6 Conceptual Design

Conceptual design is the part of the design process where—by identifying the essential problems through abstraction, establishing function structures, searching for appropriate working principles and combining these into a working structure—the basic solution path is laid down through the elaboration of a solution principle. Conceptual design *specifies the principle solution*.

From Figure 4.3 we can see that the conceptual phase is preceded by a decision. The purpose of this decision is to answer the following questions based on the requirements list agreed upon during task clarification:

- Has the task been clarified sufficiently to allow the development of a solution in the form of a design?
- Is a conceptual elaboration really needed, or do known solutions permit direct progress to the embodiment and detail design phases?
- If the conceptual stage is indispensable, how and to what extent should it be developed systematically?

6.1 Steps of Conceptual Design

According to the procedural plan outlined in Section 4.2, the conceptual design phase follows the clarification of the task. Figure 6.1 shows the steps involved, correlated in such a way as to satisfy the principles of the general problem solving process set out in Section 4.1.

The reasons for the individual steps have been examined in Section 4.2 and need not be discussed further here. It should, however, be mentioned that refinements of any one of the steps by reiteration on a higher information level should be made whenever necessary. The loops involved have been omitted from Figure 6.1 for the sake of greater clarity.

The individual steps and the appropriate working methods for the conceptual design phase will now be examined in detail.

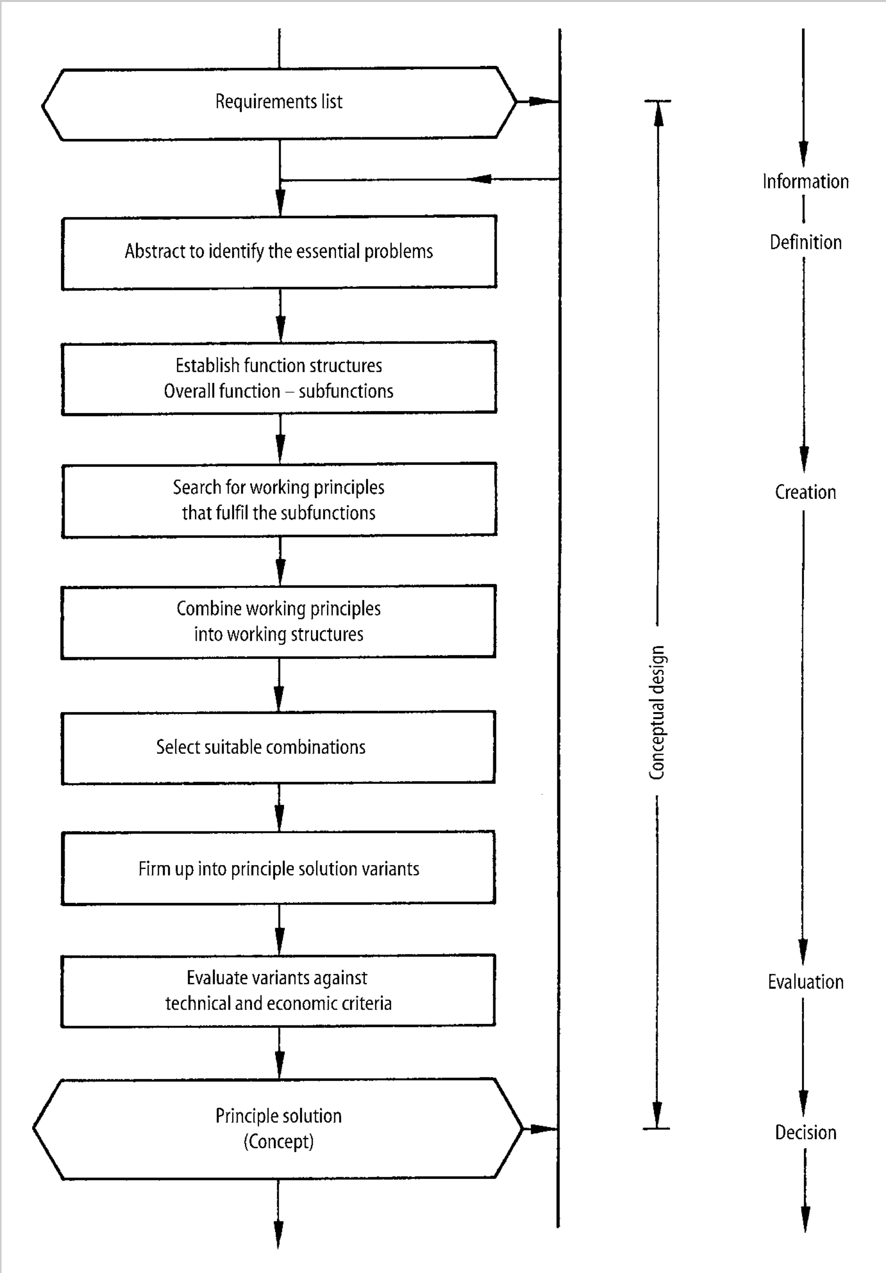


Figure 6.1. Steps of conceptual design

6.2 Abstracting to Identify the Essential Problems

6.2.1 Aim of Abstraction

Solution principles or designs based on traditional methods are unlikely to provide optimum answers when new technologies, procedures, materials, and also new scientific discoveries, possibly in new combinations, hold the key to better solutions.

Every industry and every design office is a store of experiences as well as of prejudices and conventions which, coupled to the wish to minimise risks, stand in the way of better and more economic but unconventional solutions. The client, customer or product planning group might have included specific proposals for a solution in the requirements list. It is also possible that during the discussion of individual requirements, ideas and suggestions for realising a solution will emerge. In the unconscious, at least, certain solutions might exist. Perhaps concrete ideas already exist, however these could be based on fixed ideas and fictitious constraints.

In their search for optimum solutions, designers, far from allowing themselves to be influenced by fixed or conventional ideas, must therefore examine very carefully whether novel and more suitable paths are open to them. In order to solve the problem of fixation and sticking with conventional ideas, *abstraction* is used. This means ignoring what is particular or incidental and emphasising what is general and essential. Such generalisation leads straight to the *crux of the task*. If it is properly formulated, then the overall function and the essential constraints become clear without prejudicing the choice of a particular solution in any way.

As an example, consider the improvement of a labyrinth seal in a high-speed turbine in accordance with a set of requirements. The task is described in detail by means of a requirements list and the formulation of the goal to be achieved. In the abstracting approach, the crux of the task would not so much be the design of a labyrinth seal as that of a shaft seal without physical contact, with due regard being paid to certain operating and spatial constraints, and also to cost limits and delivery times. Specifically, the designer should ask whether the crux is:

- to improve the technical functions, e.g. the sealing quality or safety
- to reduce weight or space
- to significantly lower costs
- to significantly shorten delivery times
- to improve production methods.

All of these questions might have to be satisfied by the overall solution, but their importance may differ from case to case. Nevertheless, due regard must be paid to each of them, since any one of them is likely to provide the impetus for the discovery of a new and better solution principle. New developments involving a proven solution principle, coupled to modifications in production methods, are often imposed by the need to lower costs and shorten delivery times.

Thus, if an improvement in the sealing properties were the crucial requirement in the example we have mentioned, new sealing systems would have to be found.

This would mean studying the flow of fluids in narrow passages and, from the knowledge acquired, providing for better sealing properties, while also satisfying the other subproblems we have mentioned.

If, on the other hand, cost reduction were the crucial point then, after an analysis of the cost structure, one would have to see whether the same physical effects could be produced through the use of cheaper materials, by reducing the number of components or by using a different production process. It is also possible to search for new concepts to achieve a better or at least similar sealing performance for lower cost.

It is the identification of the crux of the task with the functional connections and the task-specific constraints that throws up the essential problems for which solutions have to be found. Once the crux of the task has been clarified, it becomes much easier to formulate the overall task in terms of the essential subproblems as they emerge [6.2, 6.6, 6.13].

6.2.2 Broadening the Problem Formulation

This is the best point in the process to bring in those designers who are actually going to be responsible for the project. Having identified the crux of the task by correct problem formulation, a step-by-step enquiry is now initiated to discover if an extension of, or even a change in, the original task might lead to promising solutions.

An excellent illustration of this procedure has been given by Krick [6.5]. The task he used as an example was an improved method of filling, storing and loading bags of animal feed. An analysis gave the situation shown in Figure 6.2. It would have been a grave mistake to begin immediately by thinking of possible improvements to the existing situation. By proceeding in this way one is likely to ignore other, more useful and more economic solutions. Using abstraction and the systematic extension of what is already known about the task, the following problem formulations are possible, each representing a higher level of abstraction than the last:

1. Filling, weighing, closing and stacking bags of feed.
2. Transferring feed from the mixing silo to stacked bags in the warehouse.
3. Transferring feed from the mixing silo to bags on the delivery truck.
4. Transferring feed from the mixing silo to the delivery truck.
5. Transferring feed from the mixing silo to a delivery system.
6. Transferring feed from the mixing silo to the consumer's storage bins.
7. Transferring feed from ingredient containers to consumer's storage bins.
8. Transferring feed ingredients from their source to the consumer.

Krick has incorporated some of these formulations into a diagram (see Figure 6.3).

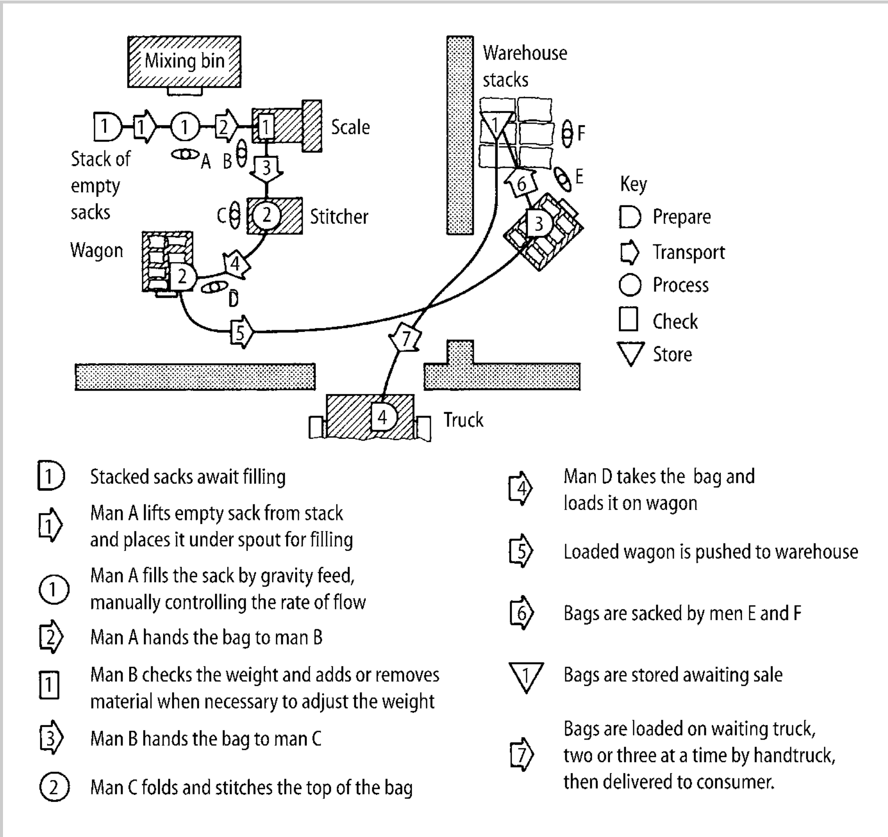


Figure 6.2. The present method of filling, storing and loading bags of feed. After [6.5]

It is characteristic of this approach that the problem formulation is made as broad as possible in successive steps. In other words, the current or obvious formulation is not accepted at face value but *broadened systematically*. Although this may conflict with decisions already taken, it opens up new perspectives. Thus, formulation 8 above is the broadest, the most general and the least circumscribed.

The crux of the task, in fact, is the transport of the correct quantity and quality of feed from the producer to the consumer and not, for instance, the best method of closing or stacking bags, or moving them into the warehouse. With a broader formulation, solutions may appear that render the filling of bags and storing them in the warehouse unnecessary.

How far this process of abstraction is continued depends on the constraints. In the case under consideration, Formulation 8 must be rejected on technical, seasonal and meteorological grounds: the consumption of feed is not confined to harvest time; for various reasons consumers will not want to store feed for a whole year; moreover, they may be reluctant to mix the required ingredients themselves. However, the transfer of feed on demand, for instance, with delivery trucks taking

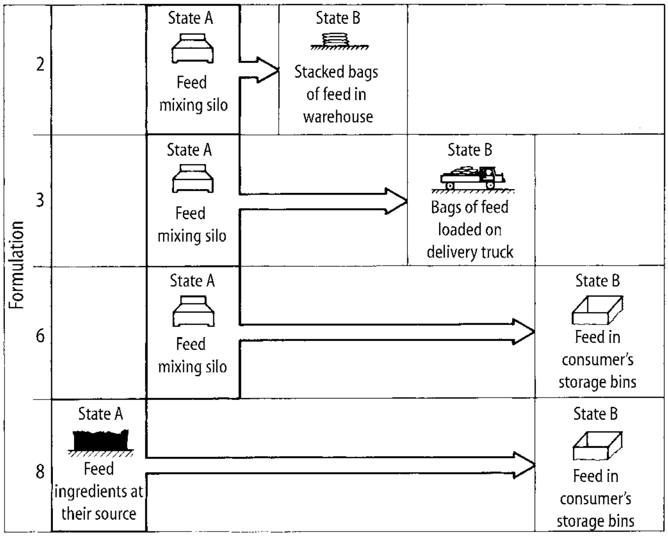


Figure 6.3. Alternative formulations of the feed distribution problem, illustrating progressively broader formulations of a problem. After [6.5]. A = initial state; B = final state

it directly from the mixing silo to consumers' storage bins (Formulation 6), is more economical than intermediate storage in a warehouse and the transport of smaller quantities in bags. In this connection, the reader might recall a development in a different field which culminated in the delivery of ready-mixed concrete direct to building sites in special vehicles.

We have tried to show how comprehensive problem formulation on an abstract plane opens the door to better solutions. This approach, furthermore, helps to raise the influence and responsibility of designers by giving them an overview of the problem and thus involving them in, for instance, environmental protection and recycling. It is useful to analyse the requirements list as set out in the next section.

6.2.3 Identifying the Essential Problems from the Requirements List

The clarification of the task with the help of a requirements list will have helped to focus attention on the problems involved and will have greatly increased the particular level of information (see Chapter 5). Elaborating the requirements list may thus be said to have prepared the way for following steps.

Here the task is to *analyse the requirements list* with respect to the required function and essential constraints in order to confirm and refine the crux of the problem. Roth [6.11] advises that the functional relationships contained in the requirements list should be formulated explicitly and arranged in order of their importance.

That analysis, coupled to the following step-by-step abstraction, will reveal the general aspects and essential problems of the task, as follows:

Step 1. Eliminate personal preferences.

Step 2. Omit requirements that have no direct bearing on the function and the essential constraints.

Step 3. Transform quantitative into qualitative data and reduce them to essential statements.

Step 4. As far as it is purposeful, generalise the results of the previous step.

Step 5. Formulate the problem in solution-neutral terms.

Depending on either the nature of the task or the size of the requirements list (or both), certain steps may be omitted.

Table 6.1 illustrates abstraction based on these steps using the requirements list for a motor vehicle fuel gauge shown in Figure 6.4. The general formulation makes it clear that, with respect to the functional relationships, the problem is the measurement of quantities of liquid, and that this is subject to the essential conditions that the quantity of liquid is changing continuously and that the liquid is in containers of unspecified size and shape.

This analysis thus leads to a definition of the objective on an abstract plane without laying down any particular solution.

In principle, all paths must be left open until such time as it becomes clear which solution principle is the best. Thus designers must question all the constraints they are given and work out with the client or proposer whether or not they should be retained as genuine restrictions. In addition, designers must learn to discard fictitious constraints that they themselves have come to accept, and to that end ask critical questions and test all their presuppositions. Abstraction helps to identify fictitious constraints and to eliminate all but genuine restrictions.

We shall conclude this section with a few examples of purposeful abstraction and problem formulation:

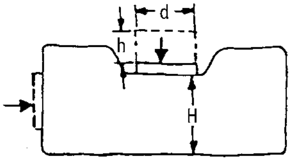
- Do not design a garage door, but look for means of securing a garage in such a way that a car is protected from thieves and the weather.
- Do not design a keyed shaft, but look for the best way of connecting a gear wheel and shaft.
- Do not design a packing machine, but look for the best way of despatching a product safely or, if specific constraints really exist, of packing a product safely, compactly and automatically.
- Do not design a clamping device, but look for a means of keeping a workpiece firmly fixed.

From the above formulations, and this is very helpful for the next step, the final formulation can be derived in a way that does not prejudice the solution, i.e. is *solution-neutral*, and at the same time turns it into a *function*:

- "Seal shaft without contact", not "Design a labyrinth seal".
- "Measure quantity of fluid continuously", not "Gauge height of liquid with a float".
- "Measure out feed", not "Weigh feed in sacks".

TH Darmstadt	Requirements list for fuel gauge	3rd issue 10/07/85 Page 1

Changes	D W	Requirements	Responsible
		• Container	
		Geometry H = 100 mm – 600 mm Volume: 20 – 160 litres	
	W	2 – 630 litres	
		Shape fixed but unspecified (rigid)	
	W	Container flexible or only partially rigid	
		Material: steel, plastic Connection to container Bayonet socket, clamped connections, top or side:	
	W	d = ∅71 mm, h = 20 mm	
		Tank not pressurised (ventilated) Pressure test for container 0.3 bar	
		Contents, temperature range	



Liquid	Operating Range °C	Storage enviroment °C
Petrol	– 25 to + 65	
Diesel	– 24 to + 65	– 40 to + 100
Engine oil (W)	up to + 140	– 40 to + 100

Changes	D W	Requirements	Responsible
	W	• Display System with electric input signal – Moving magnet instrument (catalogue) – Bimetallic instrument (catalogue) – Board computer	
		Availabel source of energy: DC at 12 V, 24 V Voltage variation – 10 % to + 25 % of nominal voltage Current consumption max. 300 mA	

	Replaces 2nd issue of 27/06/1973	

Figure 6.4. Requirements list: motor vehicle fuel gauge

TH Darmstadt	Requirements list for fuel gauge	3rd issue 10/07/85 Page 2

Changes	D W	Requirements	Responsible
		• System to be developed	
		Geometry	
		Consider connection constraints to container	
		Kinematics	
	W	No moving parts	
		Energy (see display)	
		Material (see container)	
		Signal	
		∘ Input	
		Minimum measurable content: 3 % of maximum value	
		Reserve tank contents by special signal	
	W	Signal unaffected by angle of liquid surface	
		Possibility of signal calibration	
	W	Possiblity of signal calibration with full container	
		∘ Output	
	W	Output of transmitter: electric signal	
		Output signal accuracy at max. value ±3 %	
	W	±2 %	
		(together with indicator error ±5 %)	
		Under normal conditions, horizontal level, v = const.	
		Able to withstand shocks of normal driving	
		Response sensitivity: 1 % of maximum output signal	
	W	0.5 % of maximum output signal	
		∘ Connection between input and output	
		Distance container – display: ≠ zero m;	
		3 m–4 m	
	W	1 m–20 m	
		Separate power possible	
		Production	
		large-scale production	

	Replaces 2nd issue of 27/06/1973	

Figure 6.4. (continued)

TH Darmstadt	Requirements list for fuel gauge	3rd issue 10/07/85 Page 3

Changes	D W	Requirements	Responsible
		<u>Test requirements</u>	
		<u>Operating conditions of vehicle</u>	
		Forward acceleration $\pm$ 10 m/s^2	
		Sideways acceleration $\pm$ 10 m/s^2	
		Upward acceleration (vibration), up to 30 m/s^2	
	W	Shocks in forward direction without damage, up to 30 m/s^2	
		Forward tilt up to $\pm 30°$	
		Sideways tilt max 45°	
		Salt spray tests for inside and outside components according to client's requirements (DIN 90905 to be considered)	
		Must conform with heavy vehicle regulations	
		<u>Operation, Maintenance</u>	
	W	Installation by non-specialist	
		Life expectancy 10^4 level changes (full/empty)	
		Minimum of 5 years service life	
		Fuel gauge replaceable	
		Fuel gauge maintenance-free	
	W	Fuel gauge simply modified to suite different container sizes	
		<u>Regulations</u>	
		No regulations relating to explosion safety	
		<u>Quantity</u>	
		10000/day of adjustable type	
		5000/day of the most popular type	
		Costs	
		Manufacturing costs $\leq$ DM 6.00 each (without display)	

	Replaces 2nd issue of 27/06/1973	

Figure 6.4. (continued)

Table 6.1. Procedure during abstraction: motor vehicle fuel gauge based on requirements list given in Figure 6.4

Result of Steps 1 and 2

- Volumes: 20 to 160 litres
- Shape of container: fixed or unspecified (rigid)
- Top or side connection
- Height of container: 100 mm to 600 mm
- Distance between container and indicator: $\neq 0$ m, 3 m to 4 m
- Petrol and diesel, temperature range: $-25\,°C$ to $65\,°C$
- Output of transmitter: unspecified signal
- External energy: DC at 12 V, 24 V. Variation -15% to $+25\%$
- Output signal accuracy at maximum $\pm 3\%$ (together with indicator error $\pm 5\%$)
- Response sensitivity: 1% of maximum signal output
- Possibility of signal calibration
- Minimum measurable content: 3% of maximum value

Result of Step 3

- Various volumes
- Various container shapes
- Various connections
- Various contents (liquid levels)
- Distance between container and indicator: $\neq 0$ m
- Quantity of liquid varies with time
- Unspecified signal
- (with outside energy)

Result of Step 4

- Various volumes
- Various container shapes
- Transmission over various distances
- Measure (continuously changing) quantities of liquid
- (with outside energy)

Result of Step 5 (Problem formulation)

- Measure continuously changing quantities of liquid in containers of unspecified size and shape and indicate the measurements at various distances from the containers.

6.3 Establishing Function Structures

6.3.1 Overall Function

According to Section 2.1.3, the requirements determine the function that represents the intended overall relationship between the inputs and the outputs of a plant, machine or assembly. In Section 6.2 we explained that problem formulation obtained by abstraction does much the same. Hence, once the crux of the overall problem has been formulated, it is possible to indicate an *overall function* that, based on the *flow of energy, material and signals* can, with the use of a *block diagram*, express the solution-neutral relationship between *inputs* and *outputs*. That relationship must be specified as precisely as possible (see Figure 2.3).

In our example of a fuel gauge (see Figure 6.4), quantities of liquid are introduced into and removed from a container, and the problem is to measure and indicate the quantity of liquid found in the container at any one time. The result, in the liquid system, is a flow of material with the function "store liquid" and, in the measuring system, a flow of signals with the function "measure and indicate quantity of liquid". The second is the overall function of the specific task under consideration, that is, the development of a fuel gauge (see Figure 6.5). That overall function can be broken down into subfunctions in a further step.

6.3.2 Breaking a Function Down into Subfunctions

Depending on the complexity of the problem, the resulting overall function will in turn be more or less complex. By complexity we mean that the transparency of the relationships between inputs and outputs is relatively poor, that the required physical processes are relatively intricate, and that the number of assemblies and components involved is relatively large.

Just as a technical system can be divided into subsystems and elements (see Section 2.1.3), so a complex or *overall function* can be broken down into *subfunctions* of lower complexity. The combination of individual subfunctions results in a *function structure* representing the overall function.

The aims of breaking down complex functions are to:

- determine subfunctions that facilitate the subsequent search for solutions
- combine these subfunctions into a simple and unambiguous function structure.

Let us return to the example of the fuel gauge (see Sections 6.2.3 and 6.3.1). The starting point is the problem formulation for the overall function given in Figure 6.5.

The flow of signals has been treated as the main flow. Associated subfunctions are developed in several steps. As a first step, the contents of the container have to be measured and the resulting signal received. This signal has to be channelled and

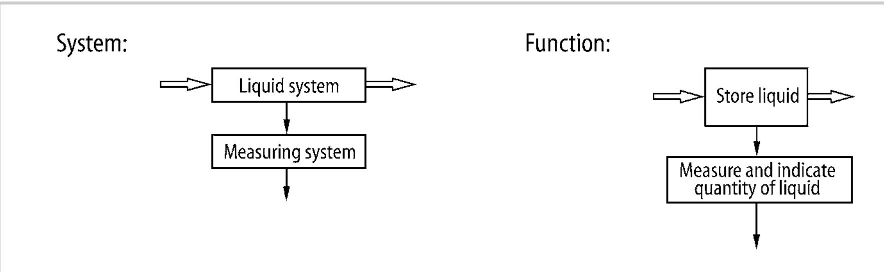


Figure 6.5. Overall functions of the systems involved in measuring the contents of a container. After Figure 6.4 and Table 6.1

finally displayed to the driver to indicate the contents of the container. Thus, three important direct main functions have been identified. Possibly the signal needs to be changed before it can be channelled. Figure 6.6 shows the development and variation of a function structure in accordance with the suggestions set out in this section.

Since the requirements list also provides for measurements in containers of different sizes holding varying initial quantities of liquid, an adjustment of the signal to the respective size of the container is expedient, and is accordingly introduced as an auxiliary function. Measurements in containers of various unspecified shapes will, in certain circumstances, demand the correction of the signal as another auxiliary function. The measuring operation may require a supply of external energy, which must then be introduced as a further flow. Finally, consider the system boundary. If existing indicating instruments are to be used, the device will have to emit an electric output signal. If they are not, then the subfunctions "channel signal" and "indicate signal" must be included in the search for solutions. In this way, a function structure with suitable subfunctions can be developed. The individual subfunctions are of a lower complexity than the overall function and, furthermore, it will become clear which subfunction provides the most useful starting point for the search for solutions.

In our example, this important solution-determining subfunction, that has the working principle upon which the others clearly depend, is "receive signal" (see Figure 6.6). The initial search for solutions should therefore focus on this subfunction. The solution selected for this will largely decide to what extent individual subfunctions can be changed round or omitted. It also allows for better judgement of whether to use existing channelling and display solutions or whether to seek a new solution for these subfunctions, i.e. an extension of the system boundary.

Further recommendations for identifying and formulating subfunctions are now described.

It is useful to start by determining the *main flow* in a technical system, if this is clear. The *auxiliary flows* should only be considered later. When a basic function structure, including the most important links, has been found, it is easier to undertake the next step; that is, to consider the auxiliary flows with their subfunctions and to achieve a further subdivision of complex subfunctions. For this step it is helpful to create a temporary working structure or a solution for the *basic function structure*, without, however, prejudicing the final solution.

The optimum method of breaking down an overall function—that is, the number of subfunction levels and also the number of subfunctions per level—is determined by the relative novelty of the problem and also by the method used to search for solutions. In the case of *original designs*, neither the individual subfunctions nor their relationships are generally known. In that case, the search for and establishment of an optimum function structure constitute some of the most important steps of the conceptual design phase. In the case of *adaptive designs*, on the other hand, the general structure with its assemblies and components is much more well-known, so that a function structure can be obtained by analysing the existing product. Depending on the special demands of the requirements list, that function

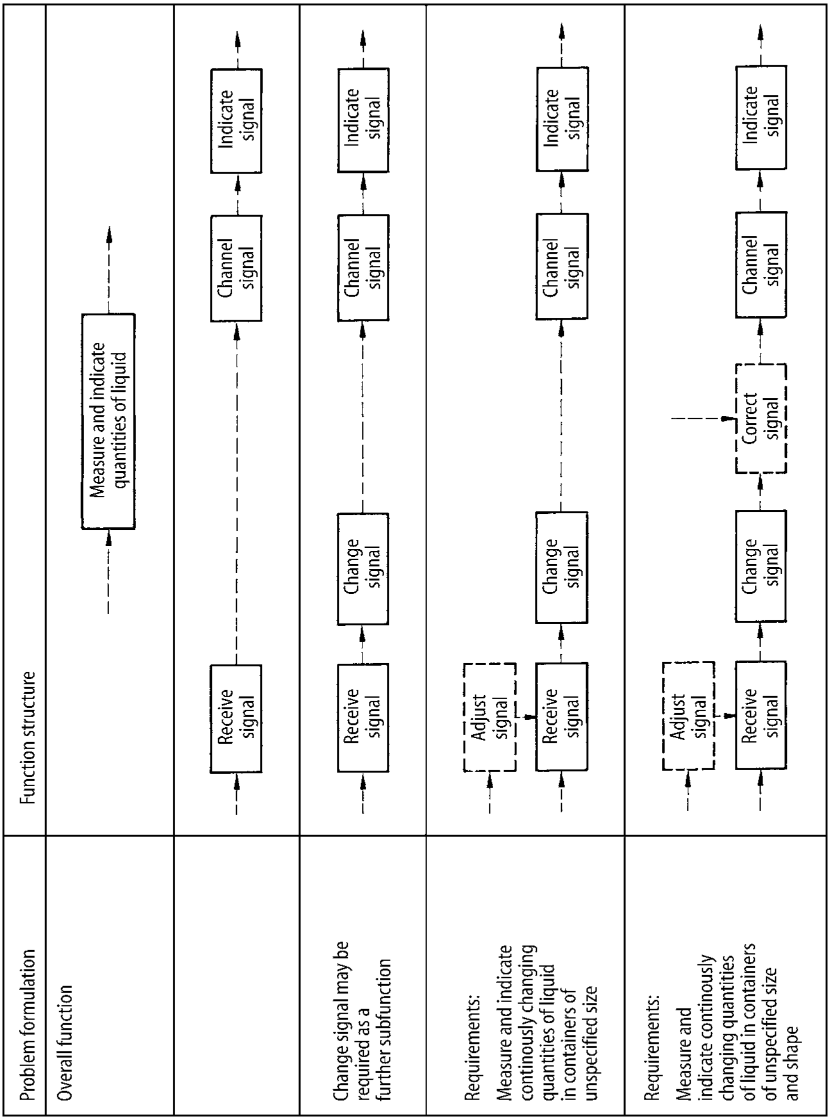


Figure 6.6. Development of a function structure for a fuel gauge

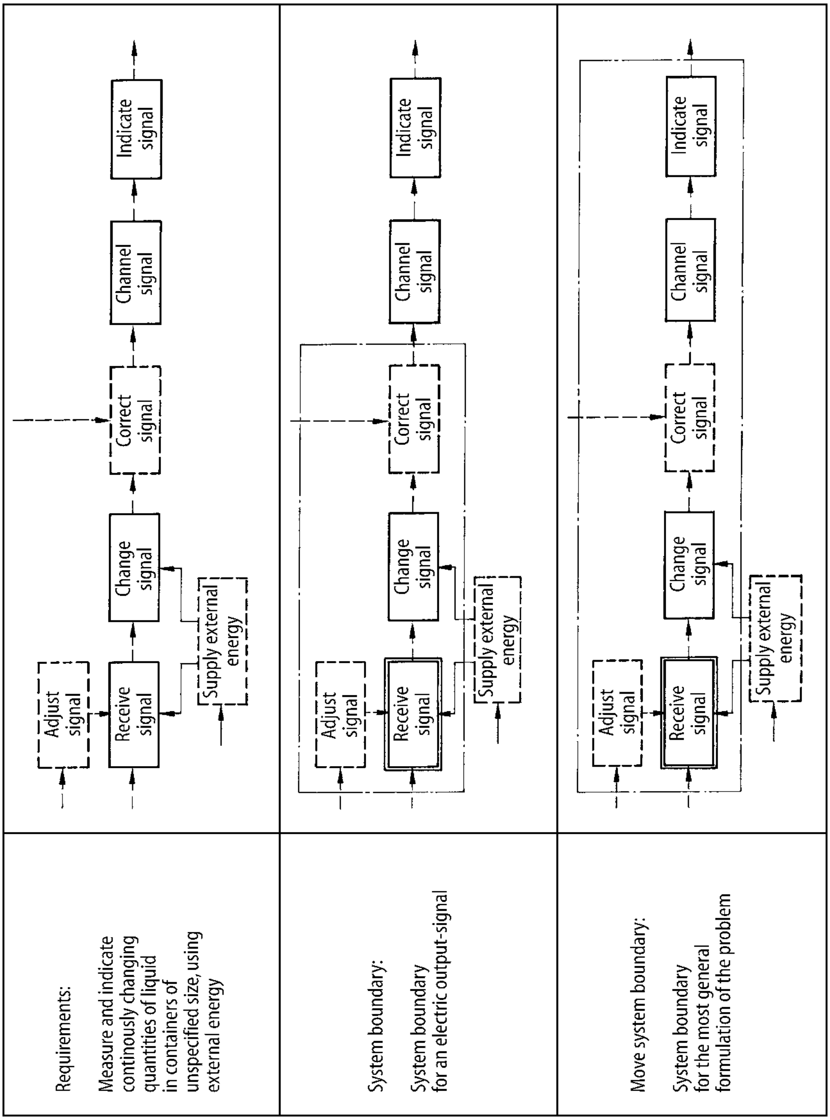


Figure 6.6. (continued)

structure can be modified by the variation, addition or omission of individual subfunctions or by changing the way that they are combined.

Function structures are of great importance in the development of modular systems. For this type of *variant design*, the physical structure—that is, the assemblies and individual components used as building blocks and also their interfaces—must be reflected in the function structure (see also Section 9.2.1).

A further advantage of setting up a function structure is that it permits the *clear definition* of existing subsystems or of those to be newly developed, so that they can be *dealt with separately*. If existing assemblies can be assigned directly as complex subfunctions, the subdivision of the function structure can be discontinued at a fairly high level of complexity. In the case of new assemblies or those requiring further development, however, the division into subfunctions of decreasing complexity must be continued until the search for solutions seems promising. By adapting function structures to the novelty of the task or the subsystem, the use of function structures can save a great deal of time and money.

Apart from aiding in the search for solutions, function structures or their subfunctions can also be used for purposes of classification. Examples are the "classifying criteria" of classification schemes (see Section 3.2.3) and the subdivision of design catalogues.

It may prove expedient not only to set up task-specific functions, but also to elaborate the function structure from *generally valid subfunctions* (see Figure 2.7). The latter recur in technical systems, and may be helpful when searching for a solution since they may lead to the discovery of task-specific subfunctions or because design catalogues may list solutions for them. Defining generally valid functions can also be of use when varying function structures, for example to optimise the energy, material and signal flows. The following list and examples should be helpful in this regard.

Conversion of energy:

- Changing energy (e.g. electrical into mechanical energy)
- Varying energy components (e.g. amplifying torque)
- Connecting energy with a signal (e.g. switching on electrical energy)
- Channelling energy (e.g. transferring power)
- Storing energy (e.g. storing kinetic energy)

Conversion of material:

- Changing matter (e.g. liquefying a gas)
- Varying material dimensions (e.g. rolling sheet metal)
- Connecting matter with energy (e.g. moving parts)
- Connecting matter with signal (e.g. cutting off steam)
- Connecting different types of materials (e.g. mixing or separating materials)
- Channelling material (e.g. mining coal)
- Storing material (e.g. keeping grain in a silo)

Conversion of signals:

- Changing signals (e.g. changing a mechanical into an electrical signal, or a continuous into an intermittent signal)
- Varying signal magnitudes (e.g. increasing a signal's amplitude)
- Connecting signals with energy (e.g. amplifying measurements)
- Connecting signals with matter (e.g. marking materials)
- Connecting signals with signals (e.g. comparing target values with actual values)
- Channelling signals (e.g. transferring data)
- Storing signals (e.g. in databases)

In many cases in industry it may not be expedient to build up a function structure from generally valid subfunctions, because they are, in fact, too general and thus do not provide a sufficiently concrete picture of the relationships to aid the subsequent search for solutions. In general, a clear picture only emerges after adding more task-specific details (see Section 6.3.3).

To illustrate the approach some expamples follow. Figures 6.7 and 6.8 show the function structure of a tensile testing machine with a relatively complex flow of energy, material and signals. In this type of overall function, the function structure is built up step-by-step from subfunctions, with attention initially focused on essential main functions. Thus, on a first functional level, only the subfunctions

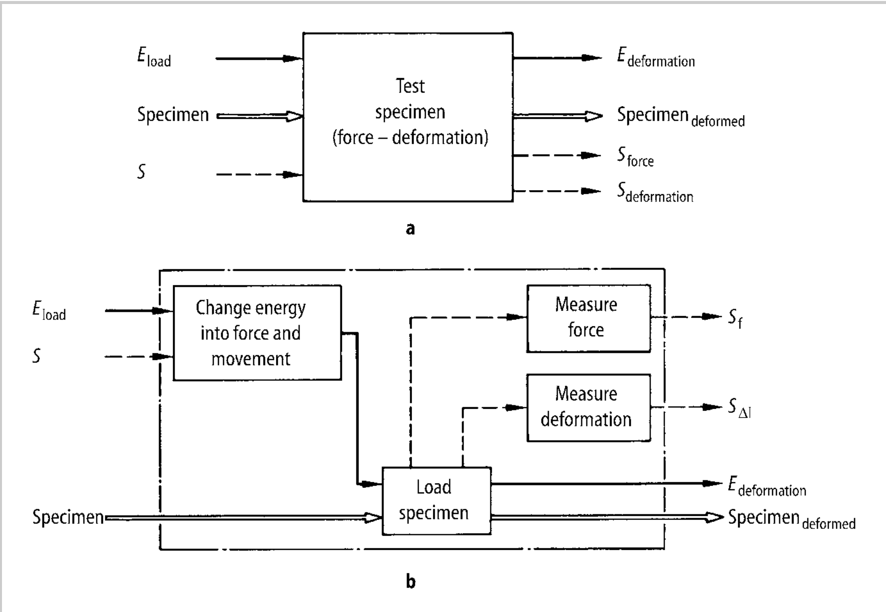


Figure 6.7. Overall function **a** and subfunctions (main functions) **b** of a tensile testing machine

that directly satisfy the required overall function are specified (see Figure 6.7). These are formulated as complex subfunctions, such as "change energy into force and movement" and "load specimen" in our example. Starting with complex subfunctions helps to establish a simple function structure.

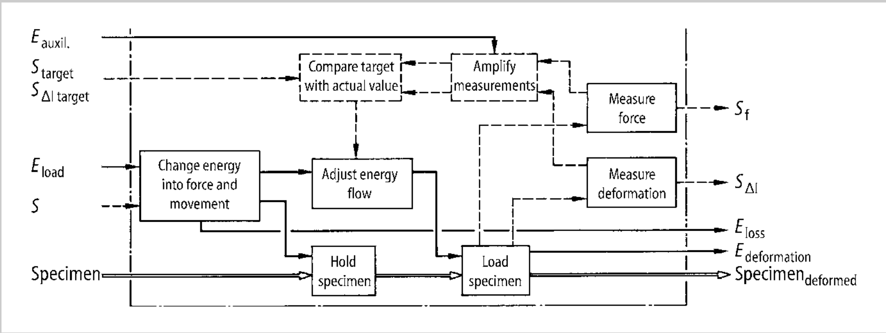


Figure 6.8. Completed function structure for the overall function set out in Figure 6.7

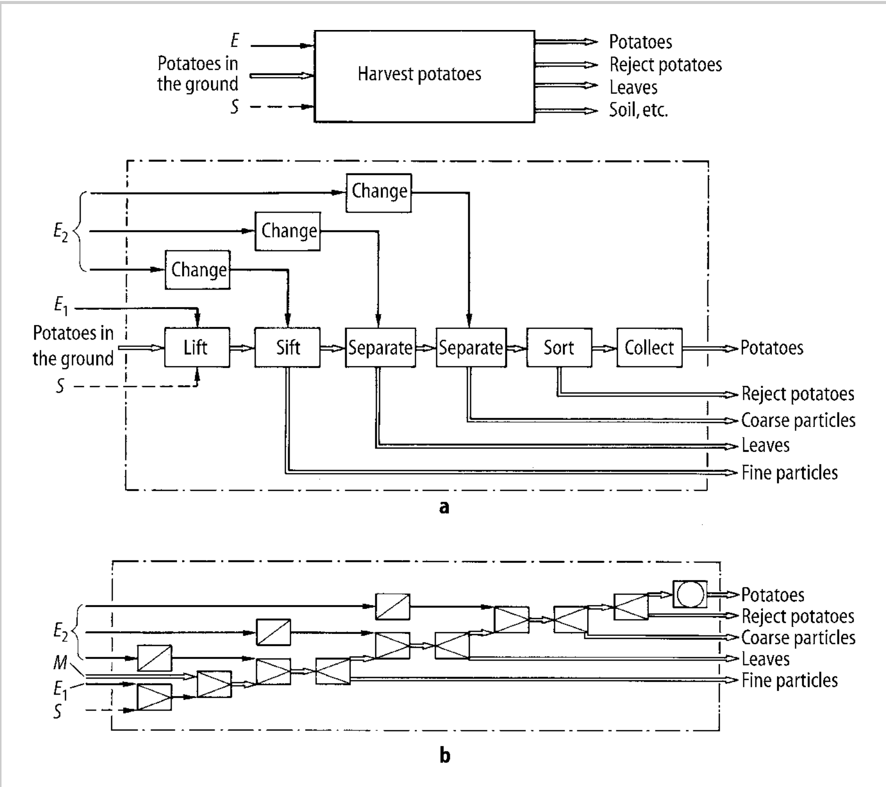


Figure 6.9. a Function structure of a potato harvesting machine **b** For comparison: diagram with generally valid functions based on [6.1], Figure 2.7

In the problem under consideration, the energy and signal flows are of roughly equivalent importance in the search for solutions, while the flow of material—the exchange of specimens—is only essential for the holding function added in Figure 6.8. In this figure, an adjusting function for the load magnitudes and, at the output of the system, the energy lost during the energy flow were also added because both clearly affect the design. The energy required to deform the specimen is lost with the material flow when the specimen is exchanged. Moreover, the auxiliary functions "amplify measurements" and "compare target with actual values" proved indispensable for the adjustment of the energy level.

There are, however, some problems in which variation of the main flow alone cannot lead to a solution, because *auxiliary flows* have a *crucial* bearing on the design and are solution-determining. As an example, let us consider the function structure of a potato harvesting machine. Figure 6.9a shows the overall function and the function structure based on the flow of material (the main flow) and the auxiliary flows of energy and signals. In Figure 6.9b, by comparison, the function structure is represented by means of generally valid functions, in order to emphasise the clear interrelationship of the different flows.

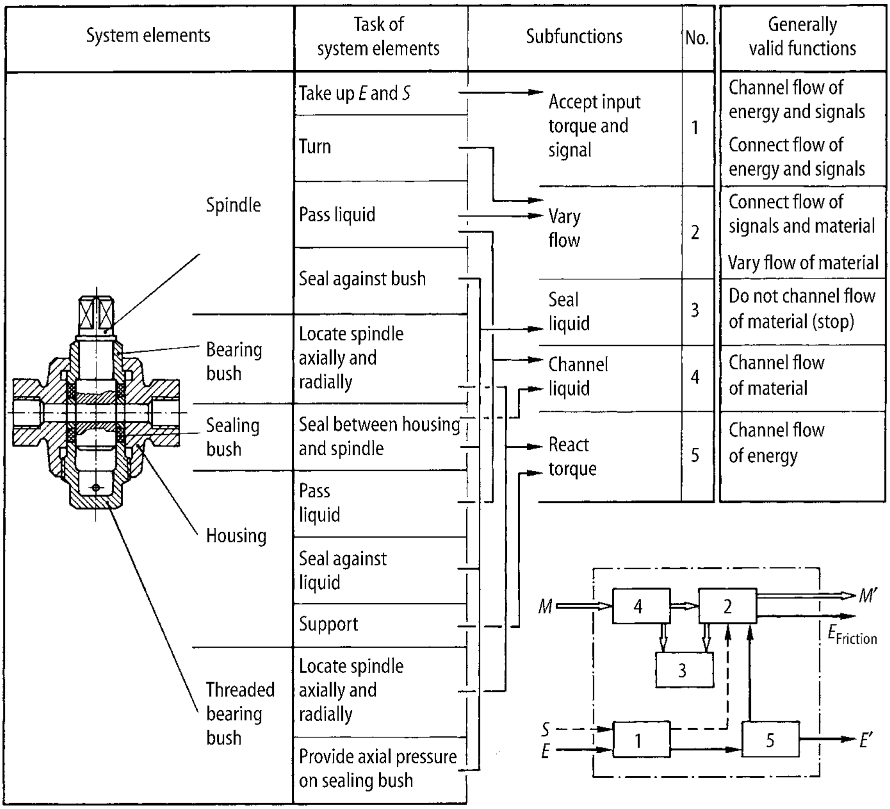


Figure 6.10. Analysis of a flow control valve with respect to its function structure

When generally valid functions are used, the separation into subfunctions is generally more pronounced than it is in the case of task-specific subfunctions. Thus, in the present example, the subfunction "separate" is replaced with the generally valid functions "connect energy with material mix" and "separate material mix" (the reverse of "connect"). The representation, however, is on such an abstract level that it is not easy to understand and requires further interpretation.

Our final example illustrates the derivation of function structures by the *analysis of existing systems*. This method is particularly suitable for developments in which at least one solution with the appropriate function structure is known, and the main problem is the discovery of better solutions. Figure 6.10 shows the steps used in the analysis of a flow control valve (a typical on–off switch), showing the individual tasks of the various elements and the subfunctions satisfied by the system. The function structure can be derived from the subfunctions and then varied in order to improve the product.

The function structure for the one-handed mixing tap examined in Section 6.6 clearly shows that the study of function structures may prove extremely useful, even after the physical effect has been selected, for determining the behaviour of the system at a very early stage of its development, and hence for identifying the structure that best suits the problem under consideration.

6.3.3 Practical Applications of Function Structures

When establishing function structures, we must distinguish between original and adaptive designs. In the case of *original designs*, the basis of a function structure is the *requirements list* and the *abstract formulation of the problem*. Among the demands and wishes, we are able to identify functional relationships, or at least the subfunctions at the inputs and outputs of a function structure. It is helpful to write out the functional relationships arising from the requirements list in the form of sentences and to arrange these in the order of their anticipated importance or in some other logical order [6.11].

In the case of *adaptive designs*, the starting point is the *function structure of the existing solution* obtained by analysing its elements. It helps to develop variants in order to open the path for other solutions, for subsequent optimisation and for the development of modular products. The identification of functional relationships can be facilitated by asking the right questions.

In modular systems, the function structure has a decisive influence on the modules and their arrangement (see Section 9.2). Here, the function structure and that of the assembly is affected not only by functional considerations, but also, and increasingly so, by production needs.

Function structures are intended to facilitate the discovery of solutions: they are not ends in themselves. The degree of detail used depends very much on the novelty of the task and the experience of the designers.

Moreover, it should be remembered that function structures are seldom completely free of physical or formal presuppositions, which means that the number of possible solutions is inevitably restricted to some extent. Hence, it is perfectly legitimate to conceive a preliminary solution and then abstract this by developing and completing the function structure by a process of iteration.

Anyone setting up a function structure ought to bear the following points in mind:

1. First derive a rough function structure with a few subfunctions from what functional relationships you can identify in the requirements list, and then break this rough structure down, step-by-step, by resolving complex subfunctions. This is much simpler than starting out with more complicated structures. In certain circumstances, it may be helpful to substitute a first solution idea for the rough structure and then, by analysing that first idea, to derive other important subfunctions. It is also possible to begin with subfunctions whose inputs and outputs cross the assumed system boundary. From these, we can then determine the inputs and outputs for the neighbouring functions; in other words, we work from the system boundary inwards.

2. If no clear relationship between the subfunctions can be identified, the search for a first solution principle may, under certain circumstances, be based on the mere *enumeration of identified subfunctions* without logical or physical relationships, but if possible these should be arranged according to the extent to which they have been realised.

3. *Logical relationships* may lead to function structures through which the logical elements of various working principles (mechanical, electrical, etc.) can be anticipated.

4. Function structures are not complete unless the existing or expected flows of energy, material and signals can be specified. Nevertheless, it is useful to begin by focusing attention on the *main flow* because, as a rule, it determines the design and is more easily derived from the requirements. The auxiliary flows then help with the further elaboration of the design, coping with faults, and when dealing with problems of power transmission, control, etc. The complete function structure, comprising all flows and their relationships, can be obtained by iteration; that is, by looking first for the structure of the main flow, completing that structure by taking the auxiliary flows into account, and then establishing the overall structure.

5. When setting up function structures it is useful to know that, in the conversion of energy, material and signals, several *subfunctions recur* in most structures and should therefore be introduced first. Essentially, these are the generally valid functions of Figure 2.7, and they can prove extremely helpful in the search for task-specific functions.

6. For the application of microelectronics, it is useful to consider signal flows as shown in Figure 6.11 [6.6]. This results in a function structure that clearly suggests the modular use of elements to detect (sensors), to activate (actuators), to operate (controllers), to indicate (displays) and, in particular, to process signals using microprocessors.

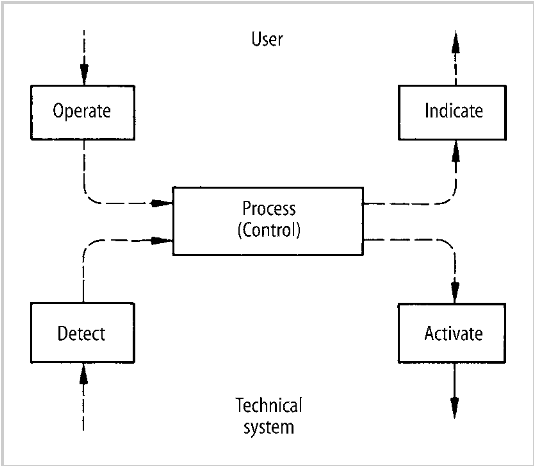


Figure 6.11. Basic signal flow functions for modular use in microelectronics. After [6.6]

7. From a rough structure, or from a function structure obtained by the analysis of known systems, it is possible to derive further *variants* and hence to optimise the solution, by:
   - breaking down or combining individual subfunctions
   - changing the arrangement of individual subfunctions
   - changing the type of switching used (series switching, parallel switching or bridge switching)
   - moving the system boundary.

   Because varying the function structure introduces distinct solutions, the setting up of function structures constitutes a first step in the search for solutions.
8. Function structures should be kept as *simple* as possible, in order to encourage simple and economical solutions. To this end, it is also advisable to aim at the combination of functions for the purpose of obtaining integrated function carriers. There are, however, some problems in which discrete functions must be assigned to discrete function carriers; for instance, when the requirements demand clarity in the solution, or when there is a need for extreme loading and quality. In this connection, the reader is referred to our discussion on the division of tasks (see Section 7.4.2).
9. In the search for solutions, only *promising function structures* should be introduced, which implies that a *selection procedure* (see Section 3.3.1) should be employed, even at this early stage.
10. For the *representation* of function structures it is best to use the *simple and informative symbols* shown in Figure 2.4, supplemented with task-specific verbal clarifications.

11. An *analysis* of the function structure leads to the identification of those subfunctions for which new working principles must be found, and of those for which known solutions can be used. This encourages an efficient approach. The search for solutions (see Section 3.2) then focuses on the subfunctions that are essential for the solution and on which the solutions of other subfunctions depend (see the example in Figure 6.6).

It is sometimes assumed wrongly that auxiliary functions are unimportant. Technical systems do not have functions that are "more important" or "less important". All functions are important because they are needed. Any functions that are not necessary or superfluous functions should be eliminated. It is only in order to reduce effort that designers start their search for solutions with the function that seems most important, i.e. solution-determining. All of the other functions are still necessary and must be fulfilled.

6.4 Developing Working Structures

6.4.1 Searching for Working Principles

Working principles need to be found for the various subfunctions, and these principles must eventually be combined into a working structure. The concretisation of the working structure will lead to the principle solution. A working principle must reflect the physical effect needed for the fulfilment of a given function and also its geometric and material characteristics (see Section 2.1.4). In many cases, however, it is not necessary to look for new physical effects, the form design (geometry and materials) being the sole problem. Moreover, in the search for a solution it is often difficult to make a clear mental distinction between the physical effect and the form design features. Designers therefore usually search for working principles that include the physical process along with the necessary geometric and material characteristics, and combine these into a working structure. Theoretical ideas about the nature and form of function carriers are usually presented by way of diagrams or freehand sketches.

It should be emphasised that the step we are now discussing is intended to lead to several solution variants, that is, a solution field. A solution field can be constructed by varying the physical effects and the form design features. Moreover, in order to satisfy a particular subfunction, several physical effects may be involved in one or several function carriers.

In Section 3.2 we discussed methods and tools for finding solutions. The same methods can be used in the search for working principles. Of particular importance, however, are literature searches, methods for analysing natural and known technical systems, and intuition-based methods (see Section 3.3.2). If preliminary solution ideas are available from product planning or through intuition, systematic analyses of physical processes and the utilization of classification schemes are also helpful (see Section 3.2.3). The last two methods usually provide several solutions.

Other important tools are design catalogues, in particular those proposed by Roth and Koller for physical effects and working principles (see Section 3.2.3)

[6.3, 6.11, 6.14]. When solutions need to be found for *several subfunctions*, it is expedient to select the functions as classifying criteria; that is, the subfunctions become the row headings and the possible working principles are entered in the columns. Figure 6.12 illustrates the structure of such a classification scheme, where the subfunctions are represented by F_i and the solution elements by S_{ij}. Depending on the level of concretisation, these solution elements can be physical effects or even working principles with geometric and material details.

As an example we consider the development of a cylinder–cylinder test rig in which two cylinders run against each other under a pulsating load. The aim was to investigate the friction characteristics for any combination of rolling and sliding speeds [6.9]. Figure 6.13 shows one possible function structure and Figure 6.14 the corresponding classification scheme. The main subfunctions identified are listed in the first column and potential solutions to those subfunctions are entered in the rows.

To sum up: the search for working principles for subfunctions should be based on the following guidelines:

- Preference should be given to the main subfunctions that determine the principle of the overall solution and for which no solution principle has yet been discovered.
- Classifying criteria and associated parameters (characteristics) should be derived from identifiable relationships between the energy, material and signal flows, or from associated systems.
- If the working principle is unknown, it should be derived from the physical effects and, for instance, from the type of energy. If the physical effect has been determined, appropriate form design features (working geometry, working motions and materials) should be chosen and varied. Checklists should be used to stimulate new ideas (see Figures 3.17 and 3.18).
- Designers should also enter solutions found intuitively and analyse which key classifying criteria influence particular working principles. These criteria should then be subdivided, limited or generalised using further headings.
- To prepare for the selection process, the important properties of the working principles should be noted.

Sub-functions \ Solutions		1	2	…	j	…	m
1	F_1	S_{11}	S_{12}		S_{1j}		S_{1m}
2	F_2	S_{21}	S_{22}		S_{2j}		S_{2m}
⋮	⋮	⋮	⋮		⋮		⋮
i	F_i	S_{i1}	S_{i2}		S_{ij}		S_{im}
⋮	⋮	⋮	⋮		⋮		⋮
n	F_n	S_{n1}	S_{n2}		S_{nj}		S_{nm}

Figure 6.12. Basic structure of a classification scheme with the subfunctions of an overall function and associated solutions

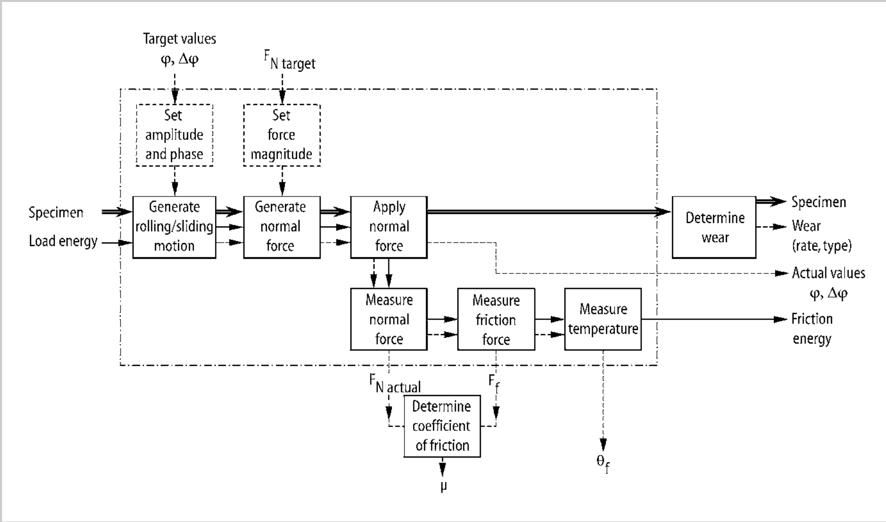


Figure 6.13. Possible function structure for a cylinder–cylinder test rig with a pulsating load for any combination of rolling and sliding motion

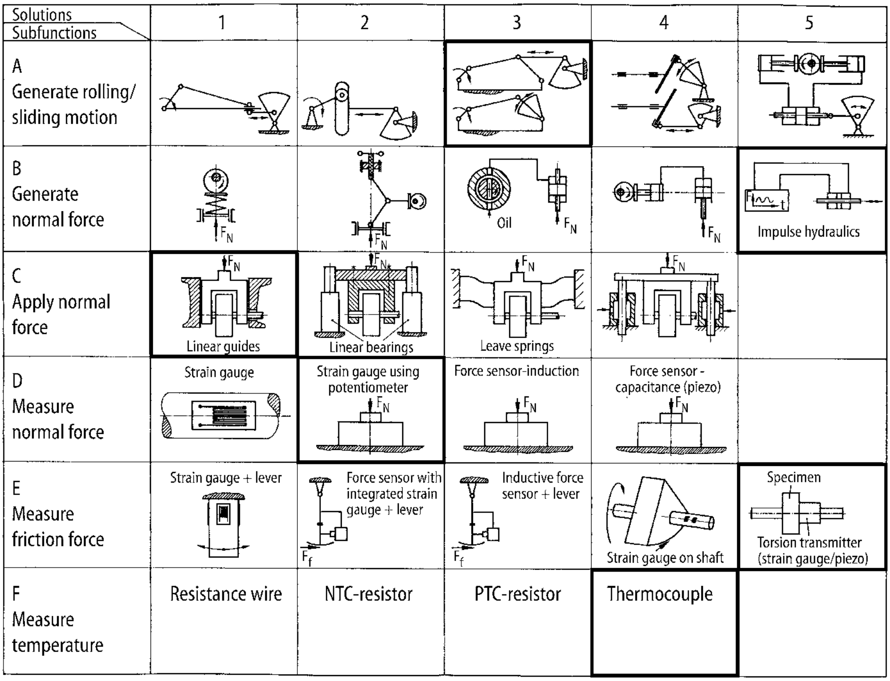


Figure 6.14. Classification scheme with possible solutions for the subfunctions identified in the function structure in Figure 6.13

Section 6.6 provides further examples that illustrate the search for working principles.

6.4.2 Combining Working Principles

To fulfil the overall function, it is then necessary to generate overall solutions by combining the working principles into a working structure, that is, system synthesis. The basis of such a combination is the established function structure, which reflects logically and physically possible or useful associations of the subfunctions.

In Section 3.2.4 the classification scheme of Zwicky (morphological matrix) was proposed as being particularly suitable for systematically combining solutions (see Figure 3.25). In this classification scheme, the subfunctions and the appropriate

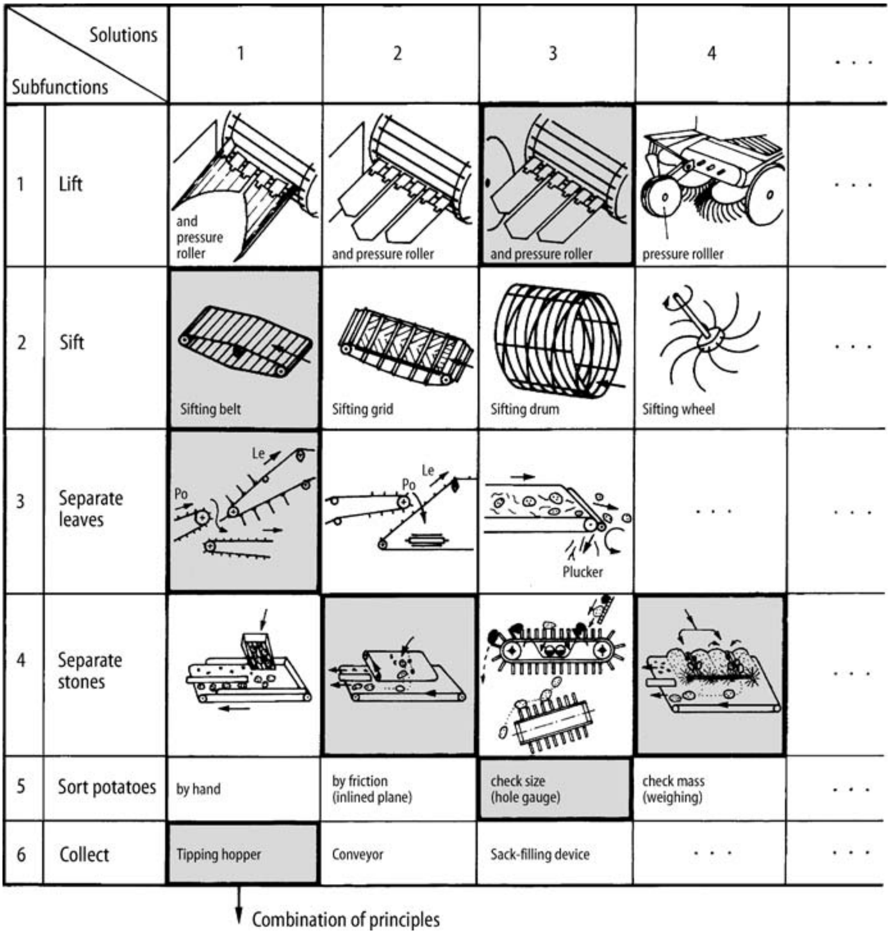


Figure 6.15. Combination of principles used to design a potato harvesting machine in accordance with the overall function structure shown in Figure 6.9. After [6.1]

solutions (working principles) are entered into the rows of the scheme. By systematically combining a working principle fulfilling a specific subfunction with the working principle for a neighbouring subfunction, one obtains an overall solution in the form of a possible working structure. In this process only those working principles that are compatible should be combined.

Figure 6.15 shows a possible combination of working principles for a potato harvesting machine [6.1]. It consists of working principles that are suitable for the subfunctions in the function structure shown in Figure 6.9. These have been made more concrete through rough sketches so that the assessment of their compatibility is facilitated. The principle solution of the harvesting machine based on this working structure is shown in Figure 6.16.

The main problem with combinatorial techniques is ensuring the physical and geometrical compatibility of the working principles to be combined, which in turn ensures the smooth flow of energy, material and signals. A further problem is the selection of technically and economically favourable combinations from the large field of theoretically possible combinations.

Combining solutions using mathematical methods (see Section 3.2.4) is only possible for working principles whose properties can be quantified. However, this is seldom possible at this early stage. Examples where it is possible are variant designs and control system designs, such as those using electronic or hydraulic components.

To sum up:

- Only combine compatible subfunctions (the compatibility matrix shown in Figure 3.26 is a useful tool).

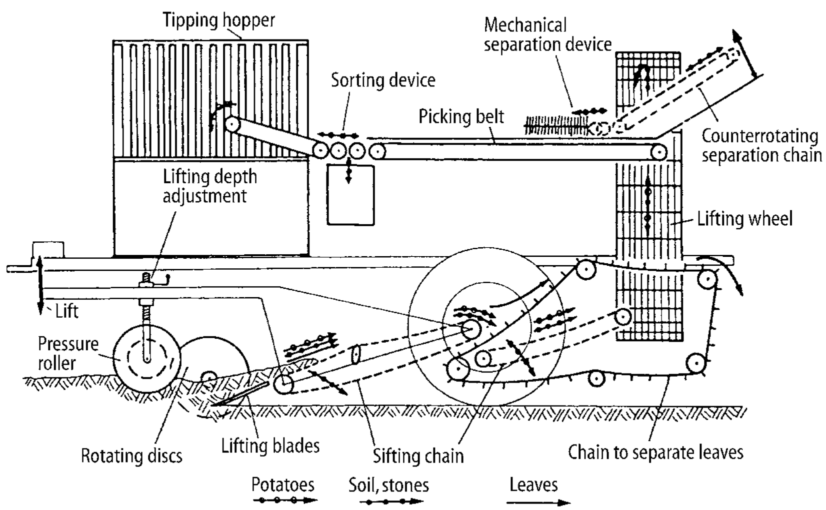


Figure 6.16. Principle solution of a potato harvesting machine, using a combination of principles from Figure 6.15

- Only pursue solutions that meet the demands of the requirements list and look like falling within the proposed budget (see the selection procedures in Sections 3.3.1 and 6.4.3).
- Concentrate on promising combinations and establish why these should be preferred above the rest.

6.4.3 Selecting Working Structures

Because working structures are generally not very concrete and the properties are only known qualitatively, the most suitable selection procedure is the one described in Section 3.3.1. This procedure is characterised by the activities of selecting and indicating preferences, and it makes use of a schematic selection chart that provides a clear overview and can be checked.

The solution field shown in Figure 6.14 for the cylinder–cylinder test rig is now evaluated for each subfunction's solution using a selection procedure. Figure 6.17 shows part of the selection chart indicating the most promising subfunction solutions, i.e. A3, B5, C1, etc. This suggests that combination A3-B5-C1-D2-E5-F4 could be a suitable combination for further concretisation. The working principles for this combination are highlighted in Figure 6.14.

Another way to make a rapid selection is to apply two-dimensional classification schemes, similar to the compatibility matrices shown in Figure 3.26. This will be illustrated using the gear coupling test rig shown in Figure 6.18.

The specification of the test rig demanded an axial displacement in the test coupling so that the axial forces which then appear could be measured. It was therefore necessary to move at least one half of the gear coupling.

The possible position of displacement (classifying criterion of the rows) and the axial force input (classifying criterion of the columns) were combined into the classification scheme shown in Figure 6.19. The various combinations were checked against the requirements list and unsuitable variants were eliminated for a number of immediately obvious reasons. These reasons were documented in the selection chart, but cannot be included because of space restrictions. The result is shown in the legend of Figure 6.19.

Selected working structures (the working combinations) now have to undergo further concretisation.

6.4.4 Practical Application of Working Structures

The development of working structures is the most important stage in the creation of original designs. This stage makes the most demands on the creativity of designers. This creativity is influenced by cognitive psychological processes associated with problem solving, by the use of a general working methodology, and by generally applicable solution finding and evaluation methods. As a consequence, various approaches can be employed at this stage and the one chosen depends on

TH Darmstadt	SELECTION CHART for *Cylinder test rig*	Part: 1 Page: 1

Solution variants (Sv) evaluated by

SELECTION CRITERIA

- (+) Yes
- (−) No
- (?) Lack of information
- (!) Check requirements list

DECISION

Mark solution variants (Sv)

- (+) Pursue solution
- (−) Eliminate solution
- (?) Collect information (re-evaluate solution)
- (!) Check requirements list for changes

Enter solution variant (Sv):

A: Compatibility assured
B: Fulfils demands of requirements list
C: Realisable in principle
D: Within permissible costs
E: Incorporates direct safety measures
F: Preferred by designer's company
G:

Sv		A	B	C	D	E	F	G	Remarks (Indications, Reasons)	DECISION
A1	1	+	−						Change of set up, rattling of bearings	−
A2	2	+	−						Change of set up, too much play	−
A3	3	+	+	+	+				Sinusoidal motion not full realised, error < 1%	+
A4	4	+	+	+	−				Production expenditure too high	−
A5	5	+	+	+	−				Total expenditure too high	−
B1	6	+	−						Not adjustable or only with high expenditure	−
B2	7	+	−						Not adjustable	−
B3	8	+	+	−					Too slow	−
B4	9	+	+	−					Too slow, little variability	−
B5	10	+	+	+	+				Flexible allocation, very fast	+
C1	11	+	+	+	+				Simple solution	+
C2	12	+	+	+	?				Expenditure questionable	?
C3	13	+	+	−					Too much space required	−
C4	14	+	+	−					Expenditure too high	−
D1	15	+	+	−					No space, force flow path too flexible	−
D2	16	+	+	+	+				Preferred measuring procedure of institute	+
D3	17	+	+	+	−				Expenditure higher than D2	−
D4	18	−	−	+	−				Expenditure higher than D2	−
E1	19	+	+	−					Too much space required, element not stiff	−
..										
..										
..										

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Figure 6.17. Part of the selection chart for the solution space shown in Figure 6.14

the novelty of the task (the number of new problems to be solved), on the mentality, ability and experience of the designers, and on the product ideas from product planning or clients.

The procedure suggested in Sections 6.4.1 to 6.4.3 only provides the basis for an expedient stepwise design process. The actual process can vary considerably.

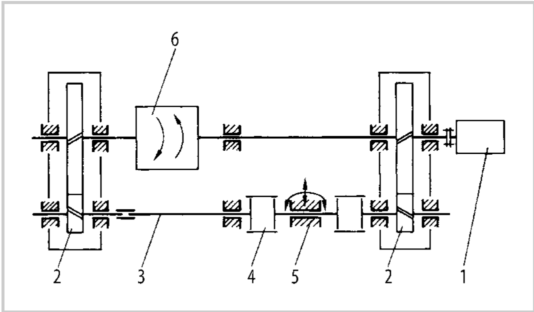


Figure 6.18. Sketch showing the principle of a test rig for gear couplings. *1* drive; *2* gearbox; *3* high-speed shaft; *4* test gear coupling; *5* adjustable bearing block for setting the alignment; *6* device for applying torque

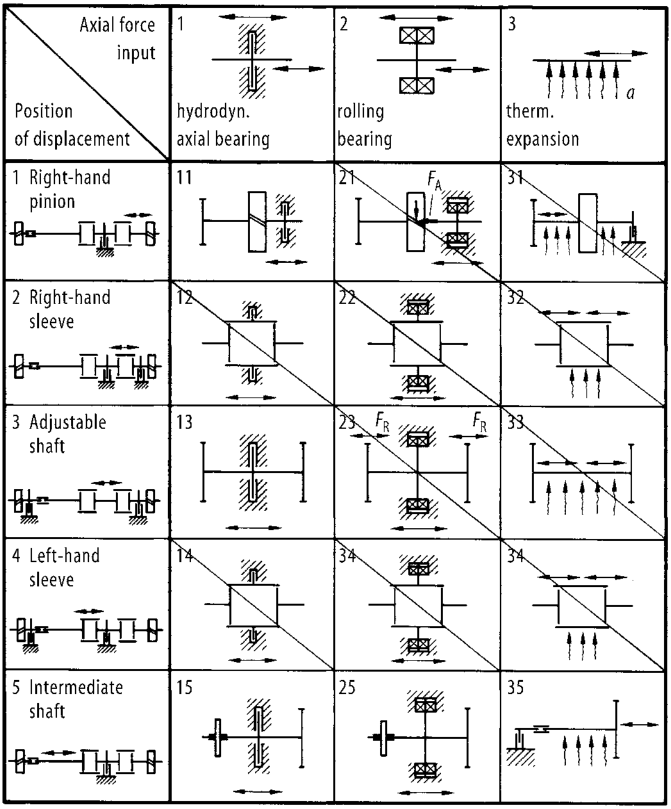


Figure 6.19. Systematic combination and elimination of variants that are unsuitable in principle.
Combinations 12, 14: Disturbance of coupling kinematics
Combination 21: F_A too great (life of rolling bearings too short)
Combination 23: 2 F_R, hence life of rolling bearings too short
Combinations 22, 24: Peripheral speed too great (life of rolling bearings too short)
Combinations 31–34: Thermal length too small

For *original designs without precedents*, the initial search for solutions should focus on the *main function* that appears to be *solution determining* for the overall function (see Figure 6.6). For the solution determining main function, one must first select some preliminary physical effects or working principles using intuition-based methods, literature and patent searches and previous products. The relationship between the functions in these solutions must be analysed to identify other important subfunctions for which physical effects and working principles need to be found. These working principles are selected from those that are compatible with the other working principles selected to fulfil the main functions. A simultaneous, independent search for working principles for all subfunctions will, in general, be too elaborate and will result in several working principles that will have to be eliminated later from the overall combination.

It is recommended that the most promising solution principles (not more than six) should be identified at a relatively low level of concretisation. One of these is then selected for elaboration to a higher level of concretisation. From the variants that then emerge at this level, the most promising is again taken forward to an even higher level of concretisation. Adopting this approach avoids the need to deal with too many variants at the same time, which can result in too much effort being devoted to variants that eventually turn out to be unsuitable.

An important strategy for the creation of solution fields is therefore the systematic variation of the physical effects and form design features that were recognised as being essential in the initial solutions. *Classification schemes* are very useful but usually need several trials, based on variation and correction of the classifying criteria, before an optimum scheme can be arrived at. This requires some experience.

When *concrete solution ideas* are available from product planning or other sources, these have to be analysed to identify their essential solution determining characteristics. These are then systematically varied and combined to arrive at a solution field.

In the case of *evolutionary developments*, the known working principles and working structures should be checked to see if they still meet current technological standards and the latest requirements.

When an approach is strongly based on *intuition*, or when previous experience is applicable, working structures that fulfil the overall function will often be found directly without first searching for solutions for the individual subfunctions.

In particular, the *stepwise* generation of working principles, through the search for physical effects and the subsequent form design features, is often integrated mentally by producing *sketches of solutions*. This is because designers think more in configurations and representation of principles than in physical equations.

The use of intuition-based and discursive–systematic methods can quickly lead quickly to extensive solution fields. To limit subsequent design effort, these should be reduced as soon as *feasible working principles* emerge by checking against the demands in the requirements list.

At this stage it is often not possible to assess the characteristics of a principle solution with quantitative data, particularly with regard to production and cost.

Therefore, the selection of suitable working principles requires an *interdisciplinary team* discussion, similar to a value analysis team (see Section 1.2.3(2)), in order to base the qualitative decision on a broad spectrum of experience.

6.5 Developing Concepts

6.5.1 Firming Up into Principle Solution Variants

The principles elaborated in Section 6.4 are usually not concrete enough to lead to the adoption of a definite concept. This is because the search for a solution is based on the function structure, and so it is aimed, first and foremost, at the fulfilment of a technical function. A concept must, however, also satisfy the conditions laid down in Section 2.1.7—at least in essence—for only then is it possible to evaluate it. Before concept variants can he evaluated they must be firmed up, and experience has shown that this almost invariably involves considerable effort.

The selection process may already have revealed gaps in information about very important properties, sometimes to such an extent that not even a rough and ready decision is possible, let alone a reliable evaluation. The most important properties of the proposed combination of principles must first be given a much more concrete *qualitative*, and often also a rough *quantitative*, definition.

Important characteristics of the working principle (such as performance and susceptibility to faults), of the embodiment (such as space requirements, weight and service life) and finally of important task-specific constraints must all be known, at least approximately. More detailed information need only be gathered for promising combinations. If necessary, a second or third selection process should follow the collection of further information.

The necessary data are essentially obtained with the help of such proven methods as:

- rough calculations based on simplified assumptions
- rough sketches or rough scale-drawings of possible layouts, forms, space requirements, compatibility, etc.
- preliminary experiments or model tests used to determine the main properties or to obtain approximate quantitative statements about the performance and scope for optimisation
- construction of models in order to aid analysis and visualisation (for example, kinematic models)
- analogue modelling and systems simulation, often with the help of computers; for example stability and loss analyses of hydraulic systems using electrical analogies
- further searches of patents and the literature with narrower objectives
- market research of proposed technologies, materials, bought-out parts, etc.

With these fresh data it is possible to firm up the most promising combinations of principles to the point at which they can be evaluated (see Section 6.5.2). The variants must reveal technical as well as economic properties, thus permitting the most accurate evaluation possible. When firming up into principle solutions, it is therefore advisable to keep in mind potential evaluation criteria (see Section 3.3.2), as this encourages purposeful elaboration of the information.

An example will show how it is possible to firm up working principles into principle solutions. To that end, we return once more to our fuel gauge.

Figure 6.20 shows the working principle of the first proposal shown in Figure 3.27 and Table 3.3. It is possible to obtain the total force statically, either by measuring three bearing forces or by measuring just one bearing force in combination with a pivot. The weight of the contents of the fuel tank, to be used as a measure of the quantity of liquid, can be determined by deducting the weight of the empty tank. The measuring devices to be used, however, measure the total force, including those components caused by accelerations. If the force is converted into motion it can be detected via a potentiometer for example.

Estimates of the weights and inertia forces form the basis of the firming up procedure.

Total force of 20 to 160 litres of the liquid (static):

$$F_{\text{tot}} = \varrho \cdot g \cdot V = 0.75 \times 10 \times (20 \ldots 160) = (150 \ldots 1200)\ \text{N (fuel)}\ .$$

Additional forces due to acceleration $\pm 30\ \text{m/s}^2$ (only the liquid is taken into consideration):

$$F_{\text{add}} = m \cdot a = (15 \ldots 120) \times \pm 30 = \pm(450 \ldots 3600)\text{N}\ .$$

The suppression of motions resulting from accelerational forces calls for considerable damping.

Conclusion: develop solution further, provide damping, seek appropriate subsolutions and firm up by means of rough scale drawings. Figure 6.21 shows the result. Once the necessary parts and their arrangements are drawn, the proposal can be evaluated. This confirms the indication in the selection chart (see Figure 3.27) that the effort required to complete solution variant 1 could be too high.

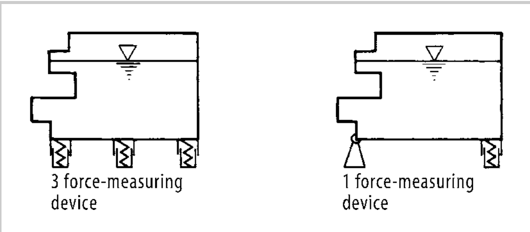


Figure 6.20. Solution principle 1 (Figure 3.27 and Table 3.3): measure weight of liquid (signal = force)

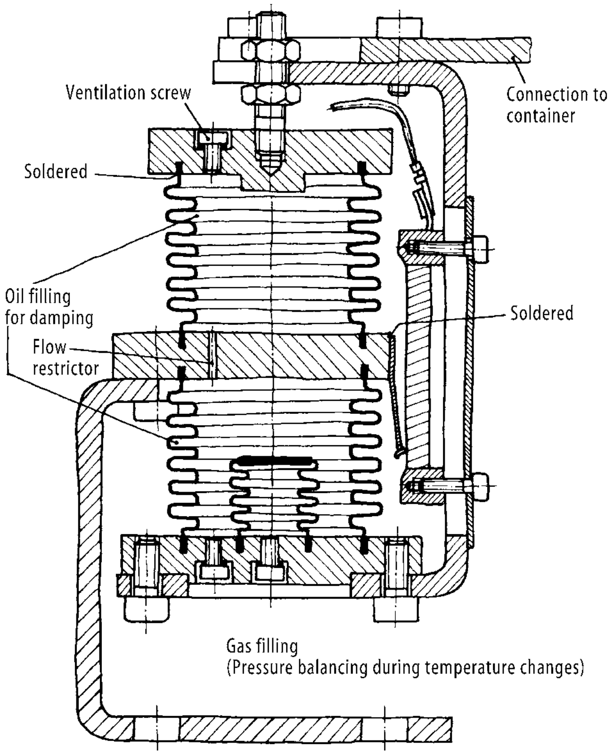


Figure 6.21. Firmed up principle solution shown in Figure 6.20

6.5.2 Evaluating Principle Solution Variants

In Section 3.3.2 we explained generally applicable evaluation methods, in particular Cost–Benefit Analysis and the VDI 2225 procedure [6.15].

When evaluating principle solution variants, the following steps are recommended.

1. Identifying Evaluation Criteria

This step is based, first of all, on the *requirements list*. During a previous selection procedure (see Section 6.4.3) unfulfilled demands may have led to the elimination of variants that were found to be unsuitable in principle. Further information was subsequently gathered during firming up into principle solutions. Hence it is advisable, with all the newly acquired information, to establish whether all of the proposals to be evaluated still satisfy the demands of the requirements list. This can involve new yes/no decisions—a new selection process.

Even though we are at a more concrete stage, we cannot expect this decision to be made with certainty for all of the variants unless much further effort is applied, which the designers may not wish or are not able to provide at this stage. At the current level of information, it may only be possible to decide how likely it is that certain requirements can be fulfilled. In that case, the likelihood of fulfilling particular requirements may become an additional evaluation criterion.

A number of requirements are minimum requirements. It is important to establish whether or not these should be exceeded. If they should, further evaluation criteria may be needed.

For evaluation during the conceptual phase, both the *technical* and the *economic characteristics* should be considered as early as possible [6.4]. At the firming up stage, however, it is not usually possible to give the costs in figures. Nevertheless, the economic aspects must be taken into consideration, at least qualitatively, and so must industrial and environmental safety requirements.

Hence it is necessary to consider technical, economic and safety criteria at the same time. It is suggested that the evaluation criteria are derived from the main headings in Figure 6.22. These are in accordance with the embodiment design checklist (see Section 7.6) and other proposals [6.8].

Main headings	**Examples**
Function	Characteristics of essential auxiliary function carriers that follow out of necessity from the chosen solution principle or concept variant
Working principles	Characteristics of the selected principle or principles with respect to simple and clear-cut functioning, adequate effect, few disturbing factors
Embodiment	Small number of components, low complexity, low space requirement, no special problems with layout or form design
Safety	Preferential treatment of direct safety techniques (inherently safe), no additional safety measures needed, industrial and enviromental safety guaranteed
Ergonomics	Satisfactory man-machine relationship, no strain or impairment of health, good aesthetics
Production	Few and established production methods, no expensive equipment, small number of simple components
Quality control	Few tests and checks needed, simple and reliable procedures
Assembly	Easy, convenient and quick, no special aids needed
Transport	Normal means of transport, no risks
Operation	Simple operation, long service life, low wear, easy and simple handing
Maintenance	Little and simple upkeep and cleaning, easy inspection, easy repair
Recycling	Easy recovery of parts, safe disposal
Costs	No special running or other associated costs, no scheduling risks

Figure 6.22. Checklist with main headings for design evaluation during the conceptual phase

Every heading in the checklist relevant to the task must be assigned at least one evaluation criterion. The criteria must, moreover, be independent of one another in terms of the overall objective, so as to avoid multiple evaluations. Consumer criteria are essentially contained in the first five and last three headings, while producer criteria are contained in the following headings: embodiment, production, quality control, assembly and costs.

Evaluation criteria are accordingly derived from:

1. The requirements list:
   - Probability of satisfying the demands (how probable, despite which difficulties?)
   - Desirability of exceeding minimum requirements (exceed by how much?)
   - Wishes (satisfied, not satisfied, how well are they satisfied?)
2. General technical and economic characteristics from the checklist, see Figure 6.22 (to what extent are they present, how well are they satisfied?)

During the conceptual phase, the total number of evaluation criteria should not be too high: 15–30 criteria are usually enough (see Figure 6.41).

2. Weighting the Evaluation Criteria

The evaluation criteria adopted may differ markedly in importance. During the conceptual phase, in which the level of information is fairly low because of the relative lack of embodiment, weighting is not generally advisable. It is much more advantageous in the selection of evaluation criteria to strive for an approximate balance, ignoring low-weighted characteristics for the time being. As a result, evaluation will be concentrated on the main characteristics and hence provide a clear picture at a glance. Extremely important requirements, however, which cannot be ignored until later, must be introduced with the help of weighting factors.

3. Compiling Parameters

It has proved useful in the past to list the identified evaluation criteria in the sequence of the checklist headings and to assign the parameters of the variants to them. Whatever quantitative information is available at this stage should also be included. Such quantitative data generally result from the step we have called "firming up into principle solution variants". However, since it is impossible to quantify all the parameters during the conceptual phase, the qualitative aspects should be put into words and correlated with the value scale.

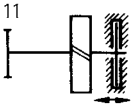
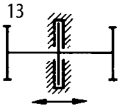
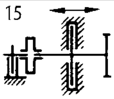
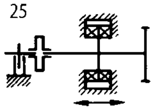
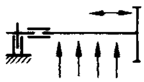
4. Assessing Values

Though the attribution of points raises problems, it is not advisable to evaluate too timidly during the conceptual phase.

Those using the 0–4 scale proposed in VDI Guideline 2225 may feel the need to assign intermediate values, particularly when there are many variants, or when the evaluation team cannot agree on a precise point. It may prove helpful in such cases to attach a tendency sign (↑ or ↓) to the point in question (see Figure 6.41). Identifiable tendencies can then be taken into account when estimating the evaluation uncertainties. The 0–10 scale, again, may suggest a degree of accuracy that does not really exist. Here, arguments about a point are often superfluous. If there is absolute uncertainty in the attribution of points, which happens quite often during the evaluation of concept variants, the point under consideration should be indicated with a question mark (see Figure 6.41).

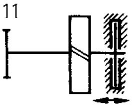
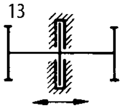
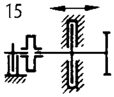
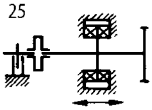
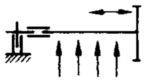
During the conceptual phase it may prove difficult to put actual figures to the costs. It is not therefore generally possible to establish an *economic rating* R_e with respect to the production costs. Nevertheless, the technical and economic aspects can be identified and separated qualitatively, to a greater or lesser extent. The *strength diagram* (see Figure 3.35) can be used to much the same effect (see also Figures 6.23 to 6.25 which are for the test rig shown in Figure 6.18).

In a similar way, a classification based on consumers' and producers' criteria often proves useful. Since the consumers' criteria usually involve *technical ratings* R_t

Technical criteria \ Variants	11 	13 	15 	25 	35 
1) Small disturbance of coupling kinematics	(1) 3	4	4	4	3
2) Simple operation	3	4	4	4	3
3) Easy exchange of coupling	4	3	4	4	4
4) Functional safety	2	4	3	3	3
5) Simple construction	(1) 2	2	2	2	3
Total	14	17	17	17	16
$R_t = \frac{\text{Total}}{20}$	0.7	0.85	0.85	0.85	0.80

(1) Torque changes with axial displacement of pinion

Figure 6.23. Technical evaluation of the remaining principle solution variants, see Figure 6.19

Variants / Economic criteria	11 	13 	15 	25 	35 
1) Low material costs	2	3	4	4	(1) 2
2) Low reassembly costs	2	(2) 1	3	3	3
3) Short testing time	2	4	3	3	2
4) Possibility of manufacturing in own workshop	3	3	3	3	2
Total	9	11	13	13	9
$R_e = \frac{\text{Total}}{16}$	0.56	0.69	0.81	0.81	0.56

(1) Austenitic shaft (2) Torque measuring shaft must be moved

Figure 6.24. Economic evaluation of the remaining principle solution variants, see Figure 6.19

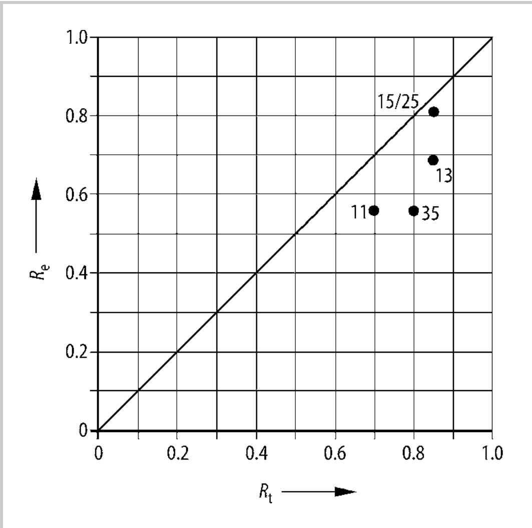


Figure 6.25. Comparison of the technical and economic ratings of the principle solution variants in Figures 6.23 and 6.24

and the producers' criteria involve *economic ratings* R_e, it is possible to proceed to a similar classification to the one mentioned above.

Depending on the problem and the amount of information available, one of the following three possible forms of representation is chosen:

- technical rating with implicit economic aspects (see Figures 6.41 and 6.55)
- separate technical and economic ratings (see Figures 6.23 to 6.25)
- additional comparison of consumers' and producers' criteria.

5. Determining Overall Value

The determination of the overall value is a matter of simple addition, once the points have been assigned to the evaluation criteria and the variants. If, because of the evaluation uncertainty, it is only possible to assign a range of points to individual variants, or if tendency signs are used, one can additionally determine the possible minimum and maximum overall point number and so obtain the probable overall value range (see Figure 6.41).

6. Comparing Concept Variants

An absolute value scale is generally more suitable for the purposes of comparison. In particular, it makes it fairly simple to tell whether particular variants are relatively close to or far from the target (theoretical ideal).

Concept variants that are some 60% below the target are not worth further development. Variants with ratings above 80% and a balanced value profile—those without extremely bad individual characteristics—can generally be moved on to the embodiment design phase without further improvement.

Intermediate variants should only be released for embodiment design after the elimination of weak spots or an improved combination.

It often happens that two or more variants are found to be practically equivalent. It is a very grave mistake, in that case, to base the final decision on such slight differences. Instead, evaluation uncertainties, weak spots and the value profile should be looked at more closely (see Figure 3.38). It may also be necessary to firm up on such variants in a further step. Schedules, trends, company policy and so on must be assessed separately and taken into account [6.4].

7. Estimating Evaluation Uncertainties

This step is very important, especially during the conceptual phase, and must not be omitted. Evaluation methods are mere tools, not automatic decision mechanisms. Uncertainties must be determined as indicated earlier. At this point, however, only the information gaps that impact on the best concept variants (for example, variant B in Figure 6.41) need to be closed.

8. Searching for Weak Spots

During the conceptual phase, the value profile plays an important role. Variants with a high rating but definite weak spots (unbalanced value profile) may prove extremely troublesome during subsequent development. If, because of an unidentified evaluation uncertainty, which is more likely to occur in the conceptual than in the embodiment phase, a weak spot should make itself felt later, then the whole concept may be put in doubt and all the development work may prove to have been in vain.

In such cases it is very much less risky to select a variant with a slightly lower rating but a more balanced value profile (see Figure 3.38).

Weak spots in favourite variants can often be eliminated by the transfer of better subsolutions from other variants. Moreover, with better information, it is possible to search for a replacement for the unsatisfactory subsolution. Thus the criteria we have listed played an essential role in the selection of the best variant in the problem discussed in Section 6.6 (see Figure 6.41). When estimating evaluation uncertainties and also when searching for weak spots it is advisable to assess the probability and magnitude of the possible risk, especially in the case of important decisions.

6.5.3 Practical Application of Developing Concepts

The selection of the concept, or the principle solution, provides the *basis for starting the embodiment design phase* (see Figure 6.1). This often indicates a need for changes in organisation and personnel because the nature of the work alters. Thus, firming up of suitable working structures into principle solution variants and the subsequent evaluation at the end of the conceptual design phase are of major importance for product development. The large number of variants has to be reduced to one concept, or just a few, to be pursued further. This decision incurs a heavy responsibility and can only be made when the principle solutions are in a state suitable for evaluation. In extreme cases this may require rough scale layouts backed up by preliminary calculations and sometimes tests. From research in industry and universities [6.8], it is known that calculating and representation add up to 60% of the total time spent on conceptual design.

The *representation* of working principles and working structures is likely to remain the domain of conventional sketching. Rough layouts, and in particular the more important details of solutions are now commonly represented using CAD. Sketching working structures by hand has the advantage that one does not need to consider the formalities of CAD user interfaces during this highly creative stage. Firming up solution principles using CAD is useful, despite the effort needed to enter the initial product model into the system, because making variations to the layout and individual components becomes very efficient. For dynamic systems it is also possible to do initial simulations using the CAD model.

In any case, it is expedient (for *reasons of efficiency* and to identify essential characteristics) not to firm up the whole working structure to the same level of detail. The aim should be to focus on those working principles, components or parts of the structure that are essential for the evaluation of the concepts and the selection of the one that will be transferred to the embodiment stage. Richter provides proposals for this task [6.10].

At this point it must be emphasised again that *iterations* often occur in the steps mentioned in Sections 6.4 and 6.5. On the one hand, it might be necessary to detail working principles in order to combine and select them, and on the other hand a completely new idea for a working principle might emerge while making a rough layout of a principle solution.

It must be stressed that principle solutions or concepts have to be *unambiguously documented*. It must also be clear which parts of the working structure or function carriers can be realised by existing and standard components, and which ones will need to be specially designed.

6.6 Examples of Conceptual Design

This section provides two examples of how the approach can be applied: the first to a task whose main flow is material, and the second to one whose main flow is energy. The embodiment design phase of the second example is continued in Section 7.7. An example of signal flow has been used throughout the previous sections in this chapter (see Figures 6.4 to 6.6 and 6.20).

6.6.1 One-Handed Household Water Mixing Tap

A one-handed mixing tap is a device for regulating water temperature and throughflow independently with one hand. This task was sent to the design department by the planning department in the form shown in Figure 6.26.

One-handed water mixing tap

Required: one-handed household water mixing tap with the following characteristics:

Throughput	10 l/min
Max. pressure	6 bar
Normal pressure	2 bar
Hot water temperature	60 °C
Connector size	10 mm

Attention to be paid to appearance. The firm's trade mark to be prominently displayed. Finished product to be marketed in two years' time. Manufacturing costs not to exceed DM 30 each at a production rate of 3000 taps per month.

Figure 6.26. One-handed mixing tap. Example of an assignment suggested by the product planning department

Step 1: Clarifying the Task and Setting Up the Requirements List

New data on fittings, standards, safety regulations and ergonomic factors led to the replacement of the original requirements list by the revised version shown in Figure 6.27.

TH Darmstadt	Requirements list for one-handed mixing tap		Page 1
Changes	**D W**	**Requirements**	**Responsible**
	D	1 Throughput (mixed flow) max. 10 l/min at 2 bar	KMW
	D	2 Max. pressure 10 bar (test pressure 15 bar as per DIN 2401)	LTMB
	D	3 Temp. of water standard 60 °C, 100 °C (short-time)	
	D	4 Temperature setting independent of throughput and pressure	
	W	5 Permissible temp fluctuation ±5 °C at a pressure diff. of ±5 bar between hot and cold supply	
	D	6 Connection 2 x Cu pipes, 10 x 1 mm, l = 400 mm	
	D	7 Single-hole attachment ∅ 35^{+2}_{-1} mm, basin thickness 0–18 mm (Observe basin dimension DIN EN 31, DIN EN 32, DIN 1368)	
	D	8 Outflow above upper edge of basin, 50 mm	
	D	9 To fit household basin	
	W	10 Convertible into wall fitting	
	D	11 Light operation (children)	
	D	12 No external energy	
	D	13 Hard water supply (drinking water)	
	D	14 Clear identification of temperature setting	
	D	15 Trade mark prominently displayed	
	D	16 No connection of the two supplies when valve shut	
	W	17 No connection when water drawn off	
	D	18 Handle not heated to above 35 °C	
	W	19 No burns from touching the fittings	
	W	20 Provide scalding protection if extra costs small	
	D	21 Obvious operation, simple and convenient handling	
	D	22 Smooth, easily cleaned contours, no sharp edges	
	D	23 Noiseless operation, (≤20 dB as per DIN 52218)	
	W	24 Service life 10 years at about 300 000 operations	
	D	25 Easy maintenance and simple repairs. Use standard spare parts	
	D	26 Max. manuf. costs DM 30 (3000 units per month)	
	D	27 Schedules from inception of development conceptual design / embodiment design / detail design / prototype after 2 / 4 / 6 / 9 months	
	Replaces 1st issue of 12.6.1973		

Figure 6.27. Requirements list for a one-handed mixing tap

Step 2: Abstracting to Identify the Essential Problems

The basis for abstraction is the requirements list, from which it is possible to arrive at Figure 6.28. Simple household solutions for mixing taps suggested that the chosen solution principle must be based on metering out the water through a diaphragm or valve. Alternatives such as heating and cooling by the introduction of external energy through heat exchangers could be dismissed: they were more expensive and involved a time lag. Selecting sound solution principles without further investigation, because they have proved their worth in previous company products, is a common and justified approach in some branches of engineering.

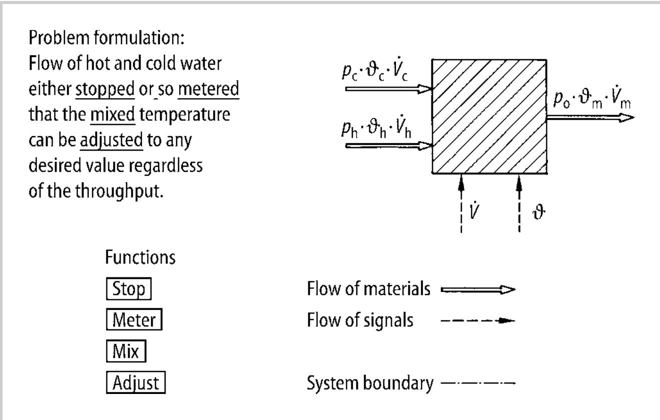


Figure 6.28. Problem formulation and overall function as per the requirements list, see Figure 6.27. $\dot{V}$ = volume rate, p = pressure, ϑ = temperature. Index: c = cold, h = hot, m = mixed, o = atmosphere

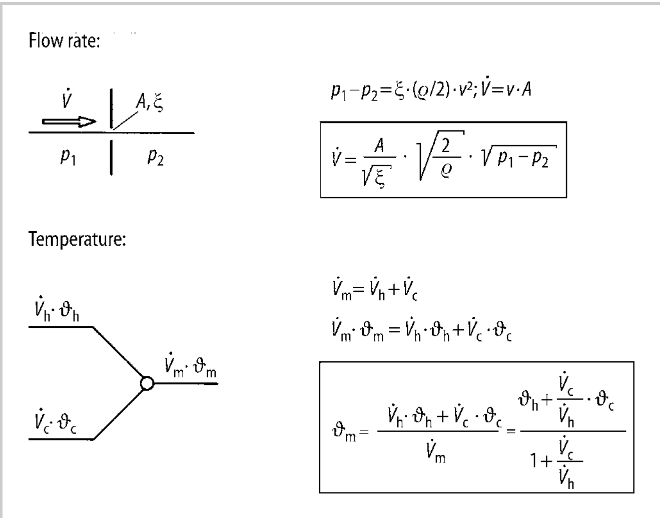


Figure 6.29. Physical relationships for flow rate and temperature of a mixed flow of the same fluid

Next, the physical relationships for the diaphragm (or valve) flow rate and the temperature of a mixed flow of similar fluids were determined (see Figure 6.29).

Temperature and flow rate adjustments are based on the same physical principle—a diaphragm or valve.

Upon *changing the flow rate* $\dot{V}_m$, the flows must be changed linearly and in the same sense as the signal setting $s_{\dot{V}}$. The output temperature ϑ_m, however, must remain unchanged: that is, the relationship $\dot{V}_c/\dot{V}_h$ must remain constant and independent of the signal positions $s_{\dot{V}}$.

Upon *changing the output temperature* ϑ_m, the volume flow rate $\dot{V}_m$ must remain unchanged: that is, the sum of $\dot{V}_c + \dot{V}_h = \dot{V}_m$ must remain constant. To that end the component flows $\dot{V}_c$ and $\dot{V}_h$ must be changed linearly and in the opposite sense to the signal setting for the output temperature s_ϑ.

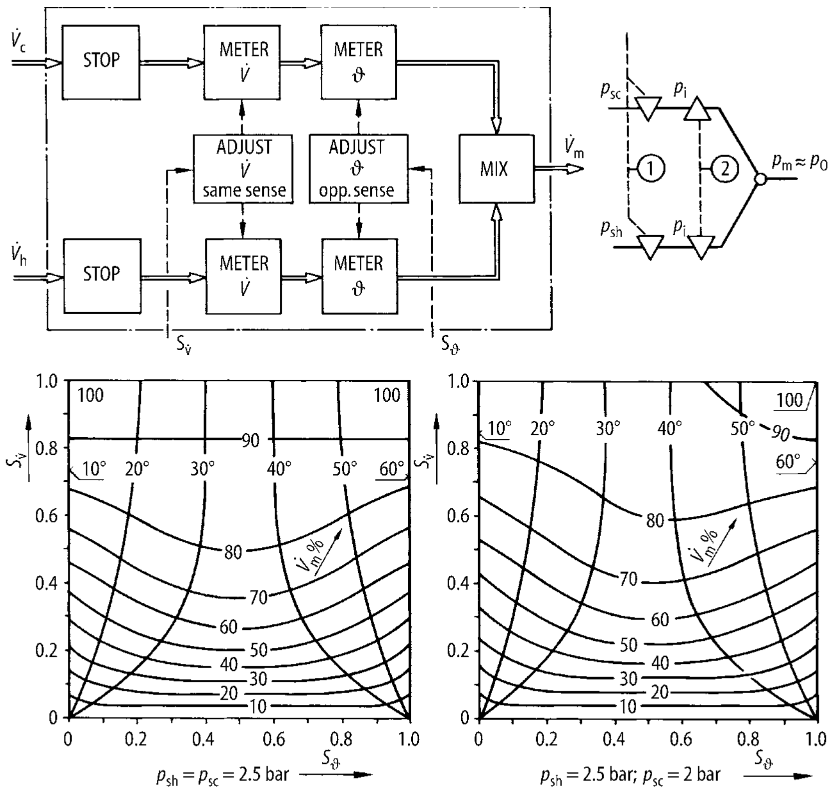


Figure 6.30. Function structure for a one-handed water mixing tap based on Figure 6.28, metering flow ① and adjusting temperature ② separately before mixing. In the graphs, lines of constant temperature and constant percentage flow rate have been plotted for given temperature settings (s_ϑ) and flow rate settings ($s_{\dot{V}}$). Due to the mutual effects of the pressures on the inlets at ① and ②, the temperature and flow characteristics are not linear except for the setting $s_{\dot{V}} = 0.825$, and hence are unsuitable for small flow rates. At a particular pressure difference between the cold and hot water supplies (in this case $p_{sh} - p_{sc} = 0.5$bar) the lines shift. The settings are no longer independent of each other, even for the settings $s_{\dot{V}} = 0.825$ (*diagram on right*)

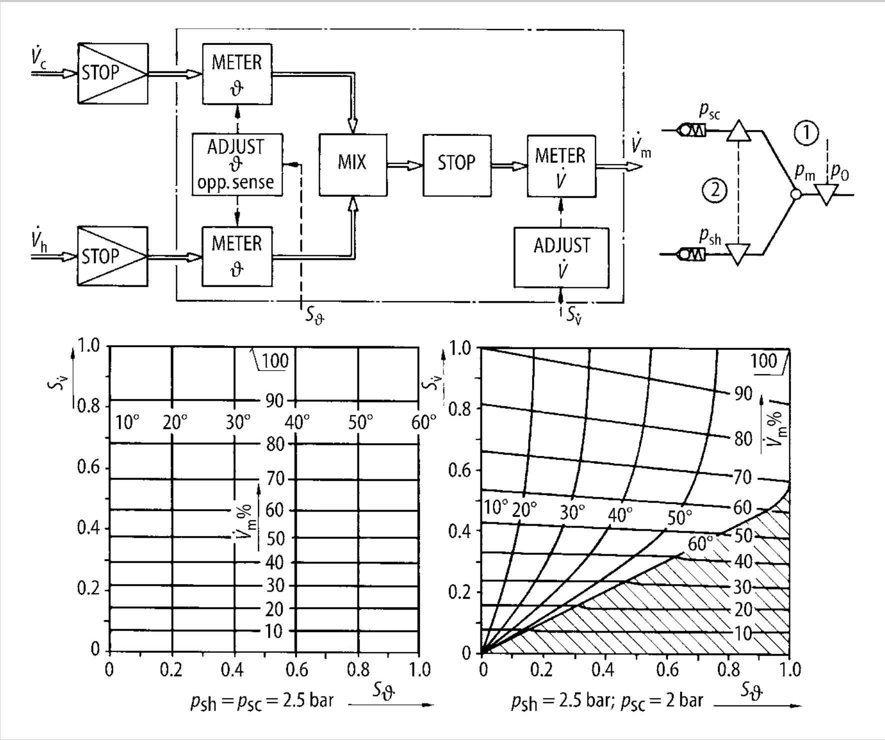


Figure 6.31. Function structure based on Figure 6.28 in which the temperature is set before and the flow metered after mixing. With equal pressures in the supply pipes, the flow and temperate settings are independent of each other due to equal pressure differences across each temperature-flow-metering valve. The behaviour is linear. With different supply pressures, however, the characteristic ceases to be linear and is strongly displaced, especially with small quantities, when the pressure in the mixing chamber approximates the smaller supply pressure. If it is exceeded, then only cold or (here) hot water will run out regardless of the temperature setting

Step 3: Establishing Function Structures

The first function structure was derived from the subfunctions:

- Stop–meter–mix
- Adjust flow rate
- Adjust output temperature.

Since the physical principle was well-known—metering using a valve—the structural layout of the first function structure was varied and developed to determine the best system and its behaviour (see Figures 6.30 to 6.32). From the results, the function structure shown in Figure 6.32 was chosen as being the most satisfactory because of its approximately linear characteristic for the output temperature.

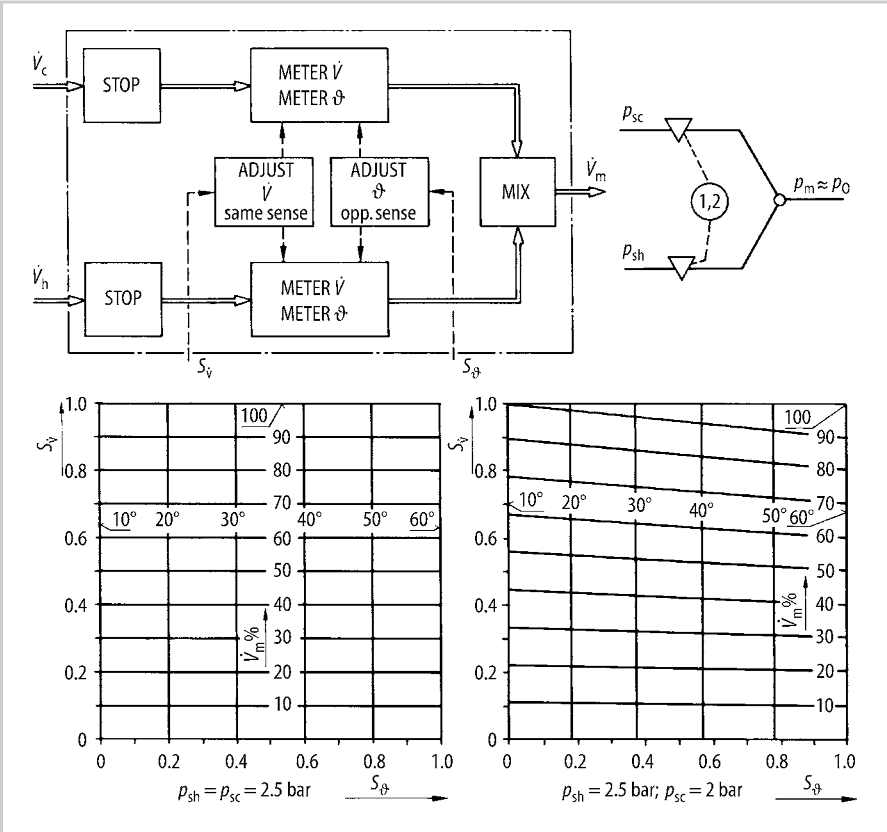


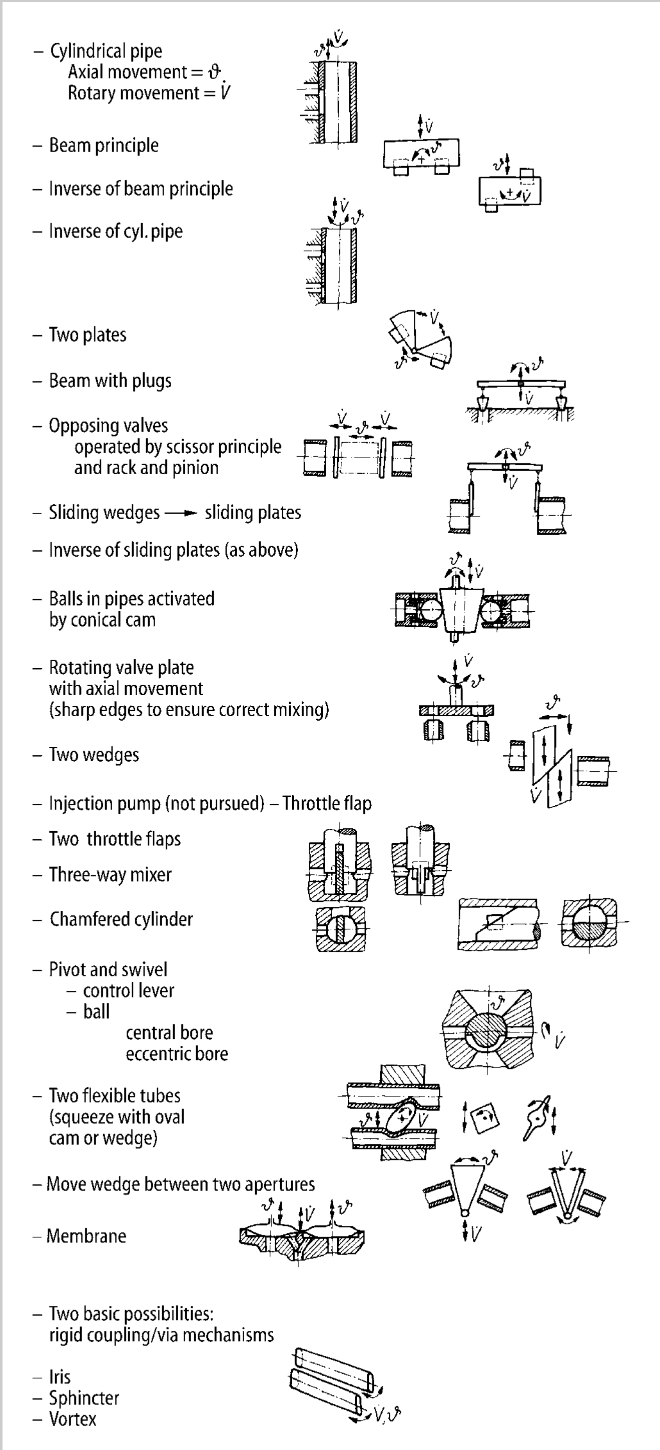
Figure 6.32. Function structure based on Figure 6.28, in which the temperature and flow at each inlet is metered out independently and then mixed. Linear temperature and flow characteristics are obtained. No serious changes are seen, even at different supply pressures

Step 4: Searching for Working Principles

Because the function structure shown in Figure 6.32 exhibited the best behaviour, the task became one of "varying two flow areas, simultaneously or successively, in one sense by one movement and in the opposite sense by a second, independent, movement". Brainstorming was used as a first attempt to find solutions. The results are shown in Figure 6.33.

The solutions suggested during the brainstorming session were checked, in particular, to establish whether the $\dot{V}$ and ϑ settings were independent. An analysis of the combined movements suggested the following characteristics for the working principles that were generated:

Figure 6.33. Result of a brainstorming session to discover solution principles for the assignment "vary two flow areas, simultaneously or successively, in one sense by one movement and in the opposite sense by a second, independent movement"


– Cylindrical pipe
Axial movement = ϑ̇
Rotary movement = V̇
– Beam principle
– Inverse of beam principle
– Inverse of cyl. pipe
– Two plates
– Beam with plugs
– Opposing valves
operated by scissor principle
and rack and pinion
– Sliding wedges ⟶ sliding plates
– Inverse of sliding plates (as above)
– Balls in pipes activated
by conical cam
– Rotating valve plate
with axial movement
(sharp edges to ensure correct mixing)
– Two wedges
– Injection pump (not pursued) – Throttle flap
– Two throttle flaps
– Three-way mixer
– Chamfered cylinder
– Pivot and swivel
– control lever
– ball
central bore
eccentric bore
– Two flexible tubes
(squeeze with oval
cam or wedge)
– Move wedge between two apertures
– Membrane
– Two basic possibilities:
rigid coupling/via mechanisms
– Iris
– Sphincter
– Vortex

1. Solutions with separate movements for $\dot{V}$ and ϑ tangential to the valve seat face

- The independence of the $\dot{V}$ and ϑ settings is only guaranteed if each of the flow areas of the valves are bounded by two edges running parallel to the corresponding movements. This implies that the movements must proceed at an angle to each other and in a straight line. Every valve setting thus has two pairs of straight and parallel bounding edges (see Figure 6.34). This ensures that when one setting is adjusted the other setting is not simultaneously adjusted.
- Distribution of bounding edges: each of the components producing the valve flow areas must have at least two edges that face each other and lie in the direction of the movement.
- When setting $\dot{V}$, both valve areas must approach zero simultaneously.
- When setting ϑ, one area must approach zero as the other approaches its maximum $\dot{V}_{max}$.
- This implies, when setting $\dot{V}$, that the bounding edges on both valve areas must move towards each other or away from each other in the same sense. When setting ϑ, the bounding edges on the two valve areas must move in the opposite sense to each other.
- The seat face may be plane, cylindrical or spherical.
- Solutions of this type can be effected with a single valve element, and seem simple to design.

2. Solutions with separate movements for $\dot{V}$ and ϑ normal to the valve seat face

- This group includes all movements which involve lifting a valve from its seat face. However, only a movement at right angles to the seat face is possible in practice.
- The independent settings of $\dot{V}$ and ϑ can only be achieved with additional control elements (coupling mechanism).
- The design seems to require greater effort.

3. Solutions with one type of movement for $\dot{V}$ and ϑ tangential to the seat face

- To guarantee the independence of the $\dot{V}$ and ϑ settings, additional coupling elements are needed.

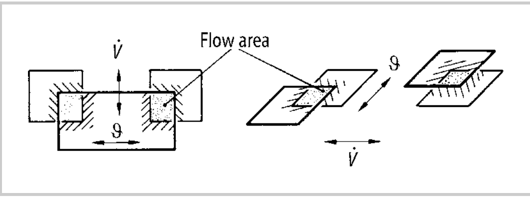


Figure 6.34. Movements and bounding edges of valve positions

	Classifying Criteria	Parameters
Rows	Form of working elements	Flate plate Wedge (–) Cylinder Cone (–) Ball Special elastic body (–)
Columns	Coupling of movements	Direct (one part) Indirect (mechanism) (–)
	Movement	$\dot{V}$, ϑ } One element $\dot{V}$, ϑ } Several elements
	Direction of movement $\dot{V}$ and ϑ	Normal to seat face (⊥) (–) Tangential to seat face (⇌)
	Type of movement $\dot{V}$ and ϑ	Transitional Rotational

Figure 6.35. Classifying criteria and parameters for working principles of one-handed water mixing tap

- The solutions are similar to those listed under 2. They only differ in the shape of the seat face and the resulting movement.

4. Solutions with one movement for $\dot{V}$ normal to, and one movement for ϑ tangential to, the seat face and vice versa

- These solutions do not, even with the help of coupling mechanisms, satisfy the demand for independent $\dot{V}$ and ϑ settings. The overall function is not achieved.

The first group of solutions (movements for $\dot{V}$ and ϑ tangential to the valve seat face) have unambiguous behaviour and seem to be less complex. Therefore they were pursued; a formal selection procedure was not necessary. On the other hand

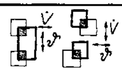
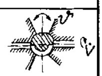
Form of valve \ Type of movement		trans./trans.	trans./rot.	rot./rot.
		1	2	3
plane plate	A		○	○
cylinder	B	○		○
cone	C	○	○	○
sphere	D	○	○	

Figure 6.36. Classification scheme for solutions to the one-handed mixing tap problem. Movement tangential to the seat face. Two independent movements at an angle for $\dot{V}$ and ϑ

useful working parts and types of movement still had to be analysed. This analysis resulted in the classification criteria shown in Figure 6.35, with the least suitable characteristics indicated with (–). Figure 6.36 shows a classification scheme of possible working principles based on different forms and working movements.

Step 5: Selecting Working Principles

All the working principles shown in Figure 6.36 fulfil the demands of the requirements list and appear to be economic. Hence all three were firmed up into principle solutions.

Step 6: Firming Up into Principle Solution Variants

With the help of further research into possible setting or operating elements that we have not discussed here, the working principles could then be firmed up into principle solution variants and evaluated (see Figures 6.37 to 6.40).

Step 7: Evaluating Principle Solution Variants

In accordance with VDI 2225, this step was taken with the help of an evaluation chart. In addition, evaluation uncertainties and weak spots were examined (see Figure 6.41).

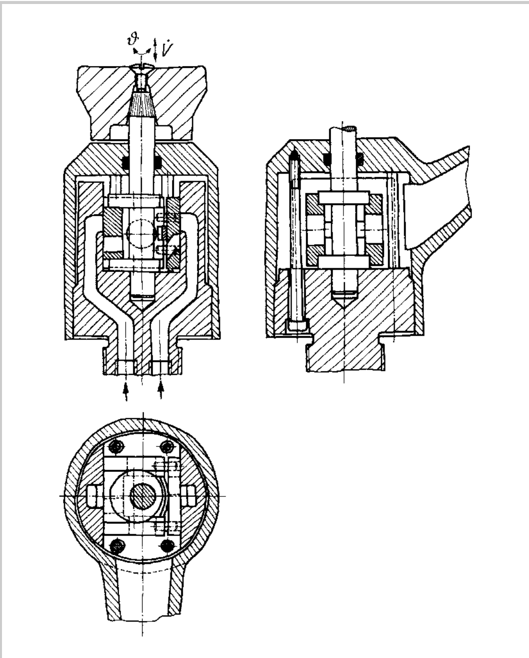


Figure 6.37. One-handed mixing tap, solution variant A: "plate solution with eccentric and pull-and-turn grip"

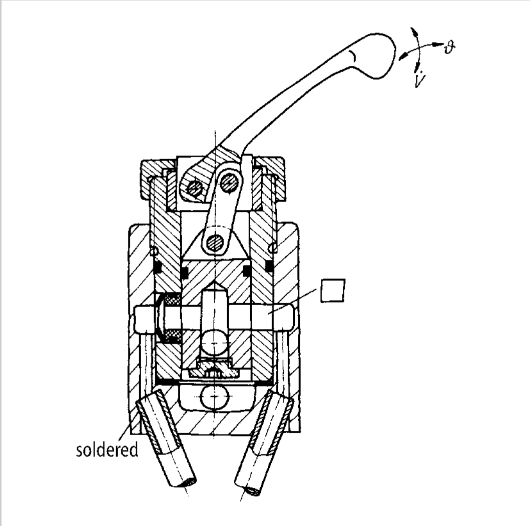


Figure 6.38. One-handed mixing tap, solution variant B: "cylinder solution with lever"

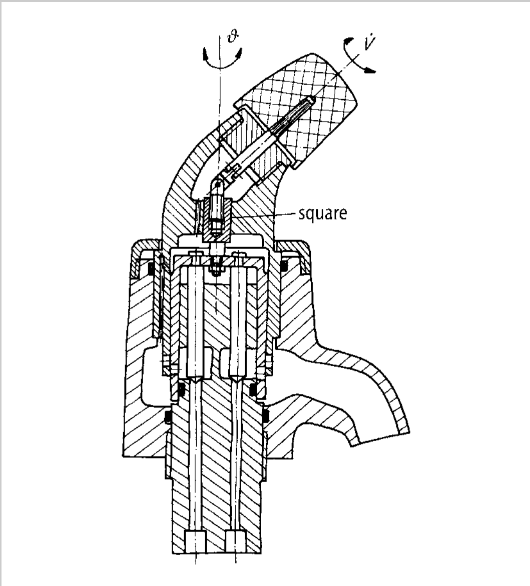


Figure 6.39. One-handed mixing tap, solution variant C: "cylinder solution with end valves and additional sealing"

Thanks to the balanced profile and the discernible improvement possibilities, Solution B (see Figure 6.38) was found to be preferable to all the others. The ball solution D (see Figure 6.40) would only have been considered if further studies into production and assembly problems had been undertaken and had led to positive results.

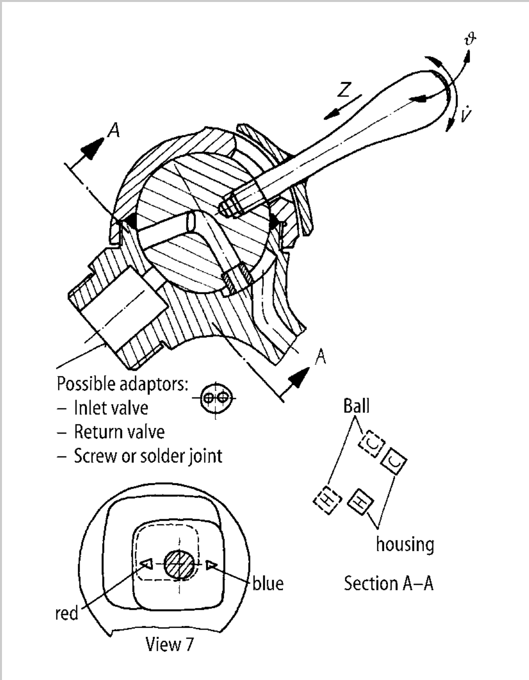


Figure 6.40. One-handed mixing tap, solution variant D: "ball solution"

Step 8: Determining the Next Steps

It was decided to produce dimensional layout drawings of Solution B with improvements to the operating lever with respect to space requirements, easier cleaning and number of parts, and also to improve the level of information for Solution D with a view to reexamining it for final evaluation.

6.6.2 Impulse-Loading Test Rig

Step 1: Clarifying the Task and Setting Up the Requirements List

The second example describes the development of a test rig [6.12]. This test rig was used to investigate the durability of shaft–hub connections subjected to impulsive loads with predefined torques, applied both singly and continuously. Prior to setting up the requirements list, the following questions had to be answered:

- What is meant by impulsive loading?
- Which impulsive torques occur in rotating machines in practice?
- Which stress measurements are possible and useful for keyed connections?

To answer the first two questions, the characteristics of torque–time variations for milling machines, crane drives, agricultural machines and rolling presses were

TH Darmstadt	EVALUATION CHART for: One-handed mixing tap	Page 1

In the order of the checklist headings	No.	Evaluation criterion	W	A P	A (P)	B P	B (P)	C P	C (P)	D P	D (P)	E P	E (P)	F P	F (P)
		P: present variant (P): possible after improvement													
Funct.	1	Reliability of stopping flow without drips	1	1		3		3 I	4	1					
Work Princ.	2	Reliable, reproducible setting (calcium-resistant, few wearing parts)	1	2		3		2 I	3	3					
Embod	3	Low space requirement	1	3↑		2		2		4					
Prod.	4	Few parts	1	1		2 I		1 W		4					
Prod.	5	Simple manufacture	1	1		3		2		1?	4				
Assy.	6	Easy assembly	1	2		3		2		2↑ J	3				
Operation	7	Convenient operation, sensitive setting	1	1		3		4		2					
Operation	8	Easy upkeep (easy to clean)	1	4↓		2 I		3		2					
Maint.	9	Simple maintenance (with standard tools, fittings need not be dismantled)	1	1		3		2 W		1? J	3				
	10														
	11														
	12														
	13														
	14														
? Evaluation uncertain		$P_{max} = 4$	Σ	16		24	(26)	21	(23)	(20)	(26)				
↑ Tendency: better		R_t		0,45		0,67		0,58		0,56					
↓ Tendency: worse		Ranking		4		1	(1)	2	(3)	3	(2)				

Justification (J), Weak spot (W), Improvement (I) of variant/criterion	
C1	Provide rubber seal
B4	Simplify lever mechanism
D6 D9	Indeterminate position of ball during assembly
B8	Improve with B4
D9	Attachment of lever

Decision	
	Develop solution B with improvement of control elements Solution D: Examine production possibilities, present result in 2 months

Date: 11.10.73	Initials: Dhz	

Figure 6.41. One-handed mixing tap: evaluation of principle solution variants A, B, C, D

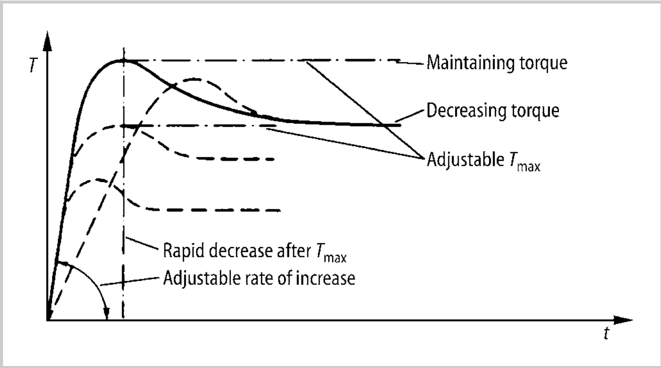


Figure 6.42. Setting magnitudes for an impulsive torque: rate of increase, magnitude and duration

TU Berlin	REQUIREMENT LIST for: Impulse-loading test ring	Part: 1	Page: 1

Changes	D W	Requirements	Responsible
		Geometry:	
	D	Test connection held in position	
	D	Diameter of shaft to be tested ≤ 100 mm (dimensions of the key according to DIN 6885)	
	D	Hubside load take off variable in axial direction	
		Kinematics:	
	D	Loading applied to stationary shaft	
	D	Oscillating load applied in one sense only	
	W	Sense of loading selectable	
	W	Torque input variable (from hub to shaft or from shaft to hub)	
		Forces:	
	D	Shaft-hub connection subjected to torque only (i.e. free of shear forces and bending moments)	
	D	Maximum torque maintained for at least 3 seconds	
	D	Loading frequency low (reason: chosen measuring principle)	
	W	As little vibration as possible in the shaft-hub-key system	
	D	Torque adjustable up to 15 000 Nm in accordance with the load capacity of a shaft of 100 mm diameter	
	D	Rapid decrease of torque after reaching the maximum should be possible	
	D	Adjustable torque increase dT/dt of up to $125 \cdot 10^3$ Nm/s	
	D	Reproducible torque profile	
	W	Plastic deformation, or even destruction, of the connection should be possible	
		Energy:	
	D	Power consumption ≤ 5 kW/380 Volt	
		Material:	
	W	Shaft and hub: C45	

	Replaces issue of	

Figure 6.43. Requirements list for impulse-loading test rig. After [6.12]

TU Berlin	REQUIREMENT LIST for: Impulse-loading test ring	Part: 1	Page: 2
Changes	**D W**	**Requirements**	**Responsible**
		Signal:	
	D	Quantities to be measured: torque in front of and behind the test connection, surface pressure over the length of the connection and the key	
	D	Quantities to be measured should be recordable	
	W	Accessible measuring locations	
		Safety and Ergonomics:	
	W	Easy operation of the test rig (i.e. quick and easy resetting of the test rig)	
	W	Environmentally-friendly operating principle (little noise, dirt, vibration ...)	
		Production and Control:	
	D	One-off production of all parts	
	D	Quality of shaft-hub-connection according to DIN 6885 (as far as described in this standard), otherwise according to standards for shaft ends on drives, electric motors etc: DIN 748, Parts 2 and 3	
	W	Production of the test rig in own workshops	
	W	Use bought-out and standard parts wherever possible	
		Assembly and Transport:	
	W	Test rig with small dimensions and low weight	
	W	No special foundation	
		Operation and Maintenance:	
	W	Parts subjected to wear should be few and simple	
	W	Preferably free of maintenance	
		Costs:	
		Manufacturing costs ~ 20 000 DM (see research proposal)	
		Schedule:	
	D	Concept phase finished by July 1973 Concept phase finished by 20 July 1973	Mr. Militz
		Replaces issue of	

Figure 6.43. (continued)

obtained from the literature. A maximum rate of torque increase of $\mathrm{d}T/\mathrm{d}t = 125 \times 10^3$ Nm/s was selected. The torque–time graph shown in Figure 6.42 was used to establish the necessary parameters to vary.

These requirements, along with others, were documented in the requirements list shown in Figure 6.43. They were classified according to the checklist in Figure 6.22.

Step 2: Abstracting to Identify the Essential Problems

Following the recommendations in Section 6.2.3, the requirements list was abstracted. The results are shown in Table 6.2.

Table 6.2. Abstraction and problem definition on the basis of the requirements list shown in Figure 6.43

Results from Steps 1 and 2

- Diameter of shaft to be tested $\leq$ 100 mm
- Hubside load take off variable in axial direction
- Loading applied to stationary shaft
- Pure torque loading: adjustable up to 15 000 Nm
- Maximum torque maintained for at least 3 seconds
- Rapid decrease of torque possible
- Maximum torque increase dT/dt of 125×10^3 Nm/s
- Reproducible torque profile
- Quantities $T_{\text{in front}}$, T_{behind} and p measurable

Results from Step 3

- Loading of the shaft-hub-key connection adjustable regarding torque magnitude, torque increase, torque holding time and torque decrease
- Check torque and loading with shaft stationary

Results from Step 4

- Adjustable dynamic torque to be applied when testing the specimen
- Measurements of input load levels and of stresses and strains should be possible

Result from Step 5

- "Apply dynamically changing torque while at the same time measuring load levels, stresses and strains"

Step 3: Establishing Function Structures

Establishing the function structure initially involved formulating the overall function, which was extracted directly from the problem statement, see Figure 6.44.

In this example, the essential subfunctions result from the energy flow and, for the measurements, from the signal flow:

- Transform input energy into load (torque)
- Transform input energy into auxiliary energy for the control functions
- Store energy for the impulsive action
- Control load energy and magnitude
- Change load magnitude
- Guide load energy
- Apply load to specimen, i.e. its working surface
- Measure load
- Measure specimen stresses

Setting up the function structure in a stepwise manner resulted in different arrangements and, by adding and removing individual subfunctions, several func-

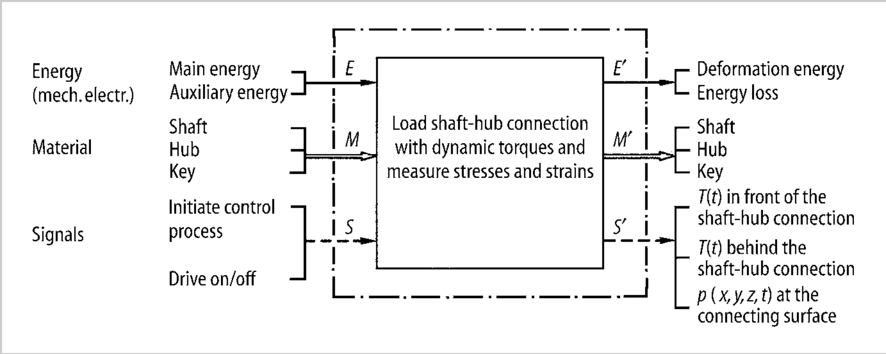


Figure 6.44. Overall function of the impulse-loading test rig

tion structure variants were produced. Figure 6.45 shows these variants in the order in which they appeared. At this stage, the measuring functions do not appear to determine the concept. Variant 4 was chosen to search for solutions because it contained all of the subfunctions of the equally promising Variant 5.

Step 4: Searching for Working Principles

To find working principles, the following methods discussed in Section 3.2 were applied:

- Conventional methods: literature search and analysis of an existing test rig
- Intuitive methods: brainstorming
- Discursive methods: systematic search with the help of classification schemes using types of energy, working movements and working surfaces, as well as the use of a catalogue on varying forces.

To combine the working principles that were found, a classification scheme was produced (see Figure 6.46). For reasons of space, only the most important subfunctions and working principles are shown. Those principles that were clearly unsuitable were either rejected early on or crossed out in the classification scheme. Timely rejection is important in order to minimise subsequent effort.

Step 5: Combining Working Principles

The working principles were combined based on the classification scheme shown in Figure 6.46. Figure 6.47 shows the seven possible combinations (variants) in accordance with the selected function structure variants 4 and 5. The sequences of the subfunctions differ in parts from those of the function structure variants.

Step 6: Selecting Suitable Combinations

A preselection is recommended when a large number of combinations (working structures) have been generated before firming up is attempted (see Section 6.4.3).

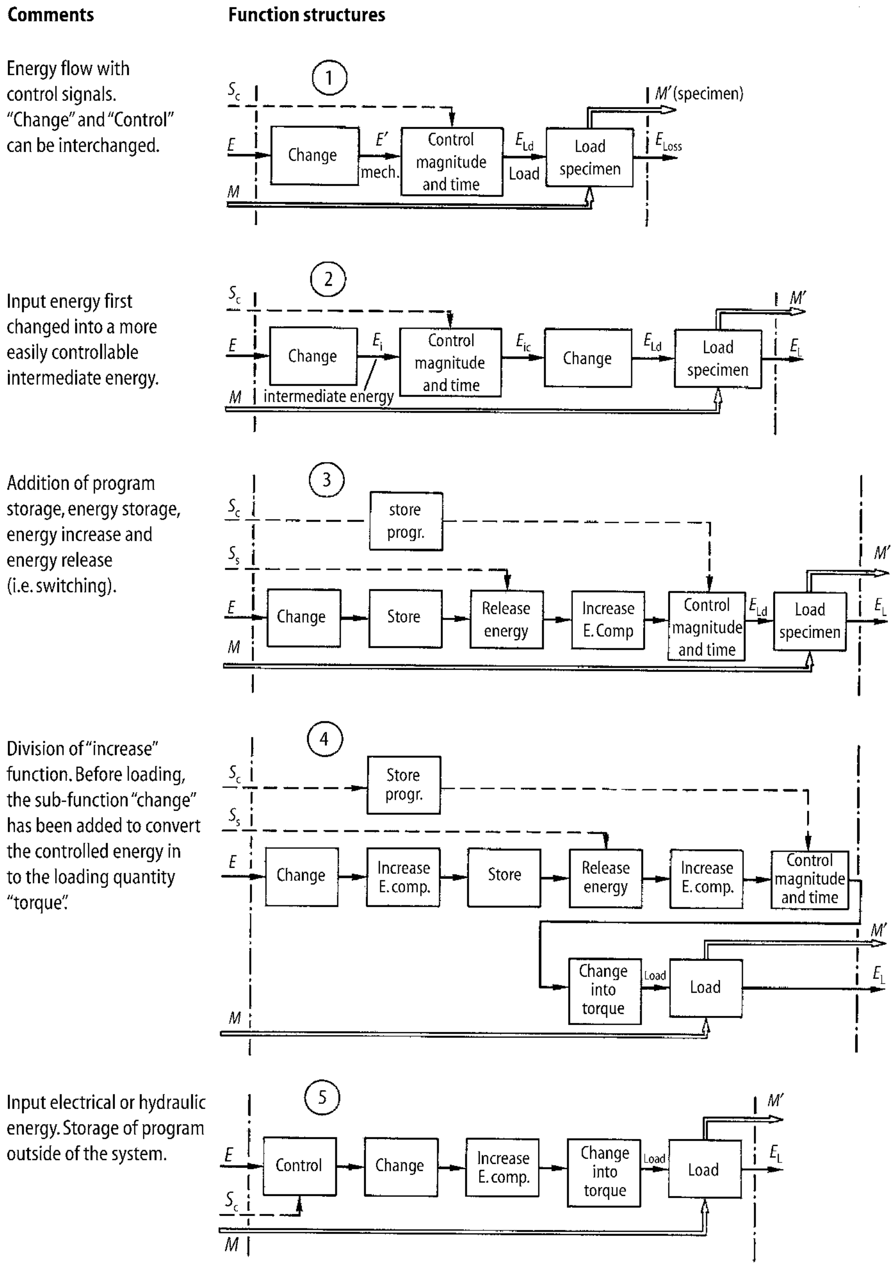


Figure 6.45. Stepwise development of function structure variants

This reduces effort by rejecting less suitable combinations as early as possible. After using the procedure presented in Section 3.3.1, four out of seven combinations appeared promising (see Figure 6.48), but had to be firmed up further to allow for more precise evaluation.

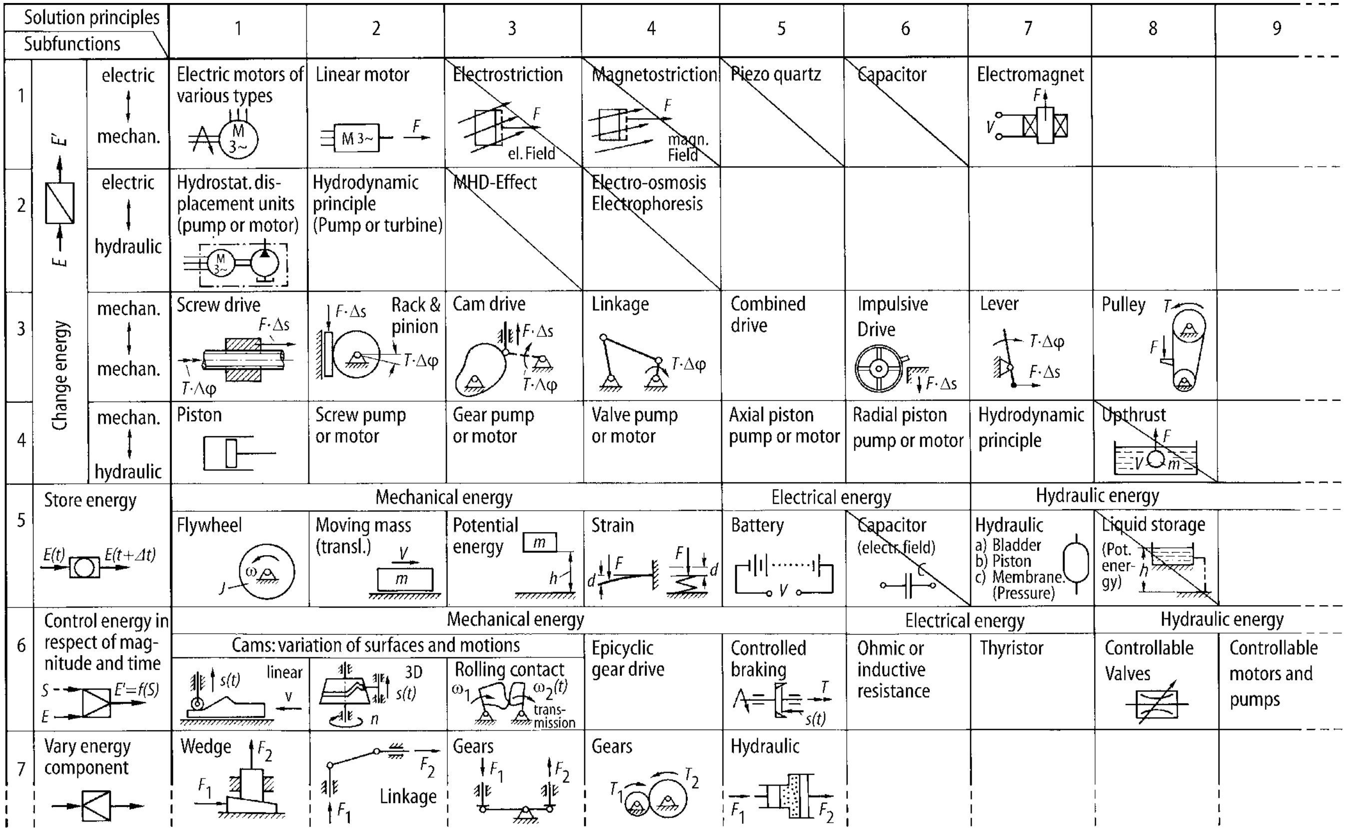


Figure 6.46. Extract from a classification scheme for an impulse-loading test rig

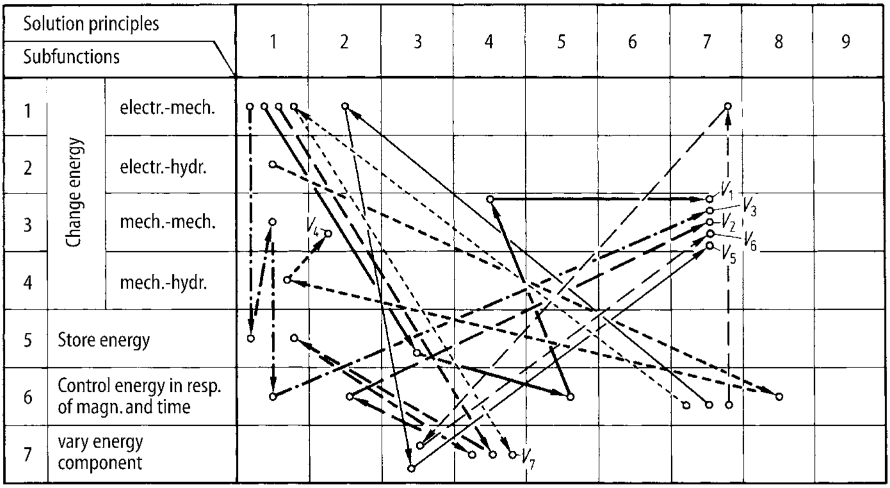


Figure 6.47. Combination scheme showing seven combinations of solution principles in accordance with Figure 6.46.
Variant 1: 1.1 – 5.3 – 6.5 – 3.4 – 3.7;
Variant 2: 1.1 – 7.4 – 5.1 – 7.4 – 6.2 – 3.7;
Variant 3: 1.1 – 5.1 – 3.1 – 6.1 – 3.7;
Variant 4: 2.1 – 6.8 – 4.1 – 3.2;
Variant 5: 6.7 – 1.2 – 7.3 – 3.7;
Variant 6: 6.7 – 1.7 – 7.3 – 3.7;
Variant 7: 6.7 – 1.1 – 7.4

Step 7: Firming Up into Principle Solution Variants

To allow a confident decision to be made about the most suitable principle solution (concept) variant, the selected working structures have to be developed to a state that allows evaluation. This requires that suitable concept drawings such as those shown in Figures 6.49 to 6.52 are produced. Rough sketches often do not provide sufficient detail to assess how well proposals fulfil their functions.

Rough calculations or model tests can be useful at this stage. As an example, calculations will now be made for the cylindrical cam drive used to control the impulsive torque and also the required moment of inertia of the flywheel (energy store) for concept variant V_2.

Can the cylindrical cam shown in Figure 6.53 produce the required torque increase of $\mathrm{d}T/\mathrm{d}t = 125 \times 10^3$ Nm/s and the maximum torque of $T_{\max} = 15 \times 10^3$ Nm?

Calculation steps:

- Time needed to reach the maximum torque at the required rate:

$$\Delta t = \frac{15 \times 10^3}{125 \times 10^3} = 0.12 \text{ s}$$

- Force at the end of the loading lever:

$$F_{\max} = \frac{T_{\max}}{l} = \frac{15 \times 10^3}{0.85} = 17.6 \times 10^3$$

TU Berlin	SELECTION CHART for Impulse-loading test rig	Part: 1 Page: 1

Solution variants (Sv) evaluated by

SELECTION CRITERIA

(+) Yes
(–) No
(?) Lack of information
(!) Check requirements list

DECISION

Mark solution variants (Sv)

(+) Pursue solution
(–) Eliminate solution
(?) Collect information (re-evaluate solution)
(!) Check requirements list for changes

Enter solution variant (Sv):

A: Compatibility assured
B: Fulfils demands of requirements list
C: Realisable in principle
D: Within permissible costs
E: Incorporates direct safety measures
F: Preferred by designer's company
G: Adequate information

Sv		A	B	C	D	E	F	G	Remarks (Indications, Reasons)	DECISION
V1	1	+	?	+	+	?	–	–	Layout of controlable brakes problematic	+
V2	2	+	+	+	+	+	+	+		+
V3	3	+	+	+	+	+	+	+		+
V4	4	+	+	+	?	+	–	+	Hydraulics not yet applied	+
V5	5	+	?	+	–	+	–	–	No experience with linear motors	–
V6	6	+	?	+	?	+	–	?	Power demand of magnet too great	–
V7	7	+	?	+	–	+	–	?	No experience with thyristor control	–
	8									
	9									
	10									
	11									
	12									
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	17									
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Figure 6.48. Selection chart for the seven combinations in Figure 6.47

The loading lever is treated as a weak cantilever spring with the end moving through a distance of $h = 30$ mm with a force of F_{max} in such a way that the permissible bending stress is not exceeded.

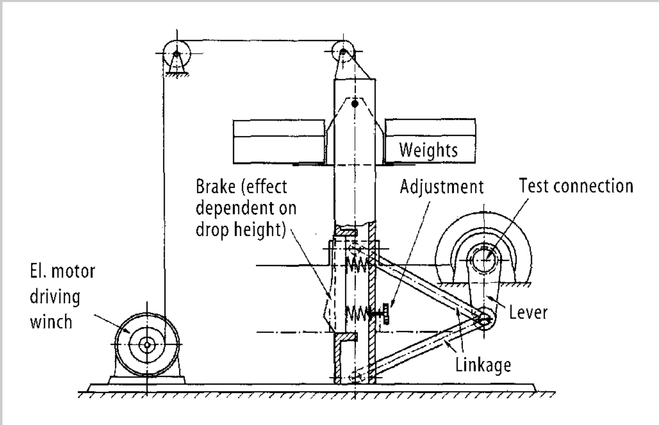

Figure 6.49. Concept variant V_1

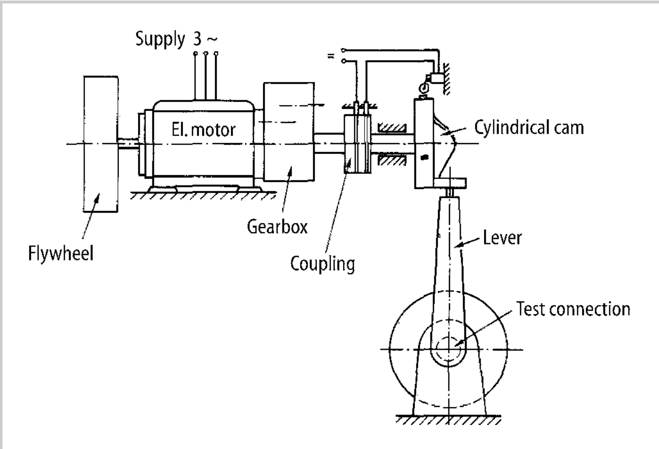

Figure 6.50. Concept variant V_2

- Tangential velocity of the cylindrical cam:

$$v_x = v_y = \frac{h}{\Delta t} = \frac{30}{0.12} = 250 \text{ mm/s}$$

- Angular velocity and rpm of cylindrical cam:

$$\omega = \frac{0.25}{0.125} = 2.0 \text{ rad/s}; \; n = \frac{60\omega}{2\pi} = 19 \text{ rev/min}$$

- Period of revolution:

$$t_r = \frac{2\pi}{\omega} = 3.14 \text{ s}$$

Since the switching times of the electromagnetically operated clutches used to connect and disconnect the cam drive are in the region of a few tenths of a second, there

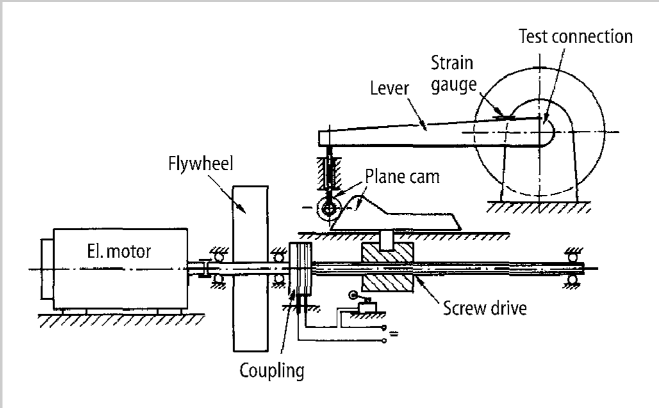

Figure 6.51. Concept variant V_3

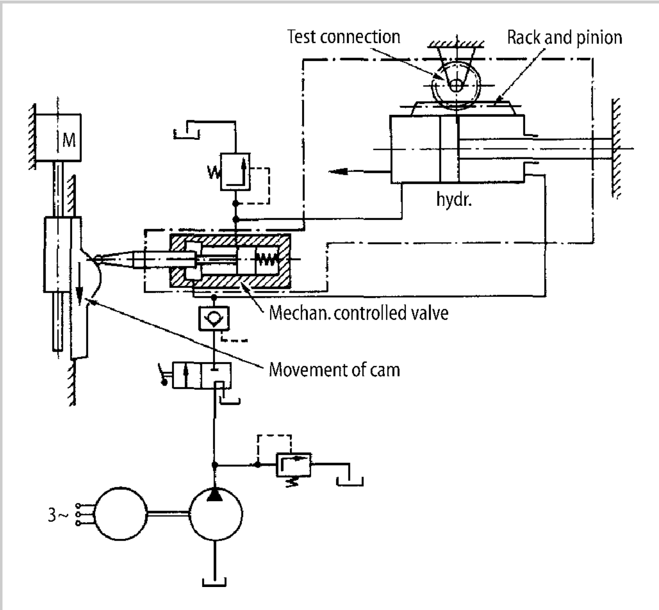

Figure 6.52. Concept variant V_4

should be no problem with applying this principle. The magnitude of, and rate of increase in, the impulse torque loading can be altered by means of interchangeable cams and also by varying the period of revolution.

Steps for estimating the flywheel's moment of inertia:

- The estimate of the energy needed for the impulse (and hence of the energy to be stored) is based on the assumption that all load-carrying parts are elastically deformed.

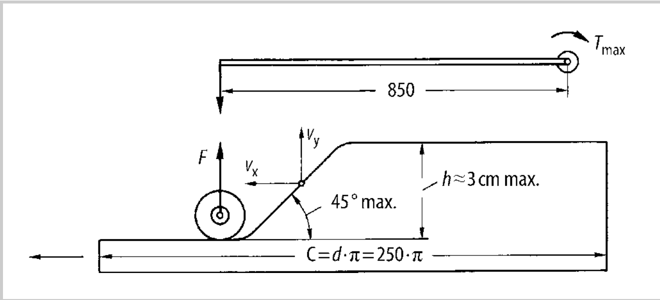

Figure 6.53. Development of cylindrical cam

Stored energy at maximum impulse torque loading:

$$E_{max} = \frac{1}{2} F_{max} \cdot h = 260 \text{ J}$$

This amount of energy is needed in the time interval $\Delta t = 0.12$ s.

- Flywheel dimensions:

  Selected maximum rpm, $n_{max} = 1200$ rev/min; $\omega \mathrel{\hat{=}} 126$ rad/s.

  For flywheel dimensions $r = 0.2$ m and $w = 0.1$ m, the flywheel mass $m_f = 100$ kg, and moment of inertia $J_f = \frac{1}{2} m_f \cdot r^2 = 2 \text{ kg m}^2$.

  Stored energy of flywheel:

$$E_f = \frac{1}{2} J_f \cdot \omega^2 = 159 \times 10^2 \text{ J}$$

- Rotational speed after the impulse:

$$E_{after} = E_f - E_{max} = 15\,640 \text{ J}$$

$$\omega_{after} = \sqrt{\frac{2E_{after}}{J_f}} = 125 \text{ rad/s}; \quad n_{after} = 1190 \text{ rev/min}$$

  The drop in rpm is therefore very low, and so a motor with a small output is all that is needed.

Step 8: Evaluating Principle Solution Variants

The four variants that were selected in Step 6 and firmed up in Step 7 are evaluated using Cost–Benefit Analysis (see Section 3.3.2).

Important wishes in the requirements list provide a series of evaluation criteria of varying complexity. These are assessed and elaborated with the help of the checklist shown in Figure 6.22. Next, a hierarchical classification (objectives tree) is drawn up to facilitate closer identification and better assignment of the weighting factors and the parameters of the variants. Figure 6.54 shows an objectives tree for the test rig. Its lowest objective level provides the evaluation criteria entered into the table shown in Figure 6.55.

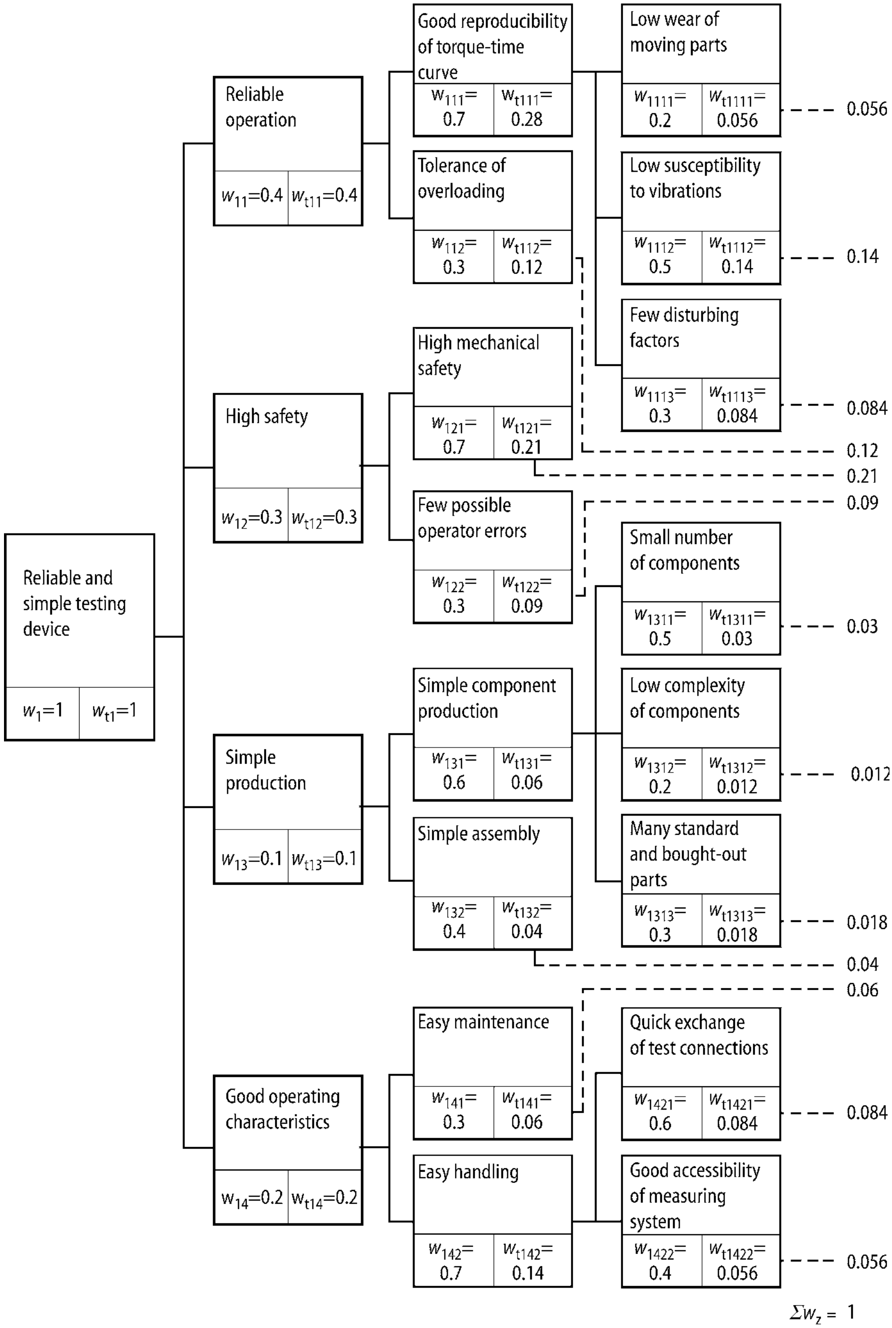

Figure 6.54. Objectives tree for impulse-loading test rig

Evaluation criteria			Parameters		Variant V_1			Variant V_2			Variant V_3			Variant V_4		
No.		Wt.		Unit	Magn. m_{i1}	Value V_{i1}	Weighted value WV_{i1}	Magn. m_{i2}	Value V_{i2}	Weighted value WV_{i2}	Magn. m_{i3}	Value V_{i3}	Weighted value WV_{i3}	Magn. m_{i4}	Value V_{i4}	Weighted value WV_{i4}
1	Low wear of moving parts	0.056	Amount of wear	–	high	3	0.168	low	6	0.336	average	4	0.224	low	6	0.336
2	Low susceptibility to vibrations	0.14	Natural frequencey	s^1	410	3	0.420	2370	7	0.980	2370	7	0.980	< 410	2	0.280
3	Few disturbing factors	0.084	Disturbing factors	–	high	2	0.168	low	7	0.588	low	6	0.504	(average)	4	0.336
4	Tolerance of overloading	0.12	Overload reserve	%	5	5	0.600	10	7	0.840	10	7	0.840	20	8	0.960
5	High mechanical safety	0.21	Expected mechanical safety	–	average	4	0.840	high	7	1.470	high	7	1.470	very high	8	1.680
6	Few possible operator errors	0.09	Possibilities of operator errors	–	high	3	0.270	low	7	0.630	low	6	0.540	average	4	0.360
7	Small number of components	0.03	No. of components	–	average	5	0.150	average	4	0.120	average	4	0.120	low	6	0.180
8	Low complexity of components	0.012	Complexity of components	–	low	6	0.072	low	7	0.084	average	5	0.060	high	3	0.036
9	Many standard and bought-out parts	0.018	Proportion of standard and bought-out components	–	low	2	0.036	average	6	0.108	average	6	0.108	high	8	0.144
10	Simple assembly	0.04	Simplicity of assembly	–	low	3	0.120	average	5	0.200	average	5	0.200	high	7	0.280
11	Easy maintenance	0.06	Time and cost of maintenance	–	average	4	0.240	low	8	0.480	low	7	0.420	high	3	0.180
12	Quick exchange of test connections	0.084	Estimated time needed to exchange test connections	min	180	4	0.336	120	7	0.588	120	7	0.588	180	4	0.336
13	Good accessibility of measuring systems	0.056	Accessibility of measuring system	–	good	7	0.392	good	7	0.392	good	7	0.392	average	5	0.280
		$\sum w_i = 1.0$				$OV_1=51$ $R_1=0.39$	$OWV_1=3.812$ $WR_1=0.38$		$OV_2=85$ $R_2=0.65$	$OWV_2=6.816$ $WR_2=0.68$		$OV_3=78$ $R_3=0.60$	$OWV_3=6.446$ $WR_3=0.64$		$OV_4=68$ $R_4=0.52$	$OWV_4=5.388$ $WR_4=0.54$

Figure 6.55. Evaluation of the four principle solution variants for the impulse-loading test rig

It appears that variant V_2 has the highest overall value and the best overall rating. However, variant V_3 follows close behind. For the detection of weak spots, a value profile was drawn (see Figure 6.56). The profile shows that variant V_2 is well-balanced with respect to all of the important evaluation criteria. With a weighted rating of 68%, variant V_2 thus represents a good principle solution (concept) with which to start the embodiment design phase, during which the identified weak spots have to be addressed (see Section 7.7).

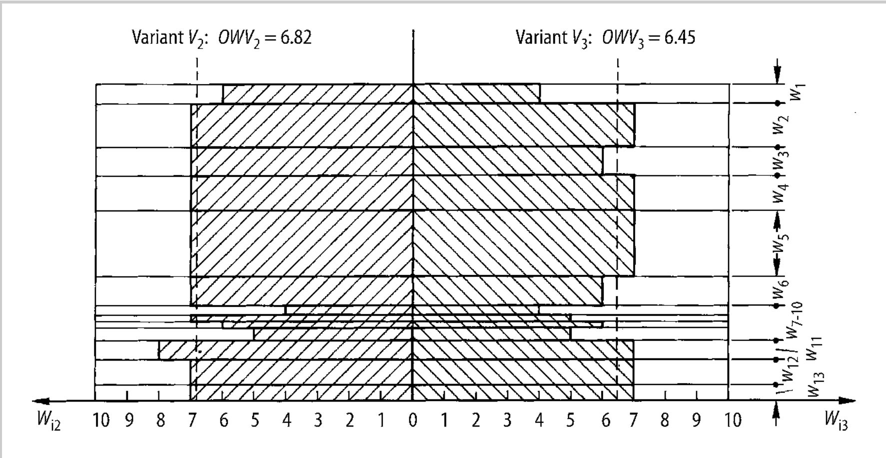

Figure 6.56. Value profile for detection of weak spots