University of Cambridge

Department of Engineering

AN INTRODUCTION TO THE DESIGN PROCESS

Ken Wallace
John Clarkson

January 1999

1 ENGINEERING DESIGN IN CONTEXT

Our society depends on technology. In recent years, the rapid developments in technology have provided many benefits, but not without giving rise to a number of associated problems. When planning future developments, the aim is to increase the benefits and reduce the problems.

Many future options are possible. For progress to be made, **decisions** must be taken at many different levels, ranging from broad policy decisions taken by governments, down to detail decisions taken by individuals. Decisions taken at a higher level obviously influence those taken at a lower level, but at whatever level a decision is made it will depend on **forecasts** and **criteria**. It should be remembered that forecasts often turn out to be wrong and that evaluation criteria depend on values. Values differ, both between cultures and between individuals. Selecting the best course of action in any situation is therefore difficult and depends on the information available and the viewpoint of the decision maker.

The fundamental stages in the life of a product are shown in **Figure 1**.

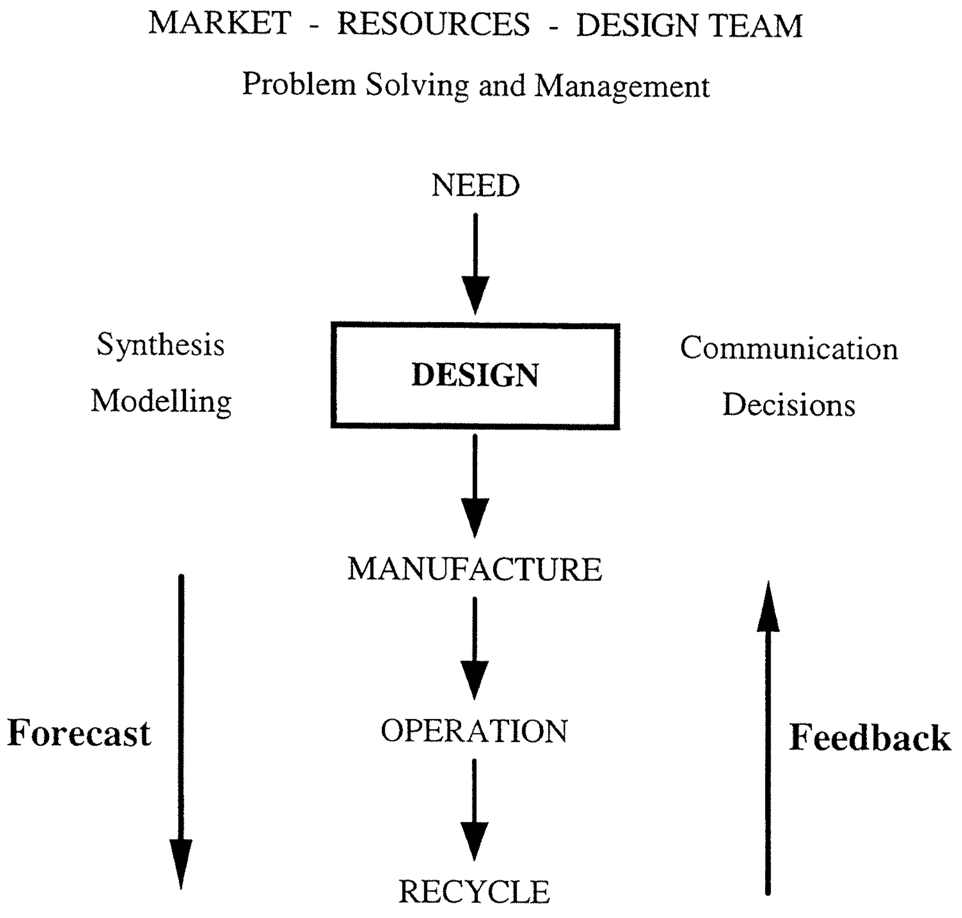


Figure 1: Life of a product

A product proposal, for example a new mountain bike for the leisure **market**, can result from a good idea, a new technological development or a carefully researched market **need**. In order to turn this proposal into a concrete product, a **design team** will be formed to undertake the complex sequence of activities necessary to define what is to be made. This team will have to be provided with sufficient **resources**, including finance, facilities, tools and information, if the task is to be completed within the required time.

Progress depends on making **decisions** and during the **design** stage the aim is to ensure that the proposed product will be economical to **manufacture**, will perform reliably, safely and economically in **operation**, and will be capable of being **recycled** at the end of its useful life. Decisions depend on the quality of the **forecasts** made during the design process and all design methods aim to improve the accuracy of these forecasts. To make forecasts a design team uses **synthesis** to generate as many solutions as possible and then **modelling** to forecast how these solutions would turn out if realised. Only seldom is it possible to get it all "right first time" and a lengthy development programme is often required.

Vast amounts of information, obtained from specialists in many different fields, must be handled during the design process. Large multidisciplinary teams are often required, introducing many potential **communication** problems. Continual **feedback** from all stages of the process provides essential information for improving the product.

Eventually it will become uneconomic to continue to update an existing product line and manufacture will cease. However, market experience and user feedback will stimulate fresh ideas and market needs and the cycle will repeat itself. A typical example is the continuing evolutionary development of bicycles.

In practice product creation is much more complicated than indicated in **Figure 1** and products evolve with time. The central engineering activities of **design** and **manufacture** are supported by other key company functions such as marketing, research and development, quality assurance and sales, the relative importance of each depending on the particular company.

A general strategy for tackling complex tasks is to break them down into smaller, more manageable problems and to solve each problem in turn. To do this it is useful to have a model for **problem solving** and a structure and some guidelines for **management**.

Because the design and manufacture processes depend on the type of market considered and the particular project being tackled, they are difficult to define precisely. However, it is helpful to have some broad definitions and the following are suggested:

- **Engineering design** is the process of converting an idea or market need into the detailed information (manufacturing instructions) from which a product or system can be made.

- **Engineering manufacture** is the process of converting detailed information into physical components and assembling those components into a product or system.

The aim is to produce the best products, for the lowest cost and in the shortest time. Markets are seldom static and some of the pressures facing modern designers include:

- **Intense competition.** International competition is intensifying, and new products offering improved value to the customer are continually appearing in the market. This is fuelled by rising customer expectations and leads to shorter lead times as new products are introduced and old ones updated to retain a competitive advantage.

- **Changing technology.** Technology is changing rapidly with new knowledge, materials and processes becoming available all the time.

- **Increasing complexity.** Products and systems are tending to become more complex.

- **Greater accountability.** There is increasing concern with individual and environmental safety, and a rapid growth of product liability legislation.

The design and manufacture processes must respond to these pressures by having clear and visible structures for their activities and using the latest techniques. A systematic approach is recommended.

Before describing the fundamentals of the systematic approach, it is useful to discuss briefly two fundamental activities: problem solving and management.

2 PROBLEM SOLVING

A general strategy for solving a difficult problem is to reduce the overall complexity by splitting it down into smaller, more manageable sub-problems. Each sub-problem can then be tackled more or less independently, though the links between them must always be kept in mind. Finally the individual solutions must be combined to produce an overall solution to the problem. A model of problem solving is shown in **Figure 2**.

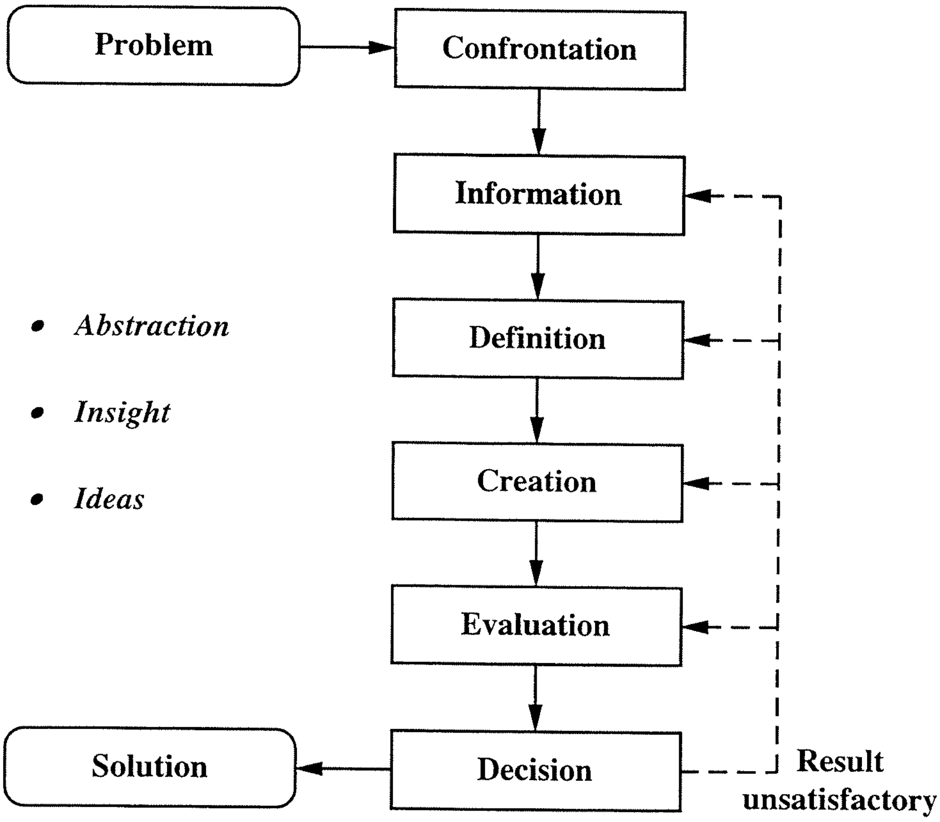


Figure 2: Model of problem solving

A problem must be identified before it can be solved. Once identified it is useful to check that it really is the correct problem. It is a waste of time and effort to produce an extremely elegant solution to the wrong problem. Having identified the core problem, it must be **confronted**, that is not put on one side to be tackled later. This is, in fact, one of the more difficult aspects of problem solving - it is all too easy to give up on a problem before actually getting into it and discovering the possibilities for solutions. The next two stages involve gathering as much **information** as possible about the problem and then making sure that the problem is clearly **defined**. The process of **abstraction** can help with these stages. Abstraction is one of a number of techniques available to increase **insight** into the problem. It is from the detailed definition that *evaluation criteria* are established. It is now necessary to **create** the widest possible range of solutions. At this stage techniques to increase the number of **ideas** are of particular value. Having generated a wide range of options, these must be **evaluated** so that a **decision** can be made. If at any stage the result is unsatisfactory, earlier stages will have to be repeated, or the problem abandoned without a solution.

Having ideas is an essential part of problem solving and the number of ideas can be increased by:

- avoiding criticism, that is do not reject apparently silly ideas straight away
- introducing some humour, which helps to generate unusual ideas
- using the "group effect", where an idea produced by one member of the group triggers off ideas in the minds of others.

The objective is to undertake the problem solving activity as **effectively** and as **efficiently** as possible and to make correct decisions. Progress in design involves making decisions on the best solutions to a large number of problems, and design is frequently referred to as an "iterative decision-making activity". **Figure 3** shows the hierarchical nature of decisions and emphasises the fact that all decisions are based on the accuracy of the forecasts made and the quality of the criteria used.

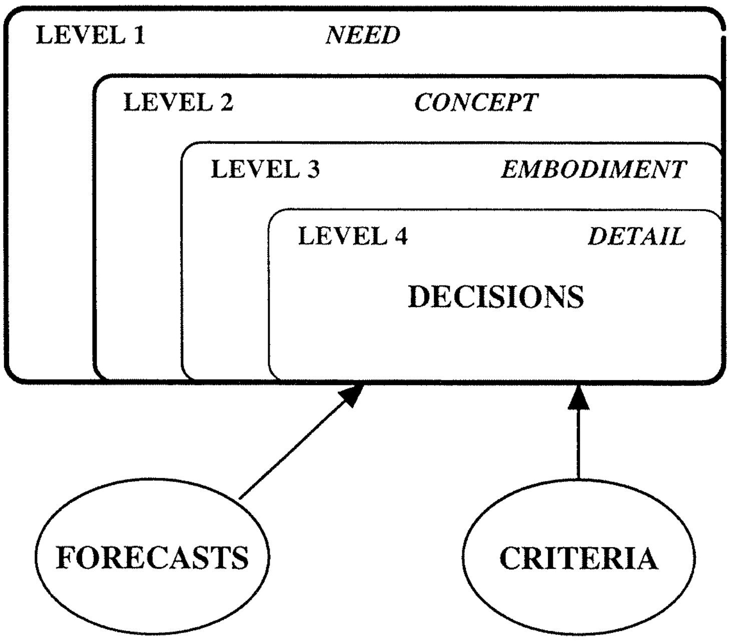


Figure 3: Basis of decisions

Design problems are often described as being "open-ended". By this it is meant that they do not have unique "correct" solutions, though some solutions will clearly be better than others. Several solutions must be developed before the best ones can be selected by judging them against the criteria. This is an iterative process involving many feedback loops during which information is updated to improve both the solution and the criteria.

Throughout the problem-solving process it is important to continually look ahead to ensure that the solutions that are being developed are capable of being realised in practice, that is they can eventually be **embodied**. Many excellent concepts have been let down and consequently failed due to poor embodiment. Useful guidelines to bear in mind when considering the embodiment of solutions are **simplicity** and **clarity**. The simplest design which fulfils the requirements is usually the best, and all functions should be clearly defined and executed.

3 MANAGEMENT

Design management involves the following activities:

- Setting the objectives
- Planning
- Communicating the plans
- Monitoring and controlling the execution of the plans
- Reviewing the outcome.

BS 7000, *Guide to Managing Product Design*, uses these basic activities to structure the Guide which is based upon the product development model shown in **Figure 4**. The Guide is split into three main sections, each addressed at a different level of management: senior management, project managers and design managers. At the end of each main section of the Guide there is a useful checklist of key points.

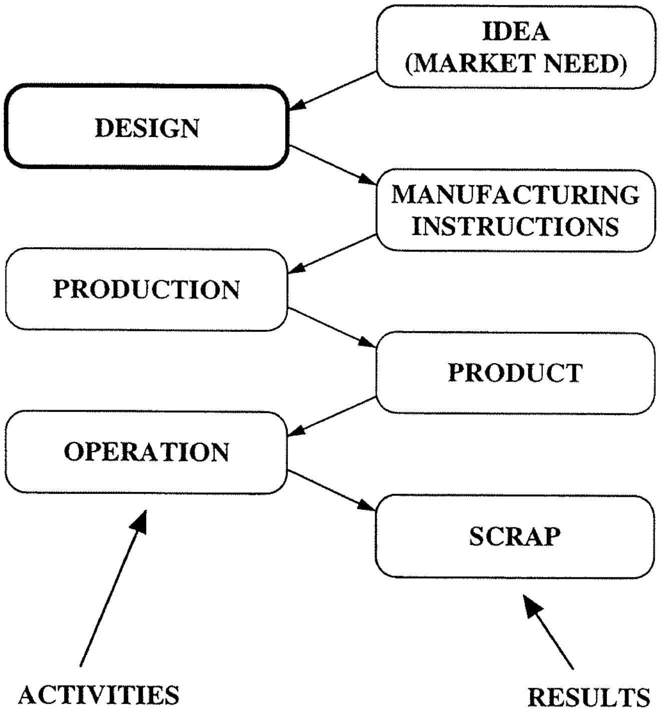


Figure 4: The BS7000 product development cycle

4 FUNCTIONAL TO PHYSICAL TRANSFORMATION

The central activity of engineering design is the conversion of a set of **technical requirements** into a set of **manufacturing instructions**. Central to this activity is the transformation from a **functional description** of the proposed product or system to a **physical description**, see **Figure 5**. At the beginning of any project, the proposed product is described in terms of a set of functions which it must fulfil. A mountain bike must, for example, transport the rider over rough terrain as comfortably and safely as possible. To achieve this a number of technical functions must be achieved including: provide power transmission, vary gear ratio, provide suspension, provide braking, provide steering, ensure adequate strength, ensure easy maintenance, etc. All these must be achieved in such a way that the resulting bike is economical to manufacture and is robust enough to provide a reasonable life, bearing in mind its intended use. The list of functions could be greatly extended, but the key feature is that no mention has been made about how these functions are to be fulfilled - they are essentially **solution-neutral**. Solutions must be found for all the required functions and these solutions transformed into physical descriptions of what is to be made. Completing this transformations is an extremely complex information processing activity.

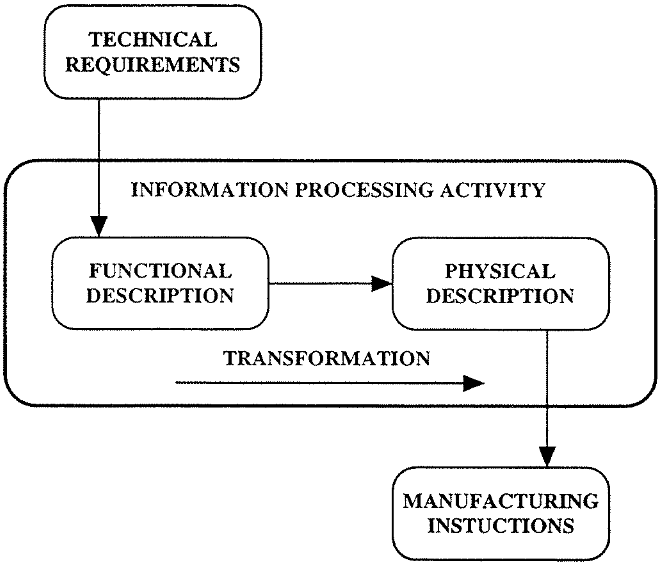


Figure 5: Functional to physical transformation

All technical systems can be modelled in terms of the flows and conversions of **material**, **energy**, and **information (signals)**. This "function" model must be mapped onto the structure of a technical system as shown in **Figure 6**.

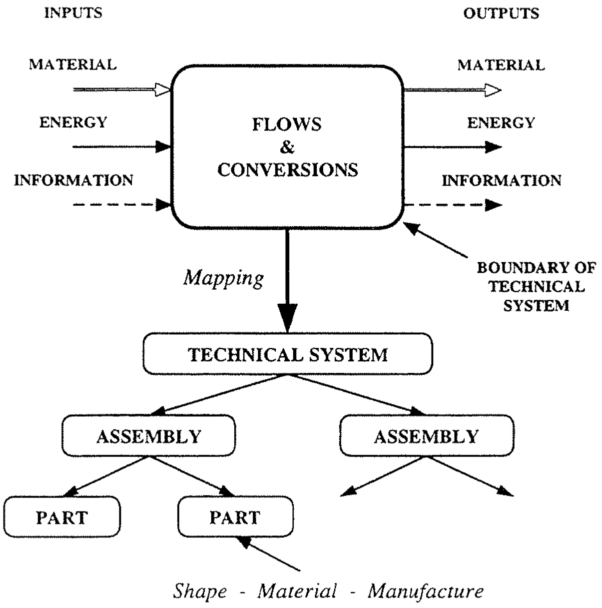


Figure 6: Structure of a technical system (product)

All technical systems exhibit the same hierarchical structure. The mountain bike represents a **technical system** (product) which uses physical effects to handle material, energy and signal flows. The system can be broken down into a number of **assemblies**, for example frame, handle bars, pedals, brakes, gears, etc. Each assembly can be broken down into individual **parts**, such as wheel rim, spoke, spindle, etc. For each of these parts, the **shape** will have to be defined, the appropriate **material** selected and the optimum method of **manufacture** chosen. Some parts are purchased as standard components from specialist suppliers, for example ball bearings, roller chain, Bowden cables, etc. All specially manufactured parts and bought-in components must be assembled together using the appropriate joining and fastening techniques to build assemblies, which are in turn connected together to build up the final product.

5 DESIGN PROCESS

In line with the general strategy for tackling complex problems, the design process is split into a number of main phases, and each phase is then broken down into a number of steps. Methods are suggested to help tackle each step.

It is important to emphasise that this systematic approach must be applied flexibly and adapted to suit the particular project being undertaken. It is not intended to replace intuition, inventiveness or insight; but rather to support and enhance these qualities by disciplining thinking and helping to focus concentration on important aspects of the problem.

The four main phases of the design process are shown in **Figure 7**. Note that the input to and output from this process is consistent with an expansion of the **design** activity of **Figure 4**.

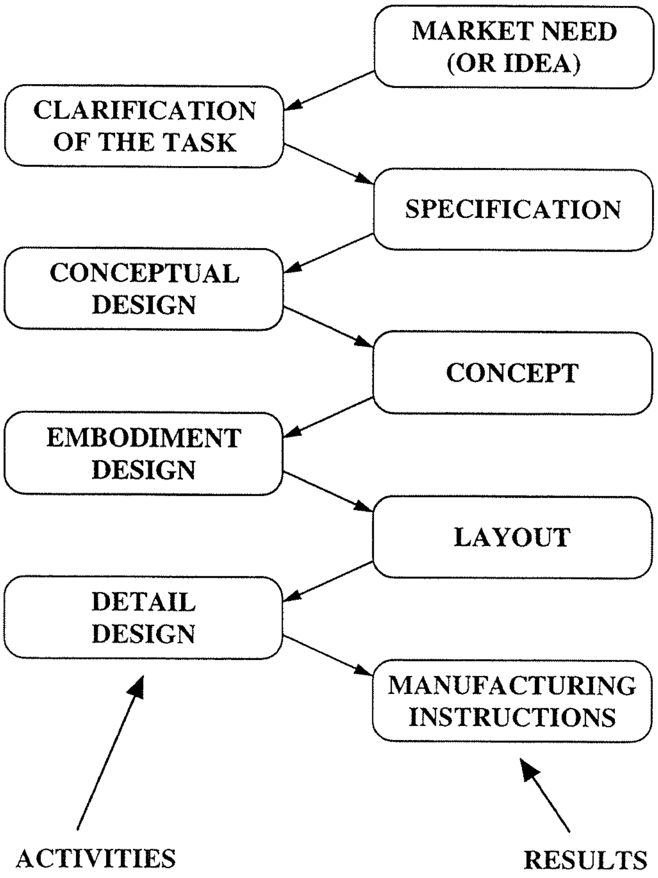


Figure 7: Model of the design process

In order to provide an overview, each phase is summarised briefly below. In subsequent sections of this booklet, the individual steps of Clarification of the Task and Conceptual Design are described in more detail.

Clarification of the Task. The starting point for the design process is an idea or a market need, often stated in vague, and sometimes contradictory, terms. Before the subsequent design phases start, it is important to clarify the task by identifying the true **requirements** and **constraints**. The result of this phase is a **design specification** which is a key working document that should be continually reviewed and updated as the design develops.

Conceptual Design. In this phase, concepts with the potential of fulfilling the requirements listed in the design specification must be generated. The overall functional and physical relationships must be considered and combined with preliminary embodiment features. The result of this phase is a **concept drawing**.

Embodiment Design. In this phase, the foundations are laid for detail design through a structured development of the concept. In the case of a mechanical product, the result of this phase would be a detailed **layout drawing** showing the preliminary shapes of all the components, their arrangement and, where appropriate, their relative motions.

Detail Design. Finally, the precise shape, dimensions and tolerances of every component have to be specified, and the material selections made, or confirmed. There is a close interrelationship between the shape of a component, its material and the proposed method of its manufacture. The result of this phase is detailed **manufacturing instructions**. The detail design phase is no less important than any of the others. Many excellent concepts have failed in the market due to lack of attention to detail.

6 CLARIFICATION OF THE TASK

The steps of task clarification are shown in **Figure 8**.

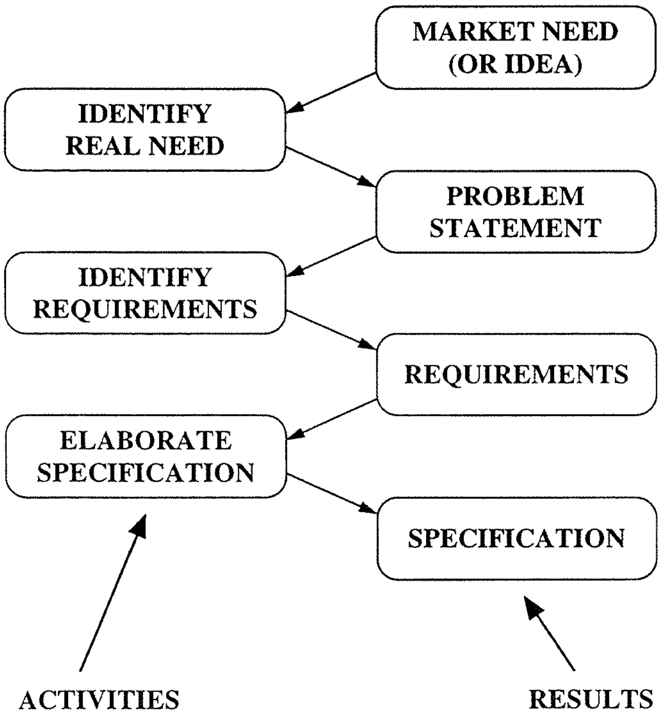


Figure 8: The steps of task clarification

The **market need** (or idea) is transformed into a **specification** by identifying the "real need" and defining a **problem statement**, refining that statement to identify **requirements** which are collated in a product **specification**.

6.1 Identify Real Need

To avoid solving the wrong problem, it is wise to spend some time identifying the true needs and preparing a clear **solution-neutral problem statement** which avoids any indication of how the problem should be solved. A useful technique is to systematically raise the level of **abstraction** using the following steps:

- Eliminate requirements that have no direct bearing on the main functions and essential constraints.
- Transform quantitative statements into qualitative ones.
- Formulate the problem in solution-neutral terms.

Abstraction broadens the range of possible solutions described by the problem statement by eliminating unnecessary constraints. It also encourages the designer to think more about general concepts and less about issues relating to specific solutions.

As an example, consider the problem statement:

Design a cylinder-type lawn-mower to cut grass.

This statement clearly indicates the direction of the solution by suggesting both the type of device and that the grass must be "cut". The size of the search field is thus restricted unnecessarily from the outset. An improved statement, at a higher level of generality, is:

Devise a means of keeping the grass short.

This statement defines a broader problem and encourages a wider range of possible solution concepts.

6.2 Identify Requirements

Having identified the real problem it is wise to limit the search field by preparing a detailed list of all the **requirements** and **constraints**. These can be listed under the headings of:

- Geometry
- Energy
- Safety
- Economics
- Quality Assurance
- Maintenance
- Kinematics
- Materials
- Ergonomics
- Manufacture
- Transport
- Timescales
- Forces
- Signals
- Aesthetics
- Assembly
- Operation
- Environment.

Where possible use **quantified statements**. For example, "Weight not to exceed 100 N" is much better than "Low weight". This appears to contradict the removal of quantitative statements when identifying the real need. However, when the real need has been identified such statements are essential to communicate acceptable performance limits for the new product.

Not all the requirements can be quantified easily and value judgements will be involved. For example, it is difficult to quantify factors such as appearance, ease of operation, etc. An ideal solution would meet all the requirements, but this is seldom possible with the resources available and compromises must be made. To aid selection and evaluation, it is useful to identify each statement as being either a **Demand** or a **Wish**.

- **Demand** (D) - ideally a requirement which **must be fulfilled**. If a proposed solution fails to meet a **single** demand, then it should be rejected.

- **Wish** (W) - ideally a requirement which will improve the value or quality of a solution, ie desirable but not essential. It is useful to indicate the weighting (Wt) of wishes as high (H = 3), medium (M = 2) or low (L = 1) importance.

Although a relatively simple idea, in practice categorising requirements as either demands or wishes is not always that easy. It may be a demand that a certain minimum requirement is met, eg for legal reasons, but a wish that the minimum requirement is exceeded by a certain amount, eg for marketing reasons. The dividing line can be a little fuzzy - however the concept is valuable as it forces one to think about the status and importance of the various requirements.

6.3 Elaborate Specification

The requirements and constraints are best compiled into a comprehensive description, or **specification**, of the product to be developed. The specification should be clear, correct and as complete as possible. It should list all the problem specific requirements in such a way that the reader is clear about the tasks the product is to perform. Demands and wishes should be clearly identified along with a **keyword** to uniquely identify each requirement.

In theory, since a solution must meet all the demands, preliminary selection from several possible solutions should be based on the demands. A proposed solution that does not meet all the demands should not proceed to the next stage of the design process. Those solutions that do meet all the demands must, usually after further work, be evaluated and the best selected. In theory, evaluation at this stage is based on the wishes. The aim is to find the solution with the highest value and quality.

To keep things simple at this stage, the demands in the specification will provide the criteria for a preliminary **selection**, and the wishes the criteria for **evaluation**.

Preparing a design specification is an extremely important task. However it can be a little tedious. A computer package, called **SpecBuilder**, has been prepared to assist. This package helps format the specification and provides an on-line tutorial to prompt possible requirements under the headings listed above. The package is available on the Design and Project Office (DPO) system. A Users Guide is available in the DPO and the package includes comprehensive on-line help. The package also generates Evaluation Tables, which are described later. **Figure 9** shows the first sheet of a design specification for a grass cutter project.

GARDEN EQUIPMENT COMPANY		**DESIGN SPECIFICATION** **Grass Cutter Project**	**Issued: 11/1/1999** **Page: 1**
D/W	**Wt**	**REQUIREMENTS**	**Keyword**
		GEOMETRY	
W	M	• Maximum storage size: 600x600x300 mm	Storage
D		• Minimum width of cut: 300 mm	Cut width
W	M	• Adjustable cutting depth: 5 - 50 mm	Cut depth
		KINEMATICS	
W	H	• Easily manoeuvred	Manoeuvre
W	L	• Cutting speed up to 2 m/s	Cut speed
		FORCES	
W	H	• Maximum weight not greater than 100 N	Weight
W	M	• Force to move not greater than 50 N	Move force
W	M	• Withstand fall onto hard surface from 2 m	Robust
		ENERGY	
W	M	• Power requirement - maximum up to 1 kW	Power
W	M	• Power source - electricity	P/source
D		• Maximum noise level not to exceed 85 dB	Noise
		MATERIAL	
W	L	• Suitable for a life expectancy of 5 years	Life
W	L	• Must not corrode within design life	Corrosion
		SIGNALS	
D		• Simple to start/stop	Start/stop
W	L	• Indication when cuttings storage need emptying	Storage
W	L	• Maintenance instructions on the machine	Maint instr
		SAFETY	
D		• Electrical safety to BSI standards	Elec safety
D		• No accessible sharp edges or hot spots	Sharp/hot
D		• Cutting blade protection	Blade prot
W	M	• Automatic electrical cut-out	Auto cut-out
		ERGONOMICS	
D		• Easy to operate and control	Easy operation
W	M	• Simple cutting height adjustment in under 1 min	Cut adjust
W	H	• Pleasant appearance	Appearance
		ECONOMICS	
W	H	• Target selling price not more than £75	Price

Figure 9: Part of a design specification for a grass cutter

7 CONCEPTUAL DESIGN

The steps of conceptual design are shown in **Figure 10**:

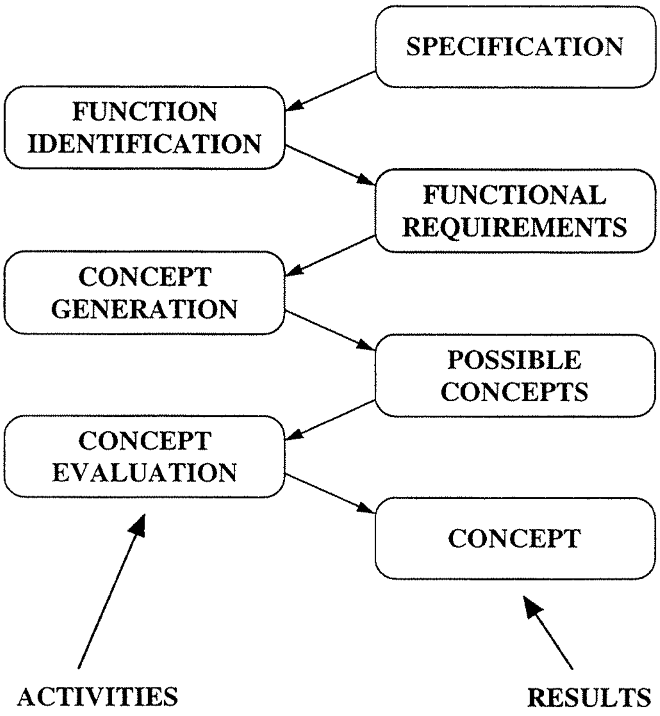


Figure 10: The steps of conceptual design

A **concept** is now developed from the **specification** by identifying the **functional requirements** for the product, generating **possible concepts** and selecting the most promising.

7.1 Function Identification

All technical devices can be analysed in terms of the flows and conversions of **material**, **energy** and **information** (signals) which take place within their **system boundaries**.

The first step is to identify the **overall function**. The overall function follows directly from the solution-neutral problem statement. For our grass cutter, the overall function might be:

Shorten grass.

This overall function, along with inputs and outputs, is shown in **Figure 11**.

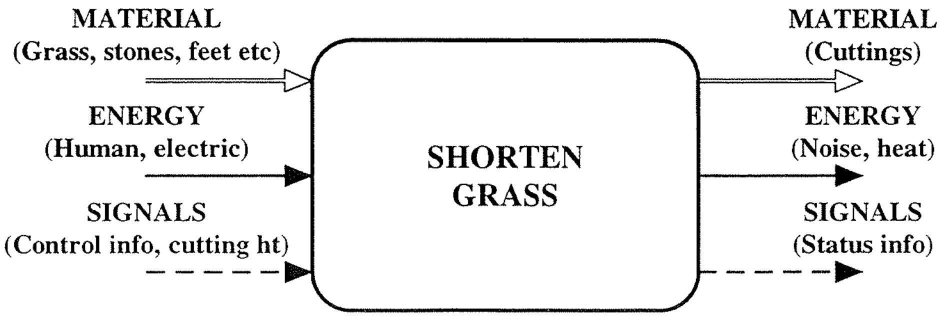


Figure 11: Overall function

The overall function can now be broken down into an appropriate number of smaller functions which indicate the **logical** and **physical** relationships between the flows and conversions of material, energy and signals. There is generally an identifiable **main flow** which dominates the situation, plus a number of supporting **auxiliary flows**. The character of a function is usually indicated by "imperative + object", for example "Adjust settings" or "Convey cuttings". The arrangement of functions can be varied to determine the most favourable function structure, remembering that the solution must eventually be embodied.

There are two different types of function structure:

- **System function structure**
- **Process function structure**

When preparing a system function structure, the system boundary is drawn around the "device", for example the grass cutter, and the relevant inputs, outputs and functions defined as shown in **Figure 12**.

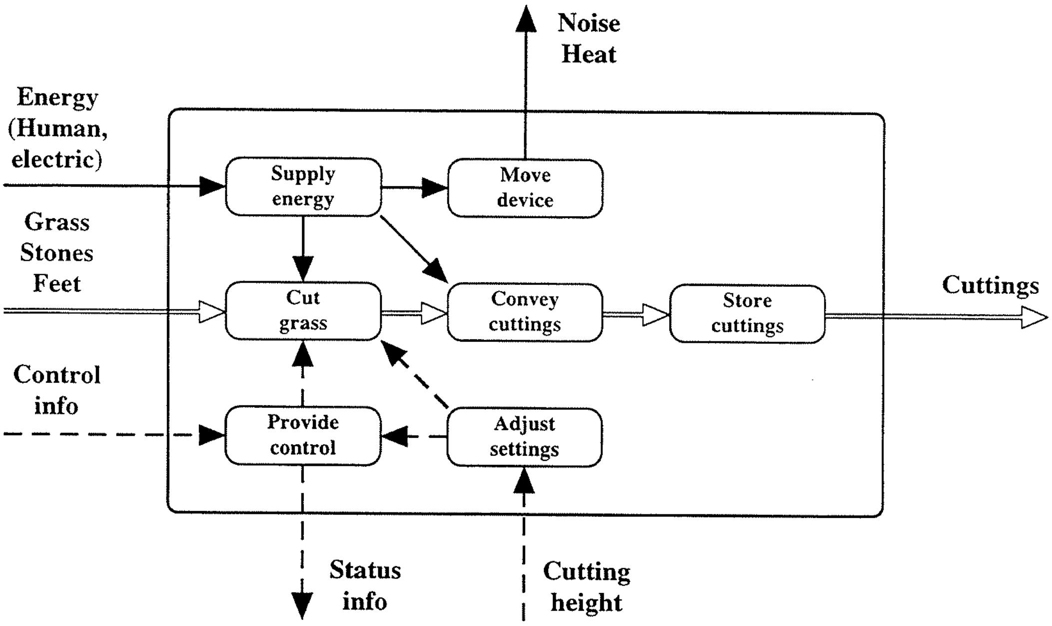


Figure 12: System function structure

Many devices are used as part of a process and in this case a process function structure (flowchart) showing a sequence of sub-functions can be illuminating. A process function structure for shortening grass is shown in **Figure 13**. The important thing is to use the method flexibly so that it provides as much help as possible.

It is possible to produce a very detailed function structure, breaking each function down into smaller and smaller units. However, the procedure should only be continued so long as it provides valuable insights - to do it purely for its own sake is pointless. A useful guideline is to aim for between **10 and 20 functions**.

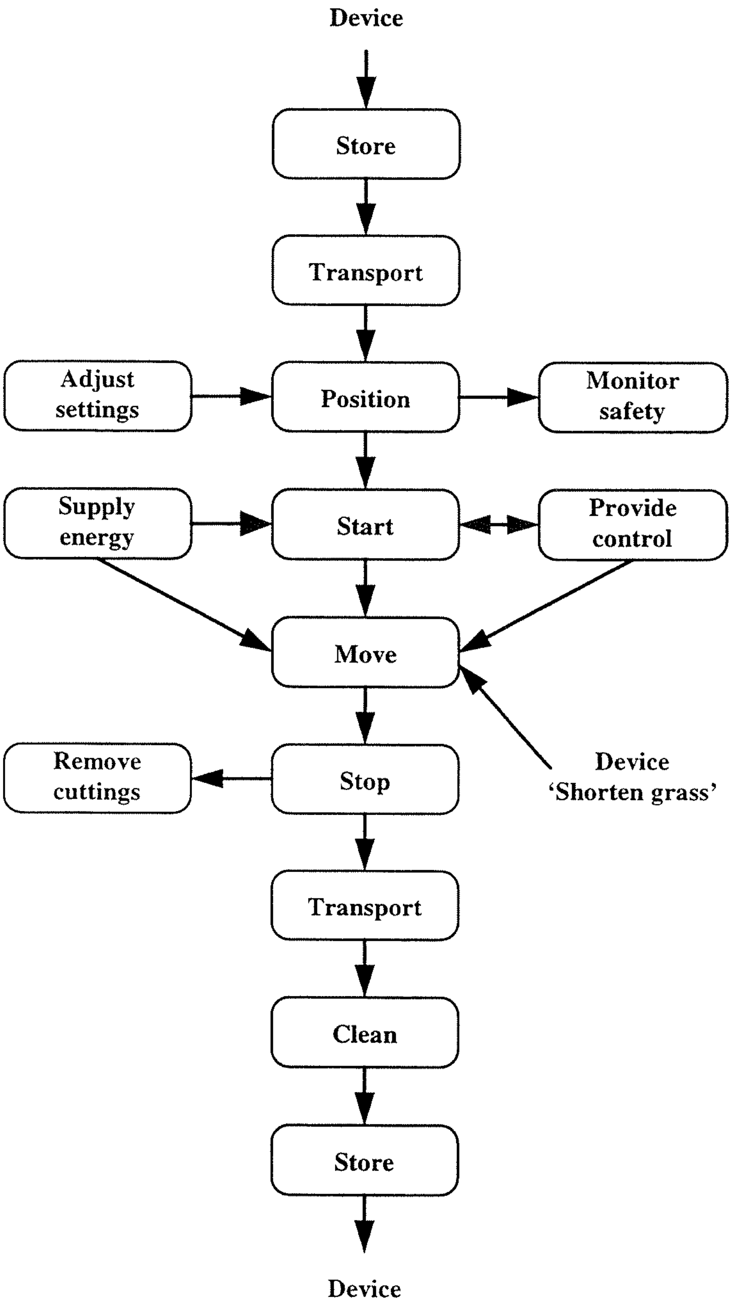


Figure 13: Process function structure

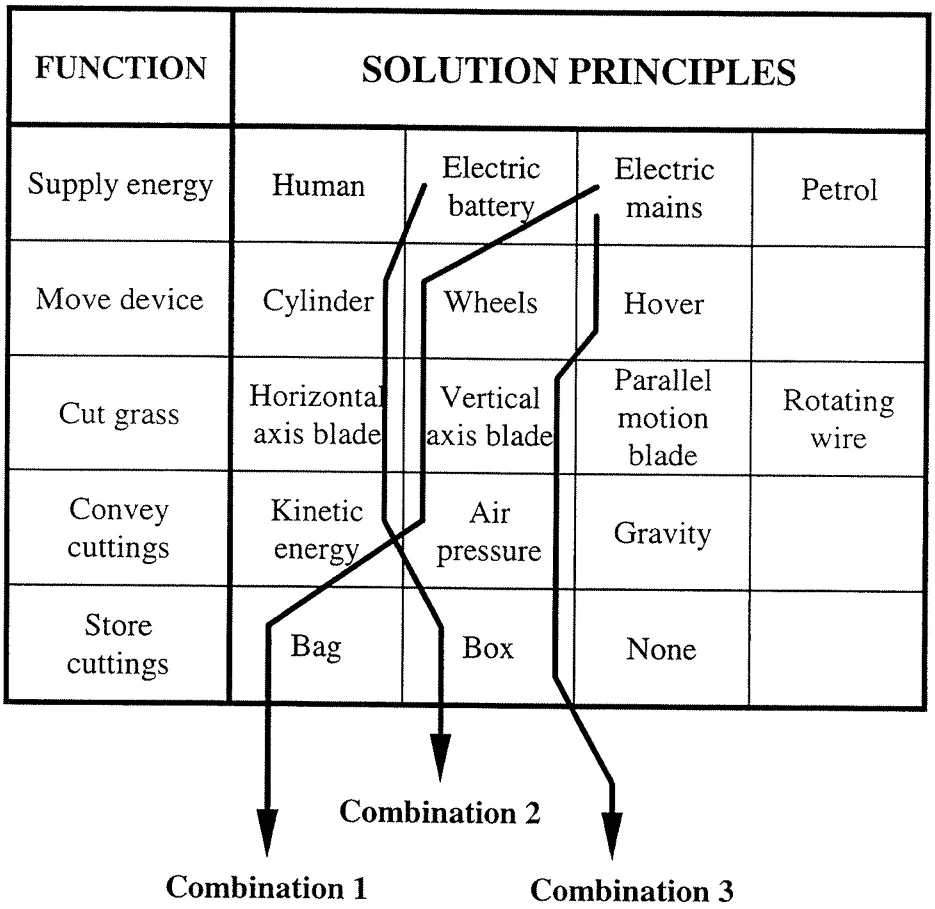
7.2 Concept Generation

In theory the function structure should be created independently of any particular physical solution. In practice, one always has a tentative solution in mind. Now one or more **solution principles** must be found for **every** function.

At this stage idea generating techniques, such as Brainstorming, can prove valuable. Existing devices can be analysed and useful ideas can be obtained from the study of natural systems. The books by French listed in the Bibliography provide useful examples and insights.

Once solution principles have been found, they can be combined systematically using a **table of options** like the one shown in **Figure 14**. Selected key functions from the function structure are listed in the left-hand column. Solution principles for each function are then identified in the rows. A **combination** is made up by selecting **one** solution principle from each row. Obviously, a great number of combinations can easily be generated. Many of these will contain incompatibilities and can therefore be rejected immediately, but the technique usually highlights a useful number of possible combinations which had not been thought of previously. Again, only pursue the technique so long as it provides valuable insights.

Selection criteria for the combinations are based on the **demands** identified in the design specification. If the demands have been correctly identified, then any combination of solution principles which fails to meet a single demand must be modified or rejected. Simple yes/no decisions will suffice. The best time to do this is while creating the combinations, that is do not include any combination which engineering common sense suggests is unlikely to meet a demand. As a guideline, select not more that **five** sensible combinations.



FUNCTION	SOLUTION PRINCIPLES			
Supply energy	Human	Electric battery	Electric mains	Petrol
Move device	Cylinder	Wheels	Hover	
Cut grass	Horizontal axis blade	Vertical axis blade	Parallel motion blade	Rotating wire
Convey cuttings	Kinetic energy	Air pressure	Gravity	
Store cuttings	Bag	Box	None	

Figure 14: Table of options

7.3 Concept Evaluation

The selected combinations will need to be firmed up into **concepts** before they can be evaluated to determine the best. The aim now is to determine which has the most favourable combination of additional features, and will thus provide the maximum competitive advantage. Three products, illustrating concepts based on the combinations selected from the table of options, are shown in **Figure 15**.

Before starting a formal evaluation procedure it is worth noting down which concept you consider to be the best and why. The formal method can then be used to "audit" your intuitive decision and provide new insights. If there is a difference between your first "guess" and the result of the procedure, it is illuminating to determine why.

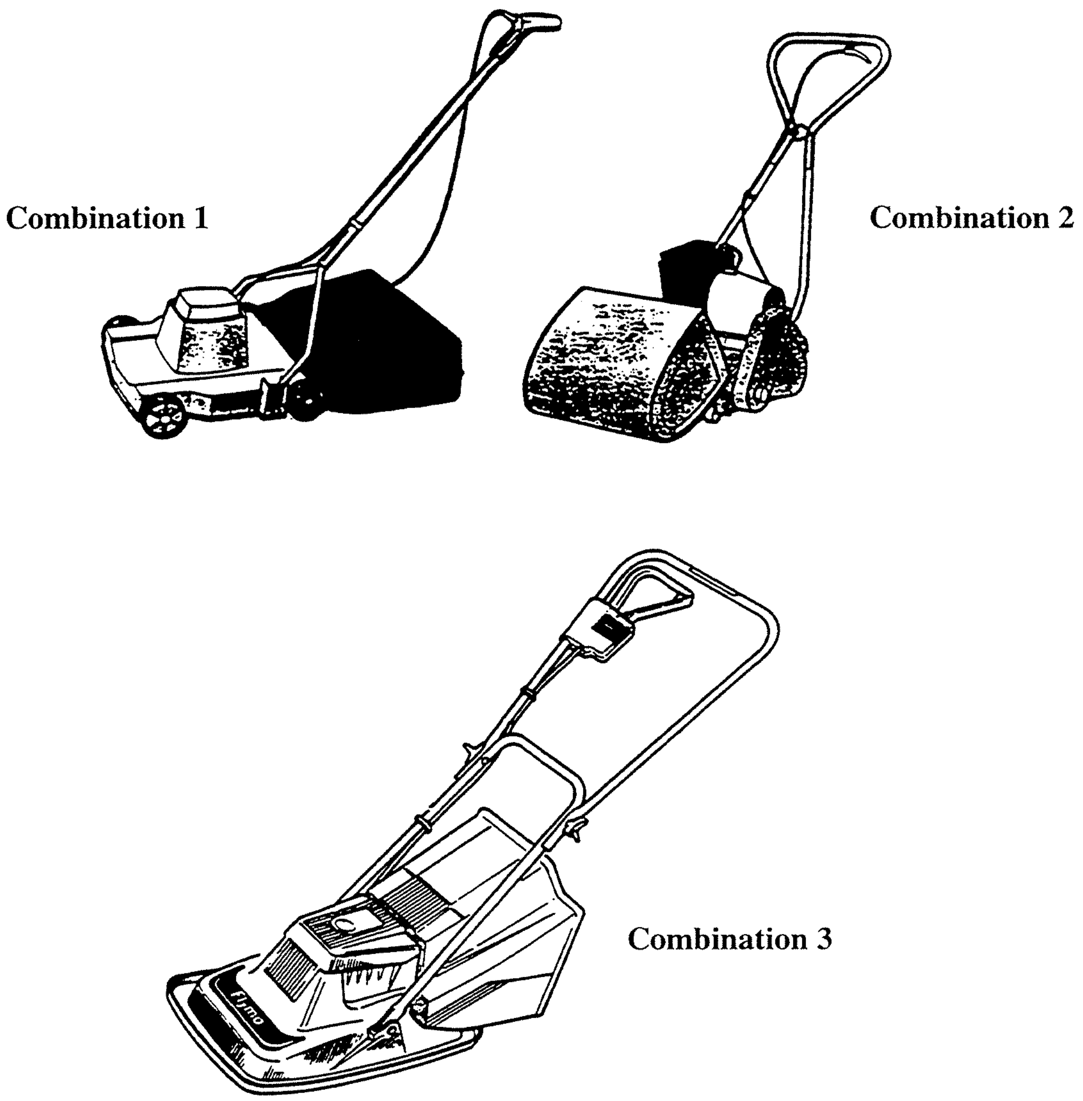


Figure 15: Grass cutter concepts

Evaluation is based on the **wishes** identified in the design specification. More than simple yes/no answers are required to determine the relative merits of each concept. To do this each criterion must be weighted to indicate its relative importance. The wishes can be ranked as being of high, medium or low importance and given numerical weightings of 3, 2 and 1 respectively. More detailed approaches are possible, leading to a much finer gradation in the weightings, but the simple approach suggested above is generally adequate, particularly for a preliminary evaluation.

The evaluation criteria need to have parameters to characterise them. Some can be quantified, such as "weight in newtons" or "power in kilowatts", but some will only have a qualitative indication, for example "easy assembly" or "pleasing appearance". So that all sorts of different parameters can be "scored" in an evaluation chart some sort of generally applicable **value** scale must be introduced. It is easiest to do this against some **datum**, so one concept is selected and the relative value for each criterion judged in turn using the following scale:

Better than the datum	**+1**	Worse than the datum	**-1**
Much better than the datum	**+2**	Much worse that the datum	**-2**

The values may now be entered into an **evaluation chart**, where each value is multiplied by the appropriate weighting to give a **weighted value** and these are then summed to give an **overall weighted value** for each concept relative to the datum. The one with the highest overall value will, generally, be the best.

An evaluation chart for the grass cutter is shown in **Figure 16**. Note that criteria which scored zero for both the wheeled and hover mowers are not shown. In this example, the hover mower is judged to be marginally better than the wheeled mower, both being considerably better than the cylinder mower. However, the results should be used cautiously bearing in mind the subjective nature of many of the numbers included in the chart. Small differences between the overall values are generally not significant, and even a concept with a high overall value can have worrying weak spots.

		CYLINDER		WHEELS		HOVER	
Criteria	**Weighting**	**Value**	**Wt val**	**Value**	**Wt val**	**Value**	**Wt val**
Manoeuvre	3	**DATUM**		+1	+3	+2	+6
Weight	3			+2	+6	+2	+6
Appearance	3			+1	+3	+2	+6
Price	3			+1	+3	0	0
Move force	2			+1	+2	+2	+4
Robust	2			-1	-2	-1	-2
Cut adjust	2			-1	-2	-2	-4
Cut speed	1			+1	+1	+2	+2
Life	1			0	0	-1	-1
			0		**+14**		**+17**

Figure 16: Evaluation chart

The **SpecBuilder** package will help will automatically select all the wishes from the design specification and set up a template evaluation chart to compare up to five concepts. The Users Guide explains this in more detail.

The technique does ensure a disciplined approach and does provide a valuable guide to the relative merits of the concepts, but in the final analysis **common sense should prevail**. Check the outcome against your first guess and check that the chosen concept meets the demands and high ranking wishes.

The selected concept must now be presented in such a way that other people are convinced that it is worth committing to the embodiment design phase - clarity and brevity are essential.

BIBLIOGRAPHY

[1] BS 7000, Guide to Managing Product Design, British Standards Institution, London, 1989.

[2] Invention and Evolution, French, M. J., Cambridge University Press, Cambridge, 1988.

[3] Form, Structure and Mechanism, French, M. J., Macmillan, London, 1992.

[4] The Design of Design, Glegg, G. L., Cambridge University Press, Cambridge, 1969.

[5] The Selection of Design, Glegg, G. L., Cambridge University Press, Cambridge, 1972.

[6] The Science of Design, Glegg, G. L., Cambridge University Press, Cambridge, 1973.

[7] The Development of Design, Glegg, G. L., Cambridge University Press, Cambridge, 1981.

[8] Engineering Design - A Systematic Approach, Pahl, G. and Beitz, W., Springer, 1996.

[9] Product Design and Development, Ulrich, K.T. and Eppinger, S.D., McGraw-Hill, 1995.

[10] Case Studies in Engineering Design, Matthews, C., Arnold, 1998.