2 Fundamentals

Designing is a many-sided and wide-ranging activity. It is based not only on mathematics, physics and their branches—mechanics, thermodynamics etc—but also on production technology, materials science, machine elements, industrial management and cost accounting, which are not discussed in this book.

To develop a theory of design that can serve as a strategy for the development of solutions, we must first examine the fundamentals of engineering systems and procedures. Only when that has been done is it possible to make detailed recommendations for design work.

2.1 Fundamentals of engineering systems

2.1.1 System, plant, equipment, machine, assembly and component

Technical tasks are performed with the help of such *technical artefacts* as plant, equipment, machines, assemblies and components, listed here in the approximate order of their complexity. These terms may not have identical uses in different fields. Thus, a piece of equipment (reactor, evaporator) is sometimes considered to be more complex than plant, and artefacts described as 'plant' in certain fields may be described as 'machines' in others.

A machine consists of assemblies and components. Control equipment is used in plant and machines alike and may be made up of assemblies and components, and perhaps even of small machines. The various uses of these terms reflect historical developments.

Hubka [2.10] has drawn up a comprehensive list of possible classifications of technical artefacts based on such criteria as function, solution principle, complexity, manufacture, product etc. It is, however, impossible to agree on a generally acceptable system of classification—the tasks, applications and forms are much too varied and complex. Hence there is much to be said for Hubka's suggestion that technical artefacts should be treated as *systems* connected to the environment by means of *inputs* and *outputs*. A system can be divided into sub-systems. What belongs to a particular system is determined by the *system boundary*. The inputs and outputs cross the system boundary (1.2.3). With this approach it is possible to define appropriate systems at every stage of abstraction, analysis or classification. As a rule such systems are parts of larger, superior systems.

A concrete example is the combined coupling shown in Figure 2.1. This can be treated as two sub-systems—a flexible coupling and a clutch. The sub-system 'clutch' can, in turn, be subdivided into system elements, in this case components.

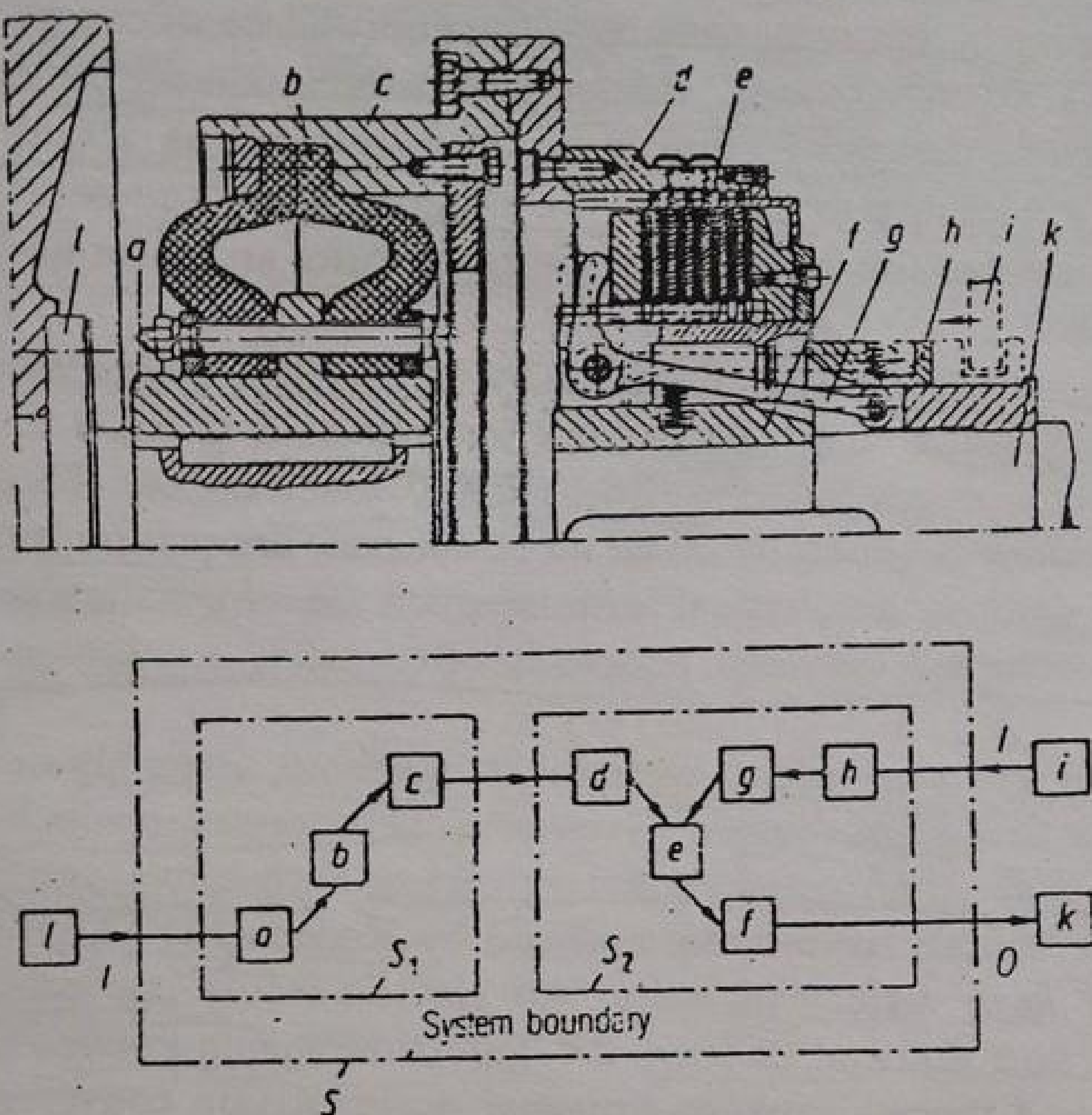


Figure 2.1. System: 'Coupling'
$a \ldots h$ system elements; $i \ldots l$ connecting elements; S overall system; S_1 subsystem 'flexible coupling'; S_2 subsystem 'clutch'; I inputs: O outputs

The system depicted in Figure 2.1 is based on its mechanical construction. It is, however, equally possible to consider it in terms of its functions (see 2.1.3). In that case, the total system 'coupling' can be split up into the sub-systems 'damping' and 'clutching'; the second sub-system into the further sub-systems 'changing clutch operating force into normal force' and 'transferring torque'. Thus the system element g could equally well be treated as a sub-system whose function it is to convert the actuating force into a larger normal force acting on the friction surfaces.

Depending on their use, any number of such subdivisions may be made. The designer has to establish particular systems for particular purposes, and must specify their various inputs and outputs and fix their boundaries. In doing this he may use what terminology he likes or is customary in his particular field.

2.1.2 Conversion of energy, material and signals

Man encounters matter in many shapes and forms. Its natural form, or the form he has impressed upon it, provides him with information about its possible uses.

Matter without form is inconceivable—form is a primary source of information about the state of matter. With the development of physics, the concept of force became increasingly important. Force was conceived as being the means by which the motion of matter was changed. Ultimately this process was explained in terms of energy. The theory of relativity postulated the equivalence of energy and matter. Weizsäcker [2.30] lists energy, matter and information as basic concepts. If change or flow is involved, time must be introduced as a fundamental quantity. Only by reference to time does the physical event in question become comprehensible, and can the interplay of energy, matter and information be adequately described.

In the technical sphere, *energy* is often specified by its manifest form. We speak of mechanical, electrical, optical energy etc. For *matter*, it is usual to substitute *material* with such properties as weight, colour, condition etc. The general concept of *information* is generally given more concrete expression by means of the term *signal*—that is, the physical form in which the information is conveyed. Information exchanged between people is often called a message [2.11].

The analysis of technical systems—plant, equipment, machine, assembly or component—makes it clear that all of them involve technical processes in which energy, material and signals are channelled and/or converted. Such conversions of energy, material and/or signals have been analysed by Rodenacker [2.23].

Energy can be converted in a variety of ways. An electric motor converts electrical into mechanical and thermal energy, a combustion engine converts chemical into mechanical and thermal energy a nuclear power station converts nuclear into thermal energy, and so on.

Materials too can be converted in a variety of ways. They can be mixed, separated, dyed, coated, packed, transported or reshaped. Raw materials are turned into part-finished and finished products. Mechanical parts are given particular shapes and surface finishes and some are destroyed for testing purposes.

Every plant must process *information* in the form of signals. Signals are received, prepared, compared or combined with others, transmitted, displayed, recorded, and so on.

In technical processes, one type of conversion (of energy, material or signals) may prevail over the others, depending on the problem or its solution. In that case, the conversion involved is treated as the main conversion. It is usually accompanied by a second type of conversion, and quite frequently all three come into play. Thus there can be no conversion of material or signals without an accompanying conversion of energy, however small.

The conversion of energy is often associated with the conversion of material, even though no such conversion may be visible (as in a nuclear, compared with a coal-fired, power station). The associated conversion of signals constitutes an important subsidiary conversion for the control and regulation of the entire process.

However, numerous measuring instruments receive, transform or display signals without any flow of material. In many cases energy has to be specially provided for this purpose; in other cases latent energy can be drawn upon directly. Every conversion of signals is associated with a conversion of energy, though not necessarily with a conversion of material.

In what follows, we shall be dealing with:

—Energy: mechanical, thermal, electrical, chemical, optical, nuclear etc . . . also force, current, heat . . .

—Material: gas, liquid, solid, dust etc . . . also raw material, test sample, workpiece etc . . . end product, component etc . . .

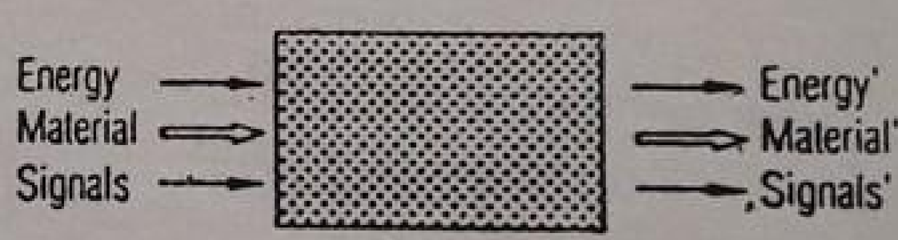
—Signals: magnitude, display, control impulse, data, information etc . . .

In every type of proposed conversion, *quantity* and *quality* must be taken into consideration if rigorous criteria for the definition of the task, for the choice of solutions and for an evaluation, are to be established. No statement is fully defined unless its quantitative as well as its qualitative aspects have been taken into account. Thus, the statement: '100 kg/s of steam at 80 bar and 500°C' is not a sufficient definition of the input of a steam turbine unless there is the further specification that these figures refer to a nominal quantity of steam and not, for instance, to the maximum flow capacity of the turbine, and unless the admissible fluctuations of the state of the steam are fixed at, say, 80 bar ± 5 bar and 500°C ± 10°C, that is, extended by a qualitative aspect.

In very many applications, it is also essential to stipulate the cost or value of the inputs and/or the maximum permissible costs of the outputs (see [2.23]).

To sum up: all technical systems involve the conversion of energy, material and/or signals which must be defined in quantitative, qualitative and economic terms (Figure 2.2).

Figure 2.2. The conversion of energy, material and signals. Solution not yet known; task or function described on the basis of inputs and outputs



2.1.3 The functional interrelationship

In order to solve a technical problem we need a system with a clear and easily reproduced relationship between inputs and outputs. In the case of material conversions, for instance, we require identical outputs for identical inputs. Also, between the beginning and the end of a process, for instance filling a tank, there must be a clear and reproducible relationship. Such relationships must always be planned—that is, designed to meet a specification. For the purpose of describing and solving design problems, it is useful to apply the term *function* to the general input/output relationship of a system whose purpose it is to perform a task.

For static processes it is enough to determine the inputs and outputs; for processes that change with time (dynamic processes), the task must be defined further by a description of the initial and final magnitudes. At this stage there is no need to stipulate what solution will satisfy this kind of function. The function thus becomes an abstract formulation of the task, independent of any particular solution.

If the *overall task* has been adequately defined—that is, if the inputs and outputs of all the quantities involved and their actual or required properties are known—then it is possible to specify the *overall function*.

An overall function can often be divided directly into identifiable sub-functions corresponding to sub-tasks. The relationship between sub-functions and overall function is very often governed by certain constraints, inasmuch as some sub-functions have to be satisfied before others.

On the other hand it is usually possible to link sub-functions in various ways and hence to create variants. In all such cases, the links must be compatible. The meaningful and compatible combination of sub-functions into an overall function produces a so-called *function structure*, which may be varied to satisfy the overall function.

To that end it is useful to make a block diagram in which the processes and sub-systems inside a given block (black box) are at first ignored (Figure 2.2).

Functions are usually defined by statements consisting of a verb and a noun, for example 'increase pressure', 'transfer torque' or 'reduce speed'. They are derived from the conversions of energy, material and signals discussed in 2.1.2. So far as is possible, all these data should be accompanied with specifications of the physical quantities.

In most engineering applications, a combination of all three types of conversion is usually involved, with the conversion either of material or of energy influencing the function structure decisively.

It is useful to distinguish between *main* and *auxiliary functions*. While *main functions* are those sub-functions that serve the overall function directly, *auxiliary functions* are those that contribute to it indirectly. They have a supportive or complementary character and are often determined by the nature of the solution. These definitions are derived from value analysis [2.4, 2.28, 2.29] and are not identical for all levels of approach. While it may not always be possible to make a clear distinction between main and auxiliary functions, the terms are, nevertheless, useful.

It is also important to examine the relationship between the various sub-functions, and to pay particular attention to their logical sequence or necessary interconnection.

As an example, consider the packing of carpet squares, stamped out of a length of carpet. The first task is to introduce a method of control so that the perfect squares can be selected, counted and packed in specified lots. The main flow here is that of material shown in the form of a block diagram in Figure 2.3. On closer examination we discover that this chain of sub-functions requires the introduction of auxiliary functions because:

— the stamping-out process creates offcuts that have to be removed;
— rejects must be removed separately and reprocessed; and
— packing material must be brought in.

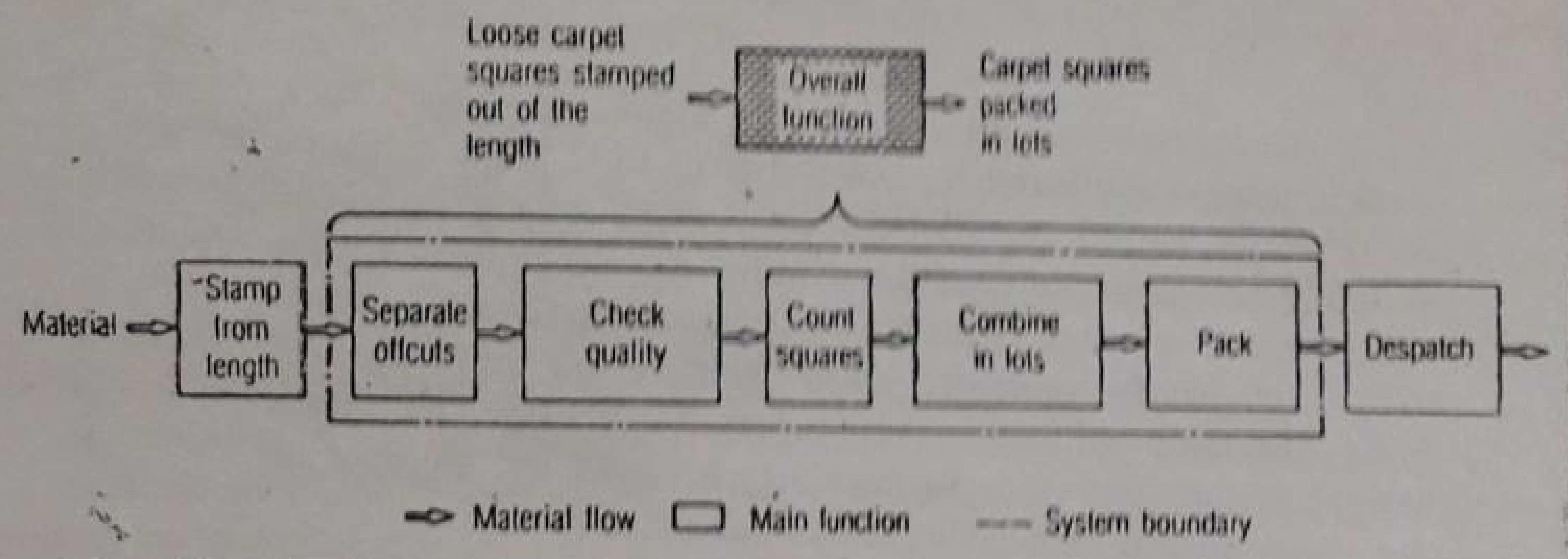


Figure 2.3. Function structure for the packing of carpet squares

The result is the function structure shown in Figure 2.4. It will be seen that the sub-function 'count squares' can also give the signal to pack the squares into lots of a specified size.

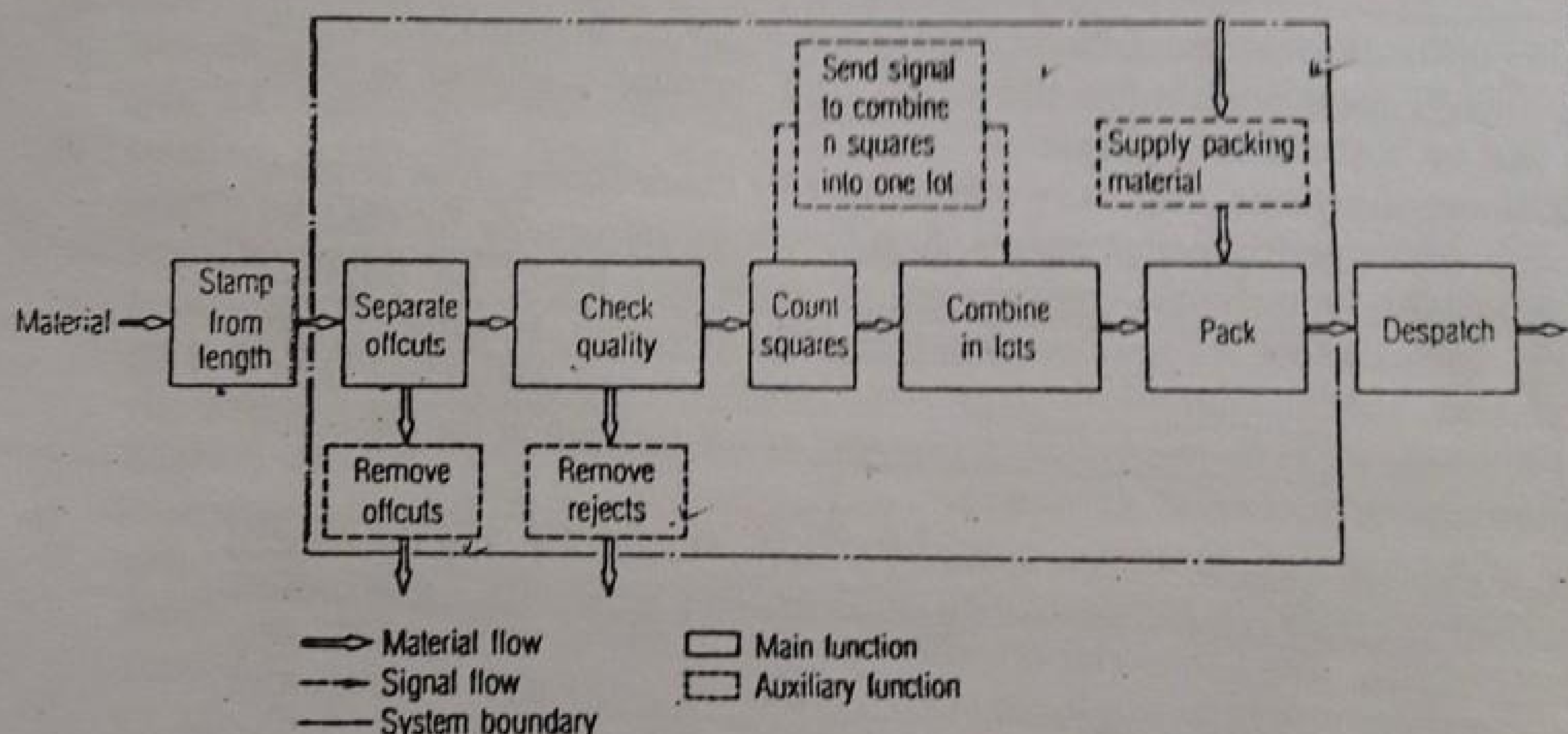


Figure 2.4. Function structure for the packing of carpet squares as in Figure 2.3 with auxiliary functions added

Brockhaus [2.19] has defined functions in general as activities, effects, goals and constraints. In mathematics, a function is the association of a magnitude y with a magnitude x so that a unique value (single-valued function) or more than one value (multi-valued function) of y is assigned for every value of x. According to the definition given in DIN 69 910 [2.4], all functions are determined by objectives (tasks, activities, characteristics).

Various writers on design methods (see 1.2.2) have put forward wider or stricter definitions of generally applicable functions (see 5.3).

In theory, it is possible to classify functions so that the lowest level of the function structure consists exclusively of functions that cannot be sub-divided further while remaining generally applicable.

Rodenacker [2.23] has defined functions in terms of two-valued logic, Roth [2.25] in terms of their general applicability, and Koller [2.12, 2.13] in terms of the required physical effects. Krumhauer [2.14] has examined general functions in the light of possible computer applications during the conceptual design phase, paying special attention to the relationship between inputs and outputs after changes in type, magnitude, number, place and time. By and large, he arrives at the same functions as Roth, except that by 'change' he refers exclusively to changes in the type of input and output, while by 'increase or decrease' he refers exclusively to changes in magnitude.

As Figure 2.5 shows, all these definitions are compatible if it is remembered that Rodenacker uses 'connect' and 'separate' to refer to the logical connections only.

2.1.4 The physical interrelationship

Establishing a function structure facilitates the discovery of solutions because it simplifies the general search for them and also because solutions to sub-functions can be elaborated separately.

Individual sub-functions, originally represented by black boxes, must now be replaced with more concrete statements. Sub-functions are usually fulfilled by physical processes—nearly all engineering solutions are based on physical phenomena. In addition, of course, chemical and biological phenomena may also be involved, but they are relatively few and far between in our chosen field. If, in what follows, we refer to *physical processes*, we tacitly include the effects of possible chemical or biological processes.

Physical processes are based on *physical effects*. A physical effect can be described quantitatively by means of the physical laws governing the physical quantities involved. Thus the friction effect is described by Coulomb's law, $F_F = \mu F_N$; the lever effect by the lever law $F_A \cdot a = F_B \cdot b$; and the expansion effect by the expansion law $\Delta l = \alpha \cdot l \cdot \Delta\theta$. Rodenacker [2.23] and Koller [2.12], in particular, have collated such effects.

Several physical effects may have to be combined in order to fulfil a sub-function. Thus the operation of a bimetal strip is the result of a combination of two effects, namely thermal expansion and elasticity. If, in concrete cases, these effects are assigned to a sub-function, we obtain the *physical principle* of that sub-function.

Figure 2.6 illustrates the stages—sub-function, physical effect, physical principle and solution principle (see 2.1.5)—of three sub-functions (only the inputs and outputs of the main flow are shown):

—transfer torque by the friction effect in accordance with Coulomb's law;
—amplify force by the lever effect in accordance with the lever law; and
—make electrical contact by bridging the gap by means of the expansion effect in accordance with the law of linear expansion of solids or liquids.

A sub-function can often be fulfilled by various physical effects. Thus a force can be amplified by the lever effect, the wedge effect, the electro-magnetic

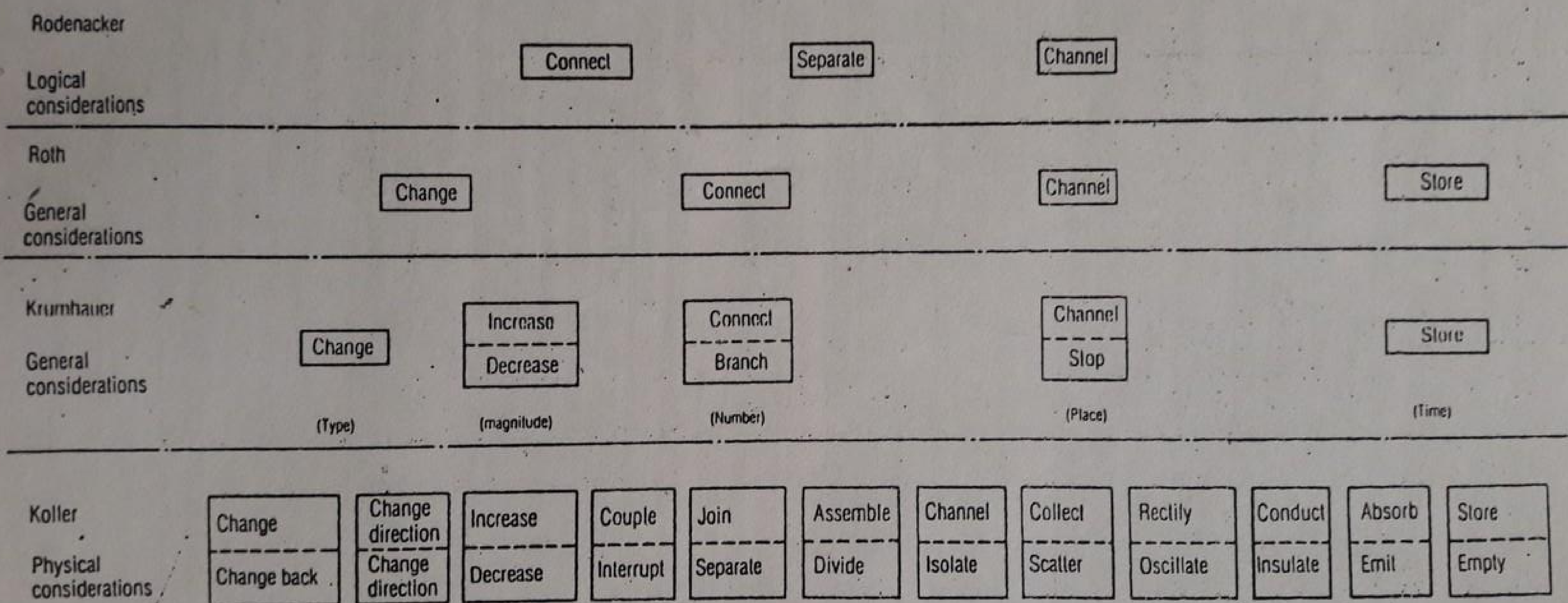


Figure 2.5. Comparison of generally valid functions according to various authors [2.12–2.14, 2.23, 2.25]

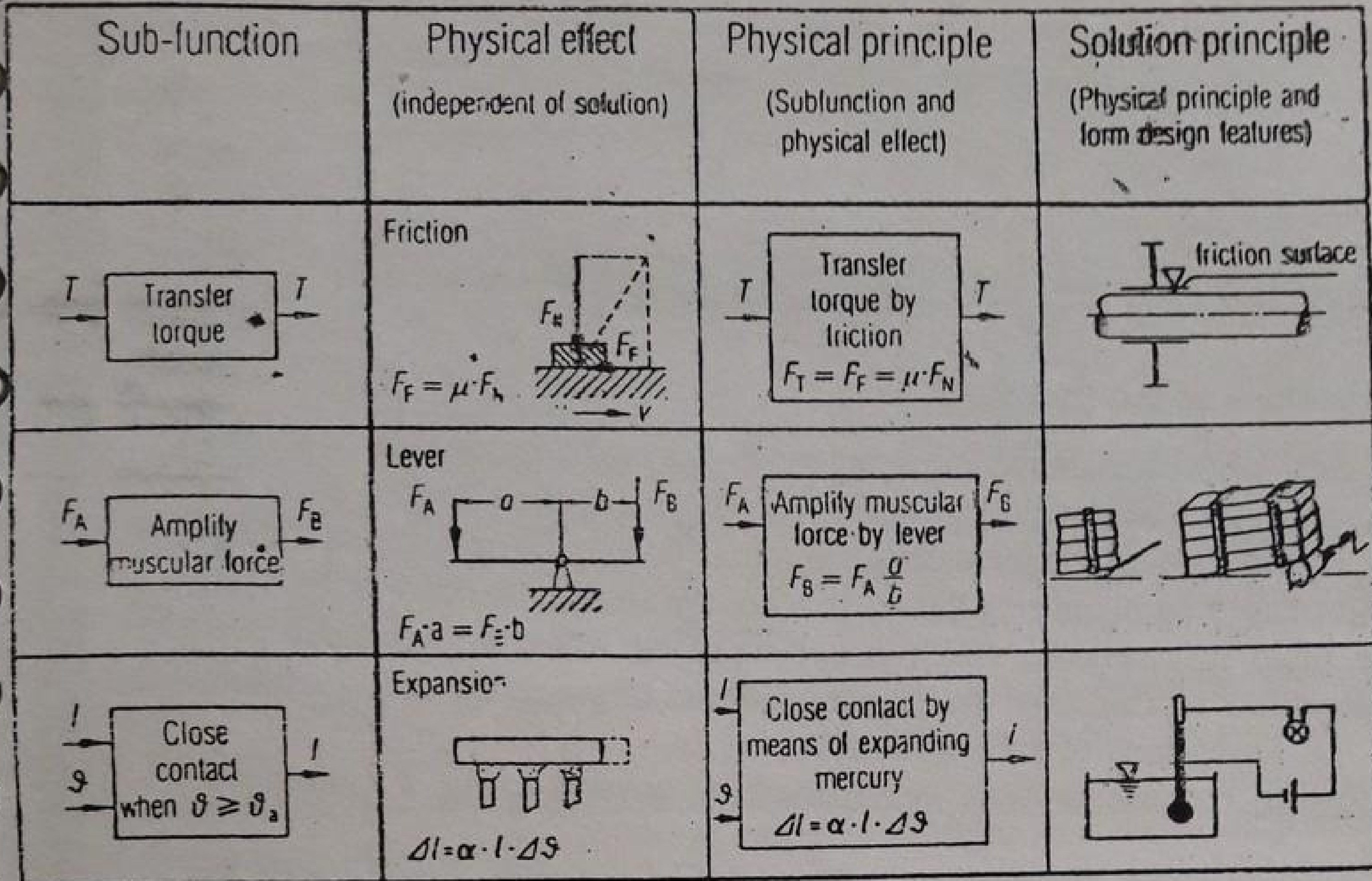


Figure 2.6. Fulfilling sub-functions by solution principles built up of physical principles and form design features

effect, the hydraulic effect etc. The physical principle found to satisfy a particular sub-function must, however, be compatible with the physical principles of other, associated sub-functions. A hydraulic amplifier, for instance, cannot be directly powered by an electric battery. Moreover, a given physical principle will fully satisfy a given sub-function under certain conditions only. Thus a pneumatic control system will be superior to a mechanical or electrical control system only in particular circumstances.

Compatibility and optimum fulfilment cannot generally be assessed except in the context of the overall function, and then only during its concrete embodiment. To that end, the required layout and final forms have to be specified.

2.1.5 The form interrelationship

The function is satisfied by the application of the solution principle, which is realised by the arrangement of *surfaces* (or spaces) and the choice of *motions* [2.23].

The surfaces are varied in respect of, and determined by:

- Type
- Shape
- Position
- Size
- Number [2.24].

Similarly the requisite motions (kinematics) are determined by:

- —Type translation—rotation
- —Nature regular—irregular
- —Direction in x, y, z-directions and/or about x, y, z-axes
- —Magnitude velocity etc
- —Number one, several etc

In addition, we need a general idea of the *type of material* with which the surfaces are to be produced, for example, whether it is solid, liquid or gaseous; rigid or flexible; elastic or plastic; stiff, hard or tough; or corrosion-resistant. A general idea of the final form is often insufficient: the *properties of the materials* must be specified before an adequate formulation of the requisite *form design* can be undertaken.

Only the combination of the physical principle with the main form design features (surfaces, motions and materials) allows the principle of the solution to emerge. This combination is called the *solution principle*, and it is the first concrete step in the implementation of the solution.

In Figure 2.6 the examples discussed in 2.1.4 have been converted into solution principles by the addition of certain form design features.

- —Transferring the torque by friction against a *cylindrical surface* in accordance with Coulomb's law will, depending on the way in which the normal force is applied, lead to the selection of a shrink fit or a clamp connection as the solution principle.
- —Amplifying muscular force with the help of a lever in accordance with the lever law after determining the *pivot and force application points* (working surfaces) and considering the necessary *motions* will lead to a description of the solution principle (lever solution, eccentric solution etc).
- —Making electric contact by bridging a gap using the expansion effect, applied in accordance with the linear expansion law. only leads to an overall solution principle after determination of the size and position of the *surfaces* needed for the *motion* of the expanding medium, a *material* (mercury) expanding by a fixed amount and serving as a switch.

To satisfy the overall function, the solution principles of the various subfunctions have to be combined. There are obviously several ways in which this can be done. Guideline VDI 2222 [2.27] calls each combination a *combination of principles*.

In many cases, a combination of solution principles must be given more concrete expression before it can be evaluated. This involves more definite ideas about the materials to be used, a preliminary dimensioned layout and a technical feasibility study. As a rule it is not until then that one obtains a *solution concept* which can be evaluated in the light of the objectives and the actual constraints (2.1.6). The solution concept is the fundamental proposal of a solution satisfying the overall function and holding out the promise that the task may be realised. Here, too, several concept variants are possible.

2.1.6 General objectives and constraints

The solution of technical tasks is determined by the general objectives and constraints.

The fulfilment of the *technical function*, the attainment of *economic feasibility* and the observance of *safety requirements* may be considered as general objectives. The fulfilment of the technical function alone does not complete the designer's task; it would simply be an end in itself. Economic feasibility is another essential requirement, and concern with human and environmental safety must impose itself for ethical reasons. Every one of these objectives has direct repercussions on the rest.

In addition, the solution of technical problems imposes certain constraints or requirements resulting from ergonomics, production methods, transport facilities, intended operation etc, no matter whether these constraints are the result of the particular task or the general state of technology. In the first case we speak of *task-specific constraints*, in the second of *general constraints* that, though not specified explicitly, must nevertheless be taken into account.

Hubka [2.10] separates the properties affected by the constraints into categories based variously on industrial, ergonomic, aesthetic, distribution, delivery, planning, design, production and economic factors.

Besides satisfying the functional, physical and form interrelationships, a solution must also satisfy certain general or task-specific constraints. These can be classified under the following headings:

— Safety	also in the wider sense of reliability
— Ergonomics	the man-machine context
— Production	type of manufacture and facilities for the production of parts
— Quality control	at any point during the manufacturing process
— Assembly	during and after manufacture
— Transport	inside and outside the factory
— Operation	intended use, handling
— Maintenance	upkeep, inspection and repair
— Expenditure	costs and schedules

The constraints that can be derived from these characteristics affect the function, the working principle and the form design, and also influence one another. Hence they should be treated as checkpoints throughout the design process, and adapted to each level of embodiment.

It is advisable to consider them even during the *conceptual phase*, at least in essence. During the *embodiment phase*, when the layout and form design of the more or less qualitatively elaborated concept is first quantified, both the objectives of the task and also the general and task-specific constraints must be considered in concrete detail. This involves several steps—the collection of further information, layout and form design, and the elimination of weak links, together with a fresh, if limited, search of solutions for a variety of sub-tasks (sub-functions), until, finally, in the *detail phase* the elaboration of detail drawings and production documents brings the design process to a conclusion.

2.2 Fundamentals of the systematic approach

2.2.1 General working method

Before we deal with the specific steps and rules of systematic design, we must first discuss a number of general principles. These come from a host of different disciplines, including non-technical ones, and are usually built on inter-disciplinary fundamentals. Management science, psychology and philosophy have been among the main inspirations, which is not suprising when we consider that methods designed to improve working procedures impinge on the qualities, capacities and limitations of human thought.

The following conditions must be satisfied by anyone using a systematic approach:

— *Ensure the requisite motivation* for the solution of the task, for instance by discussion of the objectives and of the significance of the entire project and by general intellectual stimulation.
— *Clarify the boundary conditions*, that is, define the initial and marginal constraints.
— *Dispel prejudice* to ensure the most wide-ranging possible search for solutions and to avoid logical errors.
— *Look for variants*, that is, find a number of possible solutions from which the best can be selected.
— *Make decisions*. This is facilitated by objective evaluations. Without decisions there can be no progress.

The following procedures are based not only on our own professional experience, but also and above all, on the work of Holliger [2.8, 2.9], Nadler [2.17, 2.18] and Müller [2.16]. When used as intellectual tools in the systematic search for solutions and as stimuli for orderly and effective thought they are also known as heuristic principles. They underly most systematic procedures and are applicable in all fields.

1 Intuitive and discursive thought

Intuitive thought involves sudden ideas (flashes of inspiration) and cannot normally be produced to order. As a rule, intuitive thought processes involve fairly complex associations of ideas, elaborated in the subconscious mind. Though intuition has led to a large number of good and even excellent solutions, a purely intuitive approach has the following disadvantages:

— the right idea rarely comes at the right moment since it cannot be elicited at will;

— the result depends strongly on individual talent and experience; and
— there is a danger that solutions will be circumscribed by one's special training and experience.

It is therefore advisable to use more deliberate procedures that tackle problems step by step, and such procedures are called *discursive*. Here the steps are chosen intentionally; they can be influenced and communicated. It is an important aspect of this procedure that a problem is rarely tackled as a whole, but is first divided into manageable parts and then analysed.

It must, however, be stressed that the intuitive and discursive methods are not opposites. Experience has shown that intuition is stimulated by discursive thought. Thus while complex assignments must always be tackled one step at a time, the subsidiary problems involved may, and often should, be solved in intuitive ways.

In systematic work it is helpful to exploit certain general characteristics of human thought. Holliger [2.9] distinguishes between unconscious, preconscious and conscious thought and prescribes the transformation of aimless and unconscious procedures and of disorderly and fantasy-charged preconscious procedures into a *conscious or deliberate approach*. This can be done with the help of *methodical rules, clear task formulation* and a *structured procedure*. A further aid to conscious thought is the *association of ideas*. One should, however, avoid set complexes of ideas because these may turn out to be too inflexible, and such complexes should be deliberately dissolved. It is obvious that systematic thought is needed more for original design than for routine tasks, which can generally be performed successfully even if the underlying thought processes remain unconscious. Another important property of human thought is the *inevitability of errors*, for which allowances should, if possible, be made from the start. In this connection, Holliger speaks of 'catastrophe analysis'. One should, however, be careful to minimise errors or the weak links resulting from them. This can be done by:

— clearly defining the requirements and constraints of a particular task;
— not forcing intuitive solutions but using a discursive approach;
— avoiding fixed ideas; and
— adapting methods, procedures and technical aids to the task in hand.

2 Analysis

Analysis is the resolution of anything complex into its elements and the study of these elements and of their interrelationships. It calls for identification, definition, structuring and arrangement.

If errors are to be minimised, then problems must be formulated clearly and unambiguously. To that end, they have to be analysed. *Problem analysis* means separating the essential from the inessential and, in the case of complex problems, preparing a discursive solution by resolution into individual, more transparent, subsidiary problems. If the search for the solution proves difficult, a reformulation of the problem may prove helpful. Experience has shown that careful analysis and formulation of problems are among the most important steps of the systematic approach.

The solution of a problem can also be brought nearer by *structure analysis*, that is, the search for hierarchical structures or logical connections. In general, this type of analysis can be said to aim at the demonstration of similarities or repetitive features in different systems (see 5.4).

Another helpful approach is *weak link analysis*. It is based on the fact that every system has weaknesses caused by ignorance, mistaken ideas, external disturbances, physical limitations and manufacturing errors. During the development of a system it is therefore important to analyse the design concept or design embodiment for the express purpose of discovering possible weak links and prescribing the remedies. To that end special evaluation procedures (see 5.8) and weak link identification methods (see 6.6) have been developed. Experience has shown that this type of analysis may not only lead to specific improvements of the chosen solution principle, but also may trigger off new solution principles.

3 Synthesis

Synthesis is the putting together of parts or elements to produce new effects and to demonstrate that these effects create an overall order. It involves search and discovery, and also composition and combination. An essential feature of all design work is the combination of individual findings or sub-solutions into an overall working system—that is, the association of components to form a whole. During the process of synthesis the information discovered by analyses is processed as well. In general, it is advisable to base synthesis on a *global* or *systems approach*; in other words to bear in mind the general task or course of events while working on sub-tasks or individual steps. Unless this is done, there is the grave risk that, despite the optimisation of individual assemblies or steps, no suitable overall solution will be reached. Appreciation of this fact is the basis of the inter-disciplinary development known as *value analysis* which proceeds from the analysis of the problem and function structure to a global approach involving the early collaboration of all departments concerned. A global approach is also needed in large-scale projects, and especially in preparing schedules by such techniques as Critical Path Analysis. The entire systems method is strongly based on the global approach, which is particularly important in the evaluation of solution proposals because the value of a particular solution can only be gauged after overall assessment of all the requirements and constraints (see 5.8).

4 Division of labour and collaboration

An essential finding of management science is that the implementation of large and complex tasks calls for the division of labour, the more so as specialisation increases. This is also demanded by the increasingly tight schedules of modern industry. Now, division of labour implies inter-disciplinary collaboration which, in its turn, involves special organisational and staff arrangements and attitudes, including individual receptiveness to the ideas of others. It must, however, be stressed that inter-disciplinary collaboration and teamwork also demand a rigorous allocation of responsibility. Thus the product manager should be in sole charge of the development of a particular product, regardless of departmental boundaries.

5 Generally applicable methods

The following general methods provide further support for systematic work, and are widely used [2.9].

The method of persistent questions (The 'Why?' technique)

When using systematic procedures it is often a good idea to keep *asking questions* as a stimulus to fresh thought and intuition. A standard list of questions also fosters the discursive method. In short, asking questions is one of the most important methodological tools. This explains why many authors have drawn up special questionnaires (checklists).

The method of negation

The method of *deliberate negation* starts from a known solution, splits it into individual parts or describes it by individual statements, and negates these statements one by one or in groups. This deliberate inversion often creates new solution possibilities. Thus, when considering a 'rotating' machine element one might also examine the 'static' case. Moreover, the mere omission of an element can be tantamount to a negation. This procedure is also known as 'systematic doubting' [2.9].

The method of forward steps

Starting from a *first solution attempt*, one *follows as many paths as possible* yielding further solutions. This method is also called the method of divergent thought. It is not necessarily systematic, but frequently starts with an unsystematic divergence of ideas. The method is illustrated in Figure 2.7.

The method of backward steps

Starting from the *objectives* of the development, one *retraces all the possible paths* that may have led up to it. This method is also called the method of convergent thought, because only such ideas are developed as converge on the ultimate goal.

The method is particularly useful for drawing up production plans and developing systems for the manufacture of designed components.

It is similar to the method of Nadler [2.17], who has proposed the construction of an *ideal system* that will satisfy all demands. This system is not developed in practice but formulated in the mind. It demands optimum conditions such as an ideal environment which causes no external disturbances. Having formulated such a system, there follows a step-by-step investigation of what concessions

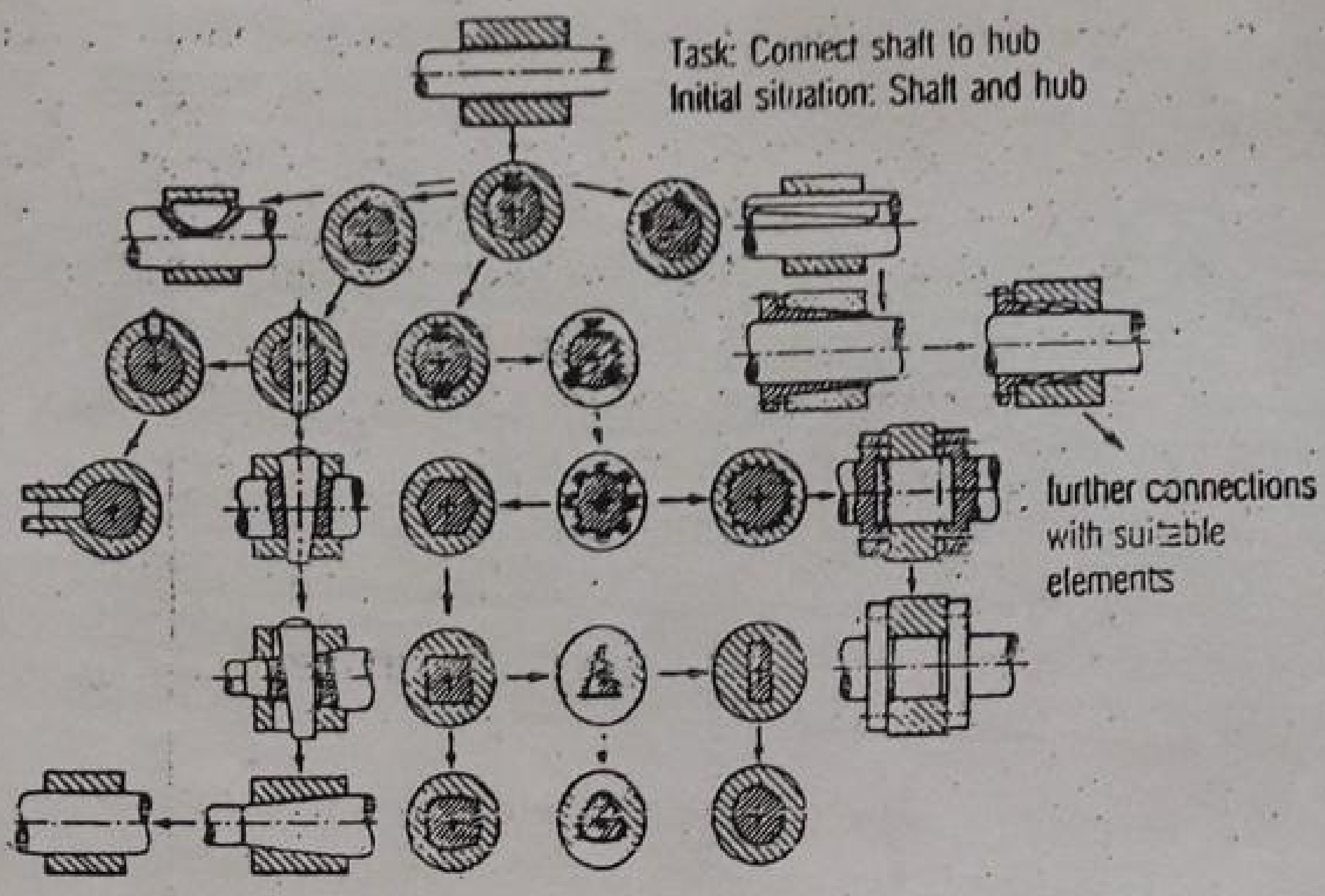


Figure 2.7. Development of shaft-hub connections in accordance with the method of forward steps

must be made to turn this purely theoretical and ideal system into a technologically feasible one, and finally into one that meets all the concrete requirements. Unfortunately, it is rarely possible to specify in advance which particular ideal system will satisfy all functions, especially those linked together in a complex system.

The method of systematic variation

Once the required characteristics of the solution are known, it is possible, by *systematic variation*, to develop a more or less complete solution field. This involves the construction of a generalised classification, that is, a schematic representation of the various characteristics and possible solutions (see 5.4.3). From the viewpoint of management science, too, it is obvious that the discovery of solutions is assisted by the construction and use of classification schemes. Nearly all authors consider systematic variation one of the most important methodical procedures.

2.2.2 Problem solving as information conversion

1 Information conversion

When we discussed the basic ideas of the systems approach (1.2.3) we found that problem solving demands a constant flow of information. Information is *received*, *processed* and *transmitted* (see Figure 2.8).

Information is *received* from market analyses, trend studies, patents, technical

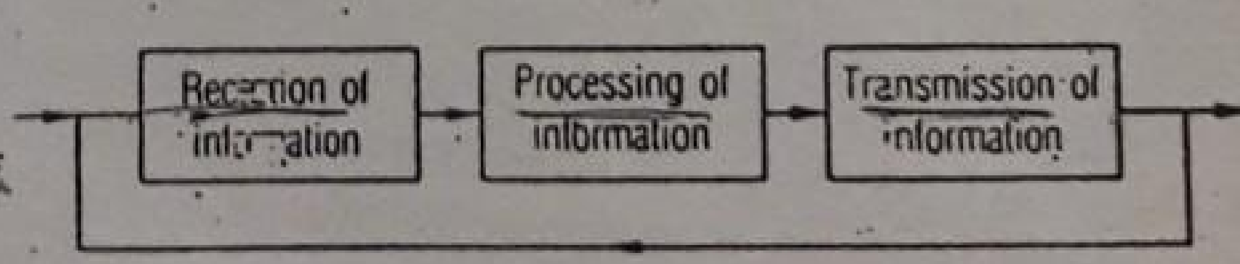


Figure 2.8. The conversion of information

journals, research, licenses, inquiries from customers, concrete assignments, design catalogues, analyses of natural and artificial systems, calculations, experiments, analogies, general and in-house standards and regulations, stock sheets, delivery instructions, computer data, test reports, accident reports, and also through 'asking questions'. Data collection is an essential element of problem solving [2.1].

Information is *processed* by analysis and synthesis, the development of solution concepts, calculation, experiment, the elaboration of layout drawings and also the evaluation of solutions.

Information is *transmitted* by means of drawings, reports, production documents etc. Quite often provision must also be made for the information to be *stored*.

Information conversion is usually a very complicated process. Thus, the solution of various problems requires information of different type, content and range. Beyond that, in order to raise the level of information and improve it, it may be necessary to reiterate certain steps.

To meet the growing demand for an optimal and rational flow of information inside an enterprise, and also about its dealings with the market, several special procedures have been developed in recent years. Zimmermann [2.32] has published a comprehensive analysis of these procedures, based on 74 theses and 206 bibliographical entries. What matters above all is, by organisational measures and the appropriate techniques, to establish a quick and adequate flow of information between the various departments working on a particular task. To that end various models have been developed for processing written or oral information to satisfy a variety of needs [2.22]. It is understandable that the research work should have been done initially for management systems. More recently this type of research has spread to engineering systems [2.15], since it is now recognised that technical developments in a particular industry depend largely on the efficiency and range of its information system.

Useful criteria for evaluating the quality of information will be found in [2.15]. They include:

— Reliability, that is, the probability of the information being trustworthy and correct.
— Sharpness, that is, the precision and clarity of the information content.
— Volume and density, that is, the indication of the number of words and pictures needed for the description of a system or process.
— Value, that is, the importance of the information to the recipient.
— Actuality, that is, an indication of the point in time when the information can be used.
— Form, that is, the distinction between graphic and alpha-numeric data.
— Originality, that is, an indication of whether or not the original character of the information must be preserved.
— Complexity, that is, the structure of, or similarity between, information symbols and information elements, units or complexes.
— Degree of refinement, that is, the quantity of detail in the information.

2 Information systems

To build up an information system, one may have to take into account, apart from the above criteria, the position of the user (for instance section leader, designer, or draughtsman); the design phase (conceptual, embodiment, detail); the type of design (original design, adaptive design, variant design); and the complexity of the system to be developed (for instance plant, machine, assembly, component). The following steps in the construction of an information system can be distinguished:

— determination of the requirements;
— identification of the sources;
— collection;
— classification and processing;
— storage;
— retrieval; and
— computerisation, if necessary.

Several information systems have already proved their practical usefulness. Here we shall merely list a few important bibliographical sources on information classification [2.6, 2.21, 2.34] and on complete data systems [2.5, 2.15, 2.20, 2.31, 2.33]. The most important concepts of information theory are covered in DIN 44 300 and DIN 44 301 [2.2, 2.3].

In conclusion, it must be stressed that the ready availability of a wide range of comprehensive and problem-oriented information is of the utmost importance in the design process [2.26]. The optimum and rational processing of information is greatly facilitated by the systematic approach.