenance?

2.3.5 Target Product Cost

Target production costs should be established from the outset and checked against existing or like products. Invariably, all target costs are on the low side, and in many cases they are unattainable within the constrains of the PDS.

If a whole-life costing attitude is being adopted by the company or market area into which you are entering, then this should be considered, with particular reference to maintenance trade-off and down time.

2.3.6 Competition

A thorough analysis of competition must be carried out, including comprehensive literature search, patents and product literature search relating not only to the proposed product area, but also to analogous product areas.

2.3.7 Shipping

It is necessary to determine how the product will be delivered:

- By land, see or air.
- Maintain competitiveness of the product when is shipped overseas.
- Lifting capabilities, provision for lifting points.

2.3.8 Packing

Depending on the type of product being designed, some form of packaging may be necessary for transportation, storage, etc. The cost of packaging will add to the product cost and volume. Should the packaging protect against environmental effects of shipping such as salt water, corrosion, shock-loading, etc.?

2.3.9 Quantity

How many products to be made in one run? How often? One-off may require very little tooling. Large number production may require permanent, expensive tooling. This has considerable effect on the supportive investment required and the plant already existing in-house.

2.3.10 Manufacturing Facilities

Are we designing to fill an existing plant or is the plant and machinery involved a constraint to out design?

Make-in or buy-out policy: is the product constrained to techniques with which the company is familiar?

2.3.11 Size

Are there any restriction on the size of the product?

2.3.12 Weight

What is the desirable weight? Give a range of weight.

2.3.13 Aesthetics, Appearance and Finish

The appearance of a product is a difficult thing to specify. Color, shape, form and texture of finish should always be considered from the outset

Don't forget, whatever the product, that the customer ***sees*** *it first, before he buys it - the physical performance comes later. The visual performance is always first.*

2.3.14 Materials

The choice of materials for a particular product design is invariably left to the design team. However, if special materials are needed, they should be specified quoting the appropriate standards.

2.3.15 Product Life Span

Some indication of the life of a product is a marketable entity. Is it likely to remain in production for 2 years or 20 years?

The answer is critical as it can affect the design approach and interacts with the market and competition, tooling policy, manufacturing facility and the like.

2.3.16 Standards and Specifications

Is the product to be designed to current international or American Standards? If so, then these should be specified and copies obtained, e.g., OSHA standards, ISO 9000, etc.

2.3.17 Ergonomics

All products have, to some degree, a man-machine interface, certainly during manufacture and if not directly usage, again at the time when maintenance is required. What height, reach, forces and operating torques are acceptable to the user. Postures and lighting should be considered; the devices must be a delight to use - potential users must be consulted.

2.3.18 Customer

It is essential to obtain first-hand information on customer likes, dislikes, preferences and prejudices. Eyeball-to-eyeball discussion, question and answer, an examination of competitor's trends and specifications are all useful inputs to the specification.

2.3.19 Quality and Reliability

A company must ensure adequate feedback of any failure analysis to the design team. *Mean time before failure (MTBF)* and *mean time before repair (MTBR)* are familiar expressions in this field.

2.3.20 Shelf Life (Storage)

Shelf life must be specified at the outset and the means to combat decay considered, other wise rusty gearboxes, perished rubber components, seized bearings, defective linings, corrosion and general decay will occur.

2.3.21 Processes

If special processes are to be used during manufacture, they should be defined - for example, plating specifications, wiring specifications.

2.3.22 Time-scale

What is the time-scale for the project as a whole?

2.3.23 Testing

Most products require some form of testing after manufacture, either in factory, on site or both. The testing is related to performance.

2.3.24 Safety

The safety aspects of the proposed design and its place in the market must be consider. There may be legislation on product liability. Labeling should give adequate warnings. likely degree of abuse, whether obvious or not, should also be considered. Definitive operating instructions must be prepared.

2.3.25 Company Constraints

These include manufacturing facility constraints, financial and investment constraints, and attitude.

2.3.26 Market Constraints

Feedback from the market place should be considered. Otherwise, during the course of the project the market may disappear.

2.3.27 Patents, Literature and Product Data

All areas of likely useful information should be investigated and researched and in particular possible patent clashing should be known about as soon as possible. It is pointless to design something for sale in ignorance of someone else's patent.

2.3.28 Political and Social Implications

Typical factors include the effect of consumer movements, the stability of the market, and the avoidance of product features that can create social unrest and upset.

2.3.29 Legal

It is essential to consider legal aspects of a design at the PDS stage. Legislation has been adopted for product defects.

2.3.30 Installation

Many products must interface with other products or be assembled into large products (buildings). Installation therefore must be considered in the PDS. This include fixing holes and lugs, access, the volume available for the product, system compatibility, power compatibility, etc.

2.3.31 Documentation

Product documentation is always important in terms of instructions to the user, the maintainer or other. With large turnkey projects, the associated documentation can be a substantial part of the overall design task.

2.3.32 Disposal

Disposal has been included as a primary element as the effects of man's design of products impinge more and more on our environment.

If the product contains hazardous or toxic parts, or indeed parts worth reclaiming, these should be considered at the PDS stage. Should we design for disassembly - example: a nuclear plant of a chemical plant.

2.4. The PDS Document

Guidelines for preparation:

- Remember that the PDS is a control document. It represents the specification of what you are trying to achieve - not of the achievement itself.
- Remember that it is a user document - for use by you and in industrial situation by others. It should be therefore be written succinctly and clear.
- Never write a PDS in a essay form. Use short, sharp definitive statements. The PDS need to be user-friendly.
- From the beginning, try to quantify parameters in each area - for example weight.
- Always date the document and put an issue number on it.
- Clearly document amendments.

Appendix A shows a an example of a Product Design Specification document. Note the "D or W" column. This column is used to determine if the specification item is a Demand (D) or a Wish (W). Demands are requirements that must be meet, where as wishes are those that the client, customer or designer would like to meet if possible.

Note also the first column is left for changes made to the specification as the design process continues. Remember that the PDS is a *dynamic* rather than a static document.

3.0 Conceptual Design

Conceptual design is the phase of design primarily concerned with the generation of solutions to meet the stated needs or the PDS. The conceptual phase of the design must never be started without a PDS. If you are ask to design something without a partial or total PDS then you should:

- seek clarification from your tutor or supervisor
- compile your own version of the PDS

3.1 How to deal with the Conceptual Design Phase

It is professionally impossible to give an opinion of any value about a design without knowing its origin -the PDS. Opinions based on experience and without context are of little value. When ideas start to appear on paper people start getting interested and start to criticize your design. Listen to them and always ask them the context of their criticisms. The answer will surprise you - usually is based on "gut-felling" and therefore are of little value.

Conceptual design is a Synthesis.

In the Webster dictionary the word synthesis is defined as:

syn•the•sis \'sin(t)-the-ses\ *n, pl* **-the•ses** \-,se¯z\
[Gk, fr. *syntithenai* to put together, fr. *syn-* + *tithenai* to put, place ° more at DO] (1589)
1a: the composition or combination of parts or elements so as to form a whole
b: the production of a substance by the union of chemical elements, groups, or simpler compounds or by the degradation of a complex compound
c: the combining of often diverse conceptions into a coherent whole; *also*: the complex so formed

The definition 1a is the most appropriated for this discussion.

Within the conceptual design core there are two major components:

1. Generation of solutions to meet the stated need.
2. The evaluation of these solutions to select the one that is must suited to matching the need - the PDS.

3.2 Generation of Solutions

In practice, during the initial PDS formulation, it will be highly likely that you will have had ideas as to how your PDS might ultimately be satisfied. Record these ideas as they occur. Always remember:

- Avoid at all costs the temptation to "cut and run" and start engineering and developing the ideas further. Sometimes the thrill of working with a new technology might stimulate you to start engineering the ideas. Remember that *technology excitement can led to "cut and run".*
- You need as many ideas as you can. Single solutions are usually a disaster.
- Stay within the Laws of Physics! Design is not an excuse to trying to to do impossible things outside the laws of physics. Every idea/concept need to be engineered to a level where each is complete and recognizable, and technically in balance with the laws of physics.

3.2.1 Getting the Ideas

Individuals working separately generate more ideas than in a group. Even when redundancy among members are deleted. The difference is large, robust and general.

- Concepts are often best generated by individuals.
- However, concept selection, evaluation and refinement is often best performed in groups.

3.3 Concepts - Form and Presentation

Having generated this ideas to meet the PDS, the next step is to manifest these ideas. You need to express your ideas both graphically, diagrammatically and through modeling. Ideas need to be communicable. Here are some techniques to communicate the ideas:

- 3D sketching
- diagrams
- circuit diagram
- block diagram
- word description

The concepts should be titled and numbered so they can be cross-referenced later.

An idea is not an idea if it cannot be communicated.

The concepts generated at this phase should NEVER be arbitrarily discarded as not been good (whatever this means). …particularly because a third party does not like them.

"Gut-feeling" design is out of the question.

3.4 Criteria for Evaluation

To effectively evaluate concepts, an agreed set of criteria is needed.

- Criteria are deduced from the PDS.
- This is carried out in a group.
- It should be written down.

Remember:

The wrong choice of concept in a given design situation can rarely, if ever, be recouped by brilliant detail design.

The requirements for maximum level of quality in the conceptual phase may be summarized as:

1. Generation of ideas by individuals with the PDS firmly in mind; not random, do-your-own-thing process.
2. Means of manifesting these ideas -drawings, documents, etc.
3. Generation of ideas and rationalization of concepts in a group.
4. An absolute embargo on the selection of concepts, acceptance or judgment of them until the group is out of ideas.
5. Generation of evaluation criteria from the PDS elements as a group activity.
6. A complete and absolute embargo of "gut-feeling" decision-making; part experience is just as likely to prove wrong as right in today's competitive world.
7. A methodology for selection that does not inhibit creativity during the process of selection of concepts, but positively stimulates the emergence of new concepts, which might not have emerged by other means.

4.0 Evaluation of Solution

It is important to distinguish between evaluation and optimization and to distinguish between quantifiable and non-quantifiable parameters.

In optimization the design is known, conceptual choices have been made before hand and some important parameters may have been isolated for use in mathematical optimization.

What we are after techniques for dealing with evaluation rather than optimization. Techniques that allow us to deal with non-quantifiable parameters.

4.0.1 Concept Evaluation/Generation: *Method of Controlled Convergence*

The purpose of any method of evaluation is to allow design principles to emerge visibly in a context and to be articulated. The method of controlled convergence developed by Professor Pugh in 1981 has been devised on these bases.

Procedure: Phase I

1. It is essential that all of the ideas and embryonic solutions are generated against the background of the PDS - that is, they are projected solutions to the same problem having the same requirements and constraints.
2. Having established a number of possible solutions to the problem in hand, depict these solutions in sketch form, to the same level of detail in each case.
3. Establish a concept comparison and evaluation matrix, which compares the generated concepts, one with the other, against the criteria for evaluation. A skeleton of the matrix is shown in Figure ?.
4. It is essential that the matrix has all the 'visuals' (sketch) of all the concepts incorporated into it, so that the design team can witness the pattern of emergence. 5. Ensure that the comparison of the different concepts is valid - that is, they are all to the same basis and to the same generic level.
6. Choose the criteria against which the concepts are to be evaluated. These must be based on the detailed requirements of the PDS.
7. Choose a datum with which all other concepts are to be compared. If a design(s) already exist(s) for the product area under consideration, this must be included in the matrix and used as a useful first datum choice. Here competitive design do not yet exist and all concepts have been generated internally, the first datum choice should be the one the group think intuitively is the 'best'.
8. In considering each concept/criteria against the chosen datum, the following legend should be used:
   + (plus): meaning better than
   - (minus): meaning worse than
   s (same): Meaning same as datum
9. Add up the +'s, -'s and s's at the bottom of the matrix. Remember, the score or numbers must not, in any sense, be treated as absolute; they are for guidance only and must not be summed up algebraically.
10. Assess the individual concepts scores. Certain concepts will exhibit exceptional strengths, while others will show the converse - that is, weakness.
11. Look at the negatives of the strong concepts -what do you need to do to the design to improve it and reverse the negative? Is it possible at all? If so, in achieving the improvement and reversal, do you in fact reverse one or more of the existing positive? If it is possible to introduce a modification concept into the matrix do so, do not just

modify the one you have got and leave it there, as you may wish to go back to it later. This expands the matrix.

12. Look at the weak concepts and attack their negatives to see whether they can be improved upon. If they can be improved and other positive are not reversed is do doing, then introduce the revised concept into the matrix. Again, this expands the matrix.

13. After step 11 and 12, truly weak concepts should then be eliminated from the matrix. There will be an overall reduction in the matrix size.

14. If a number of strong concepts do not emerge as a result of steps 11-14, (that is, all appear to have a uniformity of strength or weakness), then it is usually indicative of one of two thing ar mixture of both:

a. The criteria are ambiguous, capable of a variety of interpretations by group members, or the criteria examination of s suspect criterion will reveal that it already incorporates one or more of he other criteria - the result, confusion. Decompose into more than one criterion.

b. Persistence of uniformity of strength between concepts usually means that one or more concepts are subsets of the others (they are one and he same thing), and the matrix cannot help to make the distinction where none exist.

15. When one particular concept persists, rerun the matrix using the strongest emergent concepts from the first run as datum. Does the patter persist? If it does, this will confirm the first run. If it does not, then repeat steps 11 and 12 until strong concepts persists.

Procedure: Phase II

This phase proceeds if a decision is taken to develop the strongest concepts (note the plural) that emerged from the initial evaluation in Phase I. This entails further work on these concepts, to engineer them to a higher level and in more detail than was carried out in Phase I. Care should be taken that each concept remains comparable with the other.

Once these concepts have been further engineered, repeat Phase I again until only one concept emerges.

4.1 Conceptual Phase -Outcome

The outcome of the conceptual phase of the design core should be a complete concept engineered to an acceptable level to establish its validity. In practice, this will usually take the form of a layout or scheme drawing, either on paper or filed electronically on a CAD system.

5.0 Design Core: Detail Design (Technical Design)

Detail design is more concern with the design of subsystems and components that go to make up the whole design. The components may be integrated circuits, resisters, shafts, bearings, reinforced concrete beams, gusset plates, gullies, windows frame, door furniture, etc., depending on the nature of the product.

When you come to detail design of components, you need to harness your knowledge of materials, techniques of analysis, technology of the situation, environment of the components quantity, life, overload, loading, aesthetic appear, etc.

The following are aid for component design:

- Reduce the total number of parts
- Reduce the amount of complexity of machining required in the remaining parts.
- Reduce of materials usage and usually the overall weight
- Reduce the cost of components and hence overall machine cost.
- Reduce the assembly time - assembly become easier with fewer components
- Reduce the number of drawing required
- Improve in the overall appearance of the product or machine

The following are general points to be noted in detail design:

1. Never carry out detail design without reference to the chosen concept or vice verse.
2. The interaction between the various areas of your design must be considered together with the constrains imposed by those areas.
3. The very act of defining a component within a system places constrains on the system, from the components definition itself.
4. The simplest and cheapest component design may not always be the most economical in a total sense.
5. The simplest and cheapest component design is achievable only in context of the PDS.
6. Generally, a reduction of components variety leads to shorter lead-time and minimum cost.
7. Think of the way the components are to be manufactured. If you have a manufacturing plant, should you design to utilize it?
8. Think of subassembly breakdowns.
9. Is there a simpler way?
10. How do other industries do it?
11. Can it be abolished?
12. Can any part or function be abolished or reduced?
13. Can any or all of the parts or function be taken over by other components?
14. Can parts or functions be split, possibly giving more but simpler pieces?
15. Can parts of functions be merge into a single body?
16. Can it be bought economically?
17. can it be made for standard components?
18. Can a new or different principle be used?
19. Can it be made simpler?
20. Should it be made larger?

Bibliography

Stuart Pugh, *"Total Design: Integrated Methods for Successful Product Engineering"*, Addison Wesley Publishing Company, 1991.