9 Size Ranges and Modular Products

9.1 Size Ranges

Size ranges provide a rationalisation of design and production procedures [9.35].
For the *manufacturer* they have the following *advantages*:

- The design work can be done once and for all and can be used for a host of applications.
- The production of selected sizes can be repeated in batches and hence becomes more cost-effective.
- Higher quality is possible.

This implies the following *advantages* for the *user*:

- competitive and high quality products
- short delivery times
- easy acquisition of replacement parts and fittings.

Disadvantages for both manufacturer and user are:

- limited choice of sizes, not always with optimum operational properties.

By a size range we refer to technical artefacts (machines, assemblies and components) for a wide sphere of applications that:

- fulfil the same function
- are based on the same solution principle
- are made in varying sizes
- involve similar production processes.

If, in addition to the range of sizes, other associated functions have to be implemented, then *modular products* (see Section 9.2) will have to be developed side-by-side with size ranges. The development of size ranges may be original or based on an existing product but must, in either case, be carefully graded. One begins with one initial design, which is referred to as the *basic design*, from which the other sizes in the range are derived. These are referred to as *sequential designs* [9.35]. The basic design is assigned the index 0, the first successive member of the size range (sequential design) the index 1, the k-th member the index k.

In the development of a size range it is essential to make use of similarity laws and helpful to make use of decimal-geometric preferred number series. These generic tools are discussed in the next two sections.

9.1.1 Similarity Laws

Geometric similarity ensures simplicity and clarity of design. Designers know, however, that technical artefacts stepped up in geometric proportions are not satisfactory except in very rare cases. In particular, purely geometrical magnification is only permissible when similarity laws permit, which should always be checked. These laws are used very successfully in model testing [9.12, 9.18, 9.31, 9.34, 9.39, 9.42]. It is obvious to transfer this procedure to the development of size ranges. In general, however, the development of size ranges has a different objective from model technology, namely to achieve:

- the same level of material utilisation
- with similar materials if possible
- with the same technology.

It follows that, if the function is to be fulfilled equally well throughout the range, the relative stresses must remain the same.

We speak of *similarity* if the relationship of at least one physical quantity in the basic and sequential designs is constant. It is possible to define basic similarities with the help of the fundamental quantities length, time, force, quantity of electricity (charge), temperature and luminous intensity (see Table 9.1).[1]

Thus we have *geometric similarity* if the ratio of all the lengths of any sequential design to all the lengths of the basic design is constant. Here, the non-dimensional parameter to be held constant, the step factor, is $\varphi_L = L_1/L_0$ where L_1 is any length of the first member of the size range (sequential design); and L_0 the corresponding length of the basic design. For the k-th sequential design $\varphi_{L_k} = \varphi_L^k$. In the same way,

Table 9.1. Basic similarities

Similarities	Basic quantities	Invariants
Geometric	Length	$\varphi_L = L_1/L_0$
Temporal	Time	$\varphi_t = t_1/t_0$
Force	Force	$\varphi_F = F_1/F_0$
Electrical	Charge	$\varphi_Q = Q_1/Q_0$
Thermal	Temperature	$\varphi_T = \vartheta_1/\vartheta_0$
Photometric	Luminous intensity	$\varphi_J = J_1/J_0$

[1] Fundamental physical quantities are as listed in the German text. The basic physical quantities selected for the SI system differ slightly. These, along with their basic units shown in brackets, are: length (metre); time (second); mass (kilogram); electric current (ampere); thermodynamic temperature (Kelvin); and luminous intensity (candela). The differences do not affect the principles described.

we can describe similarities in time, force, electricity, temperature and luminous intensity.

If two or more of the basic quantities are in constant proportion, then we have special similarities. Model technology has defined dimensionless parameters for important and recurring similarities. Thus, in the case of simultaneous invariance of length and time, we have *kinematic similarity*, and in the case of simultaneous invariance of length and force we speak of *static similarity*.

A very important similarity, namely *dynamic similarity*, appears when a constant force relationship is combined with geometric and temporal similarities. Depending on the forces involved, we arrive at different dimensionless parameters. *Thermal similarity* deserves special mention because, in the case of geometrically similar size ranges and the same utilisation of materials, it is not compatible with dynamic similarity [9.37].

Table 9.2 lists important similarity relationships in the development of size ranges for mechanical systems. They are by no means exhaustive and must be supplemented from case to case, for instance in bearing developments by Sommerfeld's number and in hydraulic machines by the cavitation number and pressure index.

Table 9.2. Special similarity relationships

Similarities	Invariants	Group names	Definitions	Descriptions
Kinematic	φ_L, φ_t			
Static	φ_L, φ_F	Hooke	$Ho = \frac{F}{E \cdot L^2}$	Relative elastic force
Dynamic	$\varphi_L, \varphi_t, \varphi_F$	Newton	$Ne = \frac{F}{\rho \cdot v^2 \cdot L^2}$	Relative inertia
		Cauchy *	$Ca = \frac{Ho}{Ne} = \frac{\rho \cdot v^2}{E}$	Inertia force/elastic force
		Froude	$Fr = \frac{v^2}{g \cdot L}$	Inertia force/gravitational force
		NN **	$\frac{E}{\rho \cdot g \cdot L}$	Elastic force/gravitational force
		Reynolds	$Re = \frac{L \cdot v \cdot \rho}{\eta}$	Inertia force/frictional force in liquids and gases
Thermal	$\varphi_L, \varphi_\vartheta$	Biot	$Bi = \frac{h \cdot L}{\lambda}$	Supplied or removed/conducted quantity of heat
	$\varphi_L, \varphi_t, \varphi_\vartheta$	Fourier	$Fo = \frac{\lambda \cdot t}{c \cdot \rho \cdot L^2}$	Conducted/stored quantity of heat

* In some texts, we find $Ca = \sqrt{\rho/E}$. This is appropriate if Ca is intended as a velocity ratio relationship

** Not named

Example – Similarity at Constant Stress

In heavy engineering systems, inertia forces (forces due to mass, acceleration, etc.) and elastic forces resulting from the stress-strain relationship play a predominant role.

If the stresses are to remain constant throughout a size range, then $\sigma = \varepsilon \cdot E =$ constant. In that case the stress step factor becomes:

$$\varphi_\sigma = \frac{\sigma_1}{\sigma_0} = \frac{\varepsilon_1}{\varepsilon_0}\frac{E_1}{E_0} = 1$$

With the same material, that is $\varphi_E = E_1/E_0 = 1$, we need:

$$\varphi_\varepsilon = \varepsilon_1/\varepsilon_0 = 1\,, \quad \text{or} \quad \varphi_\varepsilon = \frac{\Delta L_1}{\Delta L_0}\frac{L_0}{L_1} = 1\,, \quad \text{or} \quad \varphi_{\Delta L} = \varphi_L$$

With this so-called Cauchy condition, all changes in length must increase with the same step factor as the appropriate lengths (geometric similarity). The elastic force step factor then becomes:

$$\varphi_{FE} = \frac{\sigma_1 A_1}{\sigma_0 A_0} = \varphi_L^2\,, \quad \text{with} \quad \varphi_0 = \varphi_\varepsilon \cdot \varphi_E = 1 \quad \text{and} \quad \varphi_A = \varphi_L^2$$

The inertia force step factor is:

$$\varphi_{FI} = \frac{m_1 a_1}{m_0 a_0} = \frac{\rho_1 V_1 a_1}{\rho_0 V_0 a_0}$$

With

$$\varphi_\rho = \rho_1/\rho_0 = 1\,, \quad \varphi_V = V_1/V_0 = L_1^3/L_0^3 = \varphi_L^3$$

and the acceleration step factor

$$\varphi_a = \frac{L_1 t_0^2}{t_1^2 L_0} = \frac{\varphi_L}{\varphi_t^2}$$

we have

$$\varphi_{FI} = \varphi_L^4/\varphi_t^2$$

A dynamic similarity, that is a constant ratio between inertia and elastic forces with geometric similarity, can only be attained if $\varphi_t = \varphi_L$:

$$\varphi_{FE} = \varphi_L^2 = \varphi_{FI} = \varphi_L^4/\varphi_L^2 = \varphi_L^2$$

Hence the velocity step factor becomes:

$$\varphi_v = \varphi_L/\varphi_t = \varphi_L/\varphi_L = 1$$

With the same material, the same result can also be derived from the Cauchy number (see Table 9.2), for when ρ and E remain constant then the dynamic similarity will only remain constant if the velocity v also remains constant.

For all important quantities such as power, torque etc., and with $\varphi_L = \varphi_t =$ constant and $\varphi_\rho = \varphi_E = \varphi_\sigma = \varphi_v = 1$, it is now possible to establish the similarity relationships shown in Table 9.3.

Table 9.3. Similarity relationships for geometrical similarity and equal stresses: dependence of important quantities on length

With $Ca = \rho v^2/E$ = constant and the same material, that is ρ and E = const., v = const. In the case of geometrical similarity the following relationships occur	
Speeds, n, ω Bending and torsional critical speeds n_{cr}, ω_{cr}	φ_L^{-1}
Strains ε, stresses σ, surface pressures p due to inertia and elastic forces, speeds v	φ_L^0
Spring stiffnesses s, elastic deformations ΔL Strains ε, stresses σ, surface pressures p due to gravity	φ_L^1
Forces F Powers P	φ_L^2
Masses M, torques T, torsion stiffnesses s_t Section moduli W, W_t	φ_L^3
Second moments of area I, J	φ_L^4
Mass moments of inertia I', J'	φ_L^5

Note: The utilisation of the materials and safety levels are only constant if the influence of the dimensions on the material properties can be ignored

It should be remembered that the utilisation of the materials and the safety levels only remain constant if the influence of the dimensions on the material properties can be ignored throughout the size range.

Size ranges developed in accordance with these laws are geometrically similar and provide for the identical utilisation of the materials. Such developments are possible whenever gravity and temperature have no decisive influence on the design. If they have, the use of semi-similar series is advisable (see Section 9.1.5).

9.1.2 Decimal-Geometric Preferred Number Series

Once we are familiar with the most important similarity relationships, we still have to determine the best method of choosing the step factor of a size range. Kienzle [9.24, 9.25] and Berg [9.5–9.9] have argued that a decimal-geometric series is the most useful.

A *decimal-geometric series* is based on multiplication by a constant factor φ and is developed within one decade. The constant factor φ is the step factor that determines the step sizes of the series and can be expressed as:

$$\varphi = \sqrt[n]{a_n/a_0} = \sqrt[n]{10}$$

where n is the number of steps within a decade. For 10 steps, the series would then have a step factor:

$$\varphi = \sqrt[10]{10} = 1.25$$

and is called R 10. The number of terms in the series is $z = n + 1$.

Table 9.4 sets out the main values of four preferred number series as defined by DIN 323 [9.13, 9.16].

The need for geometric scaling is often found in daily life and in technical practice. The resulting series conform with the Weber–Fechner law which states that the physiological sensation produced by a stimulus is proportional to the logarithm of the stimulus, e.g. sound and illumination.

Reuthe [9.40] has shown how, in the development of friction drives, designers instinctively choose the main dimensions by means of geometrical scaling. Our own work on turbine shaft oil scraper rings has confirmed these findings. In Figure 9.1, shaft diameters are plotted using a logarithmic scale against the number of oil scraper rings designed over a period of 10 years. The results show that there were 47 diameters with peaks at more or less regular intervals, which clearly demonstrates a geometrical scaling. However, the number of nominal sizes was disturbingly large—some differed by only a few millimetres and gave rise to very small production batches. Luckily, as Figure 9.1 also shows, if preferred sizes are selected with the help of the R 20 series, the number of variants can be reduced to less than half, giving a considerably more balanced and higher requirement per nominal size. Had the designers chosen such preferred numbers deliberately, a much more suitable size range would have emerged by itself.

The use of preferred number series thus provides the following *advantages* [9.13]:

- Appropriate scaling leads to the selection of nominal sizes in accordance with demand. The finer series have common numerical values with the coarser.

Table 9.4. Main values of preferred numbers

Basic series				Basic series			
R 5	R 10	R 20	R 40	R 5	R 10	R 20	R 40
1.00	1.00	1.00	1.00		3.15	3.15	3.15
			1.06				3.35
		1.12	1.12			3.55	3.55
			1.18				3.75
	1.25	1.25	1.25	4.00	4.00	4.00	4.00
			1.32				4.25
		1.40	1.40			4.50	4.50
			1.50				4.75
1.60	1.60	1.60	1.60		5.00	5.00	5.00
			1.70				5.30
		1.80	1.80			5.60	5.60
			1.90				6.00
	2.00	2.00	2.00	6.30	6.30	6.30	6.30
			2.12				6.70
		2.24	2.24			7.10	7.10
			2.36				7.50
2.50	2.50	2.50	2.50		8.00	8.00	8.00
			2.65				8.50
		2.80	2.80			9.00	9.00
			3.00				9.50

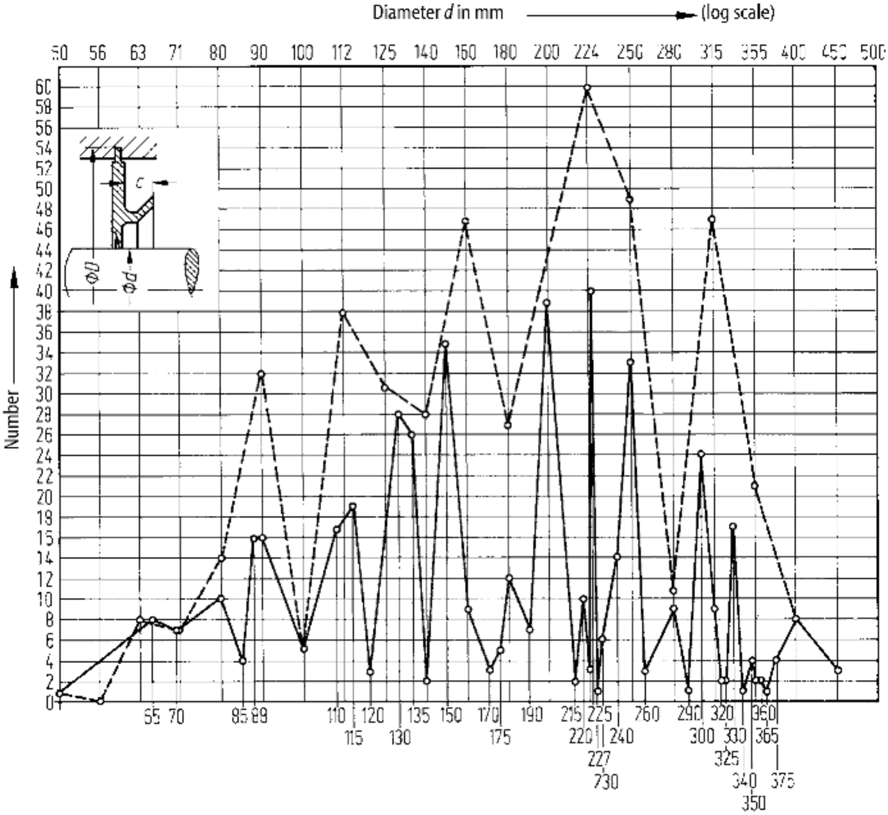

Figure 9.1. Frequency of seal diameters d of scraper rings for turbine shafts; *continuous line*: actual situation; *broken line*: suggested size range

With proper gradation it is possible to approximate an arithmetical series. This facilitates jumping from row to row and hence provides the different steps needed for matching the distribution of the market requirement. The preferred number series contain both decimal powers and also doubles and halves (see Section 9.1.3).

- There is a reduction of the dimensional variants by the choice of dimensions based on preferred numbers with a consequent saving in production documents, equipment and measuring tools.
- Since the products and quotients of terms of the series are in turn terms of a geometrical series, analyses and calculations reduce mainly to multiplication and division. As π is contained in the preferred number series with a good approximation, geometric gradation of component diameters will generate circumferences, circular areas, cylinder contents and spherical surfaces that are, in their turn, terms of the preferred number series.
- If the dimensions of a component or of a machine are terms of a geometrical series, then linear magnifications or diminutions will give rise to preferred num-

bers in the same series provided, of course, that the magnification or diminution factor is also selected from the series.

- Automatic growth of the size range will be compatible with existing or future ranges.

9.1.3 Representation and Selection of Step Sizes

1. Preferred Number Diagram

For the following discussion *preferred number diagrams* are useful. Preferred numbers in a size range can be represented as logarithms to the base 10 by means of their powers (see the derivation in Section 9.1.2). That is, every preferred number PN can be expressed by $PN = 10^{m/n}$ or:

$$\log(PN) = m/n$$

where m is the step number in the PN range and n the number of steps within one decade.

On the other hand, nearly all technical relationships can be expressed in the general form:

$$y = cx^p$$

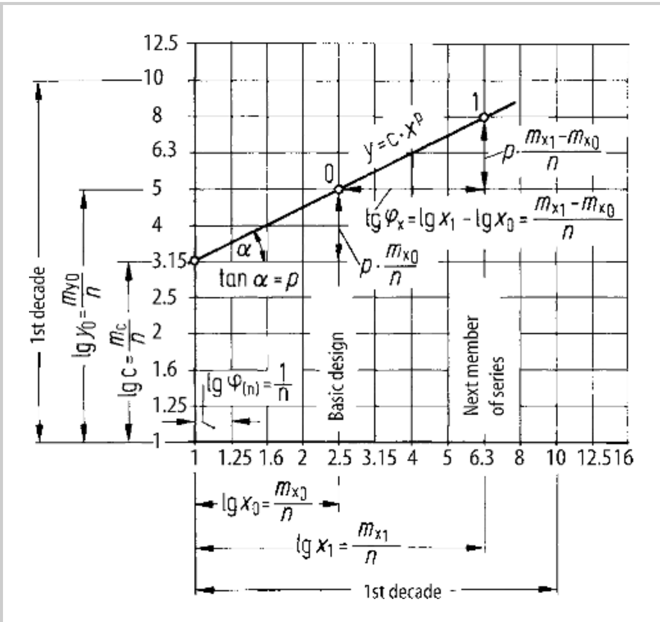

Figure 9.2. Technical relationships in the PN diagram; n step number in the finest underlying PN series; every intersection is a preferred number of this series; every integral exponent leads back to another preferred number

or in its logarithmic form as

$$\log y = \log c + p \log x$$

Hence the technical relationship can also be expressed by:

$$\frac{m_y}{n} = \frac{m_c}{n} + p\frac{m_x}{n}$$

Entering this into a coordinate graph and labelling the axes directly with natural numbers rather than logarithms, one obtains a preferred number diagram as shown in Figure 9.2. Every preferred number of a certain range (in this case R 10) is then located along each axis at equal spacings, each space representing the step factor (in this case 1.25).

If the dependent and independent quantities are associated by a power law $y = cx^p$ (see Figure 9.2) then both preferred numbers can be graded by a preferred number series, either with exponent $p = 1$ (linear growth, 45° line) or with $p \neq 1$ (non-linear growth, slope $p = 0.5, 2, 3 : 1$ or similar).

This type of representation of preferred numbers and number series is very useful, as we will show in the examples in Sections 9.1.4 and 9.1.5.

2. Selection of Step Sizes

In general, when trying to rationalise a product size range, designers will select their increments once and for all. To that end they make an *appropriate selection of step sizes*, for instance in respect of power and torque. That selection can be based on several considerations. First of these is the market situation, which as a rule requires small increments so that the varied demands of customers can be met most effectively. The second consideration is efficient design and production. For technical and economic reasons, the selected step sizes must be fine enough to meet the technical demands (for instance, power), and yet coarse enough to allow large-batch production based on a simplified range.

The selection of optimum step sizes thus involves an integrated approach to the "market – design – production – sales" system, and requires information about:

- market expectations (sales) in respect of individual sizes
- market behaviour in respect of simplified ranges and the resulting gaps
- production costs and times of the various step sizes (see Section 11.3.4) and the effect on the overall production costs [9.36]
- constant properties of each product in the size range.

Since the optimum selection of step sizes must be based on all the factors we have mentioned, it is not always possible to opt for a constant step factor; more often technical and economic considerations will demand the break up of a particular range of sizes into several sets.

If we define a *characteristic number N* of a range such that:

$$N = \frac{\text{Greatest term of the range}}{\text{Smallest term of the range}} = \varphi^n$$

where n is the number of the steps in any particular range and $z = n + 1$ is the number of terms, then the step factor:

$$\varphi = \sqrt[n]{N}$$

The range can be split up by means of a *constant* or a *variable step factor*, that is, by jumps within and between preferred number series (R 5–R 40). The resulting step characteristics are shown in Figure 9.3.

Type A has a constant step factor (for instance $\varphi = 1.25$ corresponding to R 10) over the entire range.

In Type B, the lower part of the range is divided up coarsely (for instance $\varphi = 1.6$ corresponding to R 5) and the upper part more finely (for instance $\varphi = 1.25$ corresponding to R 10). Such degressive geometrical product ranges should be used whenever a coarser grading for the smaller product sizes is economically justifiable, e.g. because of smaller batch sizes.

Type C has a greater increment in the upper range and is used if demand is concentrated on smaller sizes. It is also known as a progressive geometrical range.

Type D has a smaller step factor in the middle part of the range, which is characteristic of situations where demand is concentrated there.

Type E a larger step factor in the middle part of the range, however this is hardly ever required.

We can generally take it that the size gradation must be finer the greater the demand and the more precisely certain technical stipulations have to be met. A different gradation can be chosen easily whenever the market demands and without great design effort if a decimal-geometric preferred number series is used. Needless to say, the effects on production must be taken into account as well.

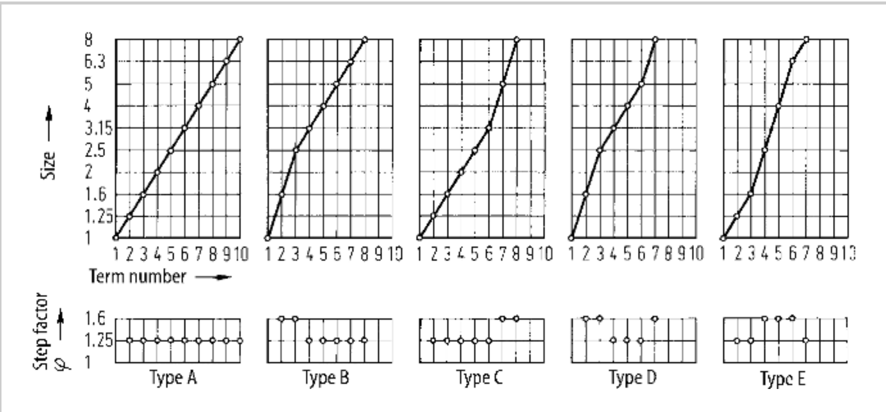

Figure 9.3. Step characteristics of size ranges. Factors assigned to each step

For economic reasons, it is often advisable to split the range into parts and to replace several sizes with just one for each part (semi-similar size range). Such a gradation leads to a stepped line.

In grading, a distinction must be made between *independent* and *dependent quantities*. As a rule, the task itself determines which sizes must be treated as dependent and which as independent. For example, geometric grading of the power output may be advantageous for market reasons and grading of sizes by preferred number series for production reasons.

In Figure 9.4, the dependent and independent quantities have been plotted logarithmically. If the preferred numbers have the same factor, then the spacing is constant (see Figure 9.2).

However, technical systems may not involve power relationships between dependent and independent quantities. In that case, not all the sizes can be geometrically graded. Here designers must decide, depending on the task, whether they grade the independent or the dependent quantities in accordance with a preferred number series.

The following example illustrates this situation. Independent sizes I_{12}, I_{23} etc. have been assigned to the geometrically graded parts of the range D_1D_2, D_2D_3 etc. (see Figure 9.4). This correlation is obtained by replacing the D_1D_2, D_2D_3, etc. with their geometric mean values $D_{12} = \sqrt{D_1 \cdot D_2}$ and then drawing the stepped line accordingly. This is preferable to fixing the line intuitively. It can be seen that the dependent relationships based on curve *a* once again result in a geometric grading of the steps, while the non-linear relationships based on curve *b* do not (in other words, the I'-values are not geometrically graded). Here designers must again decide for what sizes a gradation based on preferred numbers is still appropriate.

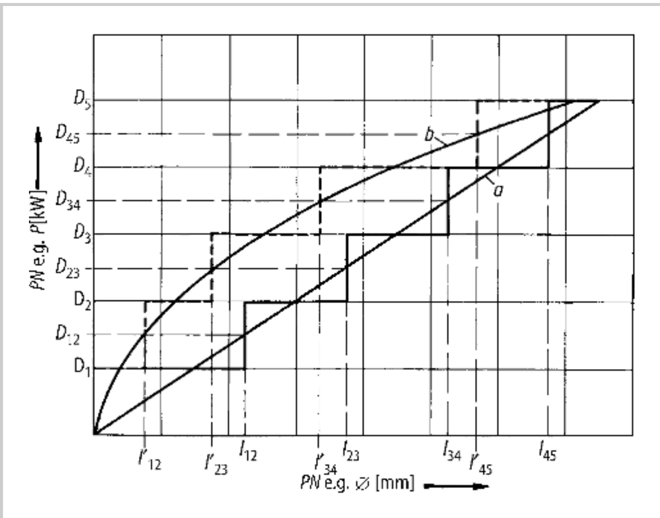

Figure 9.4. Grading of independent (I) and dependent (D) quantities. For a power function there is a linear relationship on the PN (preferred number) diagram (*curve a*); for others there is a non-linear relationship (*curve b*)

Deviations from strictly geometric gradings may, as we have already said, be imposed by production considerations. Practice has shown that it may be more economical to provide arithmetic or even irregular increments for some component dimensions, so that, in a product size range, semi-finished materials, which are not usually geometrically graded, can be exploited more fully, or the production process can be simplified. This leads to semi-similar size ranges (see Section 9.1.5). Even though grading based on preferred number series is generally advisable, designers should not use it rigidly, but decide each case individually after cost analysis (see Section 11.3.4).

9.1.4 Geometrically Similar Size Ranges

If the basic design, the choice of materials and the necessary calculations are to hand, and if the nominal dimensions lie roughly in the middle of the intended size range, then, as already discussed (see Section 9.1.3), nearly all technical relationships can be expressed in the general form:

$$y = cx^p$$

or in its logarithmic form as

$$\log y = \log c + p \log x$$

All dependencies can be represented on a *preferred number diagram* (double logarithmic graph) as straight lines. The slope of each line corresponds to the exponent p of the technical relationship (dependence) (see Figure 9.2). For simplicity, we enter the preferred numbers instead of the logarithms and so obtain a very practicable visual tool for the development of size ranges, as Berg [9.7, 9.9] has pointed out. Every intersection represents a preferred number, and is always produced by lines with integral exponents. If the abscissa gives the nominal size x, then the step factor $\varphi_x = x_1/x_0$. In geometrically similar size ranges it is equal to the length factor φ_L. Once the basic design has been fixed, all other magnitudes—dimensions, torques, power, speeds, etc.—can be derived from the known exponents of their physical or technical relationships (see Table 9.3) and can be drawn as straight lines with the appropriate slope (thus weight, $\varphi_W = \varphi_L^3$, will have a slope of 3:1).

As a result, the main dimensions of the product can be expressed in diagram form without the need for further drawings. Figures 9.5 and 9.6 provide an example for a gear coupling.

Such data sheets (preferred number diagrams) enable designers, starting from the basic design, to provide the sales department, the purchasing department, the planning department and the production department with crucial information on every size in the range.

It should, however, be remembered that the measurements cannot be transferred directly from the data sheets to the drawings and other production documents, which need only be made once an order has been received, unless the following factors have also been taken into consideration:

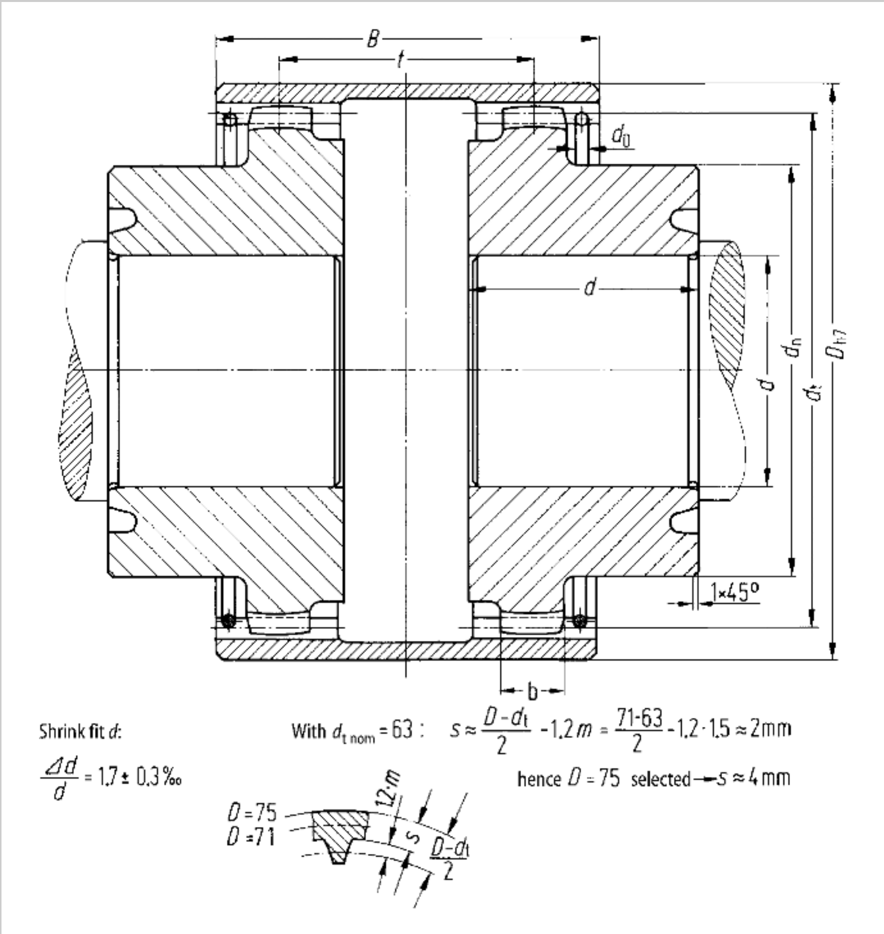

Figure 9.5. Basic design ($d_t = 200$ mm) for gear coupling size range

1. *Fits and tolerances* are not in geometric step with the nominal sizes, the size of a tolerance unit *i* for a dimension *D* being given by $i = 0.45 \times \sqrt[3]{D} + 0.001\,D$, that is, the factor for the tolerance unit being determined by the relationship $\varphi_i = \varphi_L^{1/3}$. Particularly in the case of shrink and interference fits, but also of function-determined bearing clearances etc., the tolerances must, because the elastic deformations tend towards φ_L, be adapted accordingly. In other words, smaller dimensions make more, and larger dimensions less, severe demands (see Figure 9.6).
2. *Technological limitations* often demand deviations. Thus a cast wall cannot be reduced below a minimum thickness, and certain thicknesses cannot be completely hardened by quenching. In all such cases, the limiting dimensions must be ascertained, as was done, for instance, with the smallest sleeve for the gear coupling shown in Figure 9.6, which had to be strengthened by an

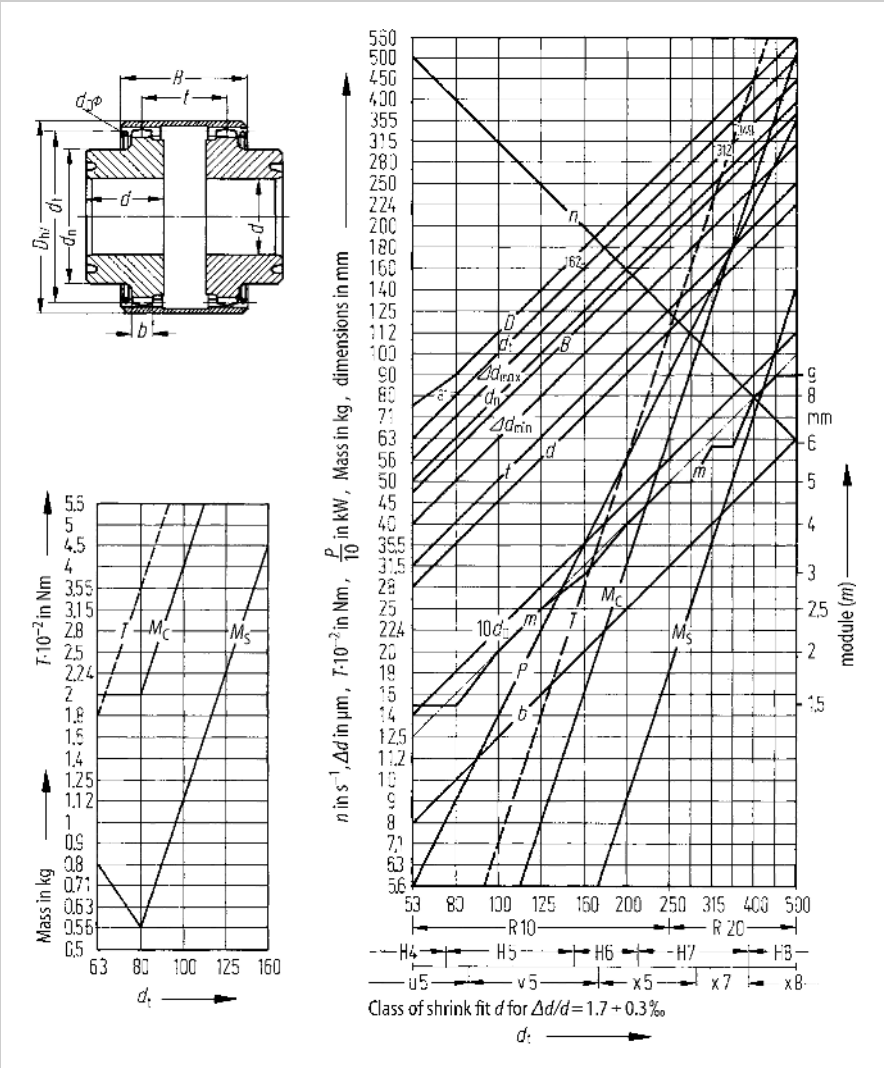

Figure 9.6. Data sheets for the gear coupling size range plotted for the range of nominal diameters d_t corresponding to the basic design shown in Figure 9.5. Dimensions geometrically similar. Exceptions: outer sleeve diameter D of the smallest member for reasons of stiffness; the standardised gear moduli m cannot be stepped in accordance with preferred numbers; and these moduli in combination with the need for an integral, even number of teeth require a slight adaptation of the pitch circle diameters of some steps

increase in the wall thickness (D = 71 mm to D = 75 mm). The same principle applies to measurement and machining provisions (see Figure 9.5).

3. *Overriding standards* are not always based on preferred numbers, so the relevant components must be adapted accordingly (see Figure 9.6 fixing the module).

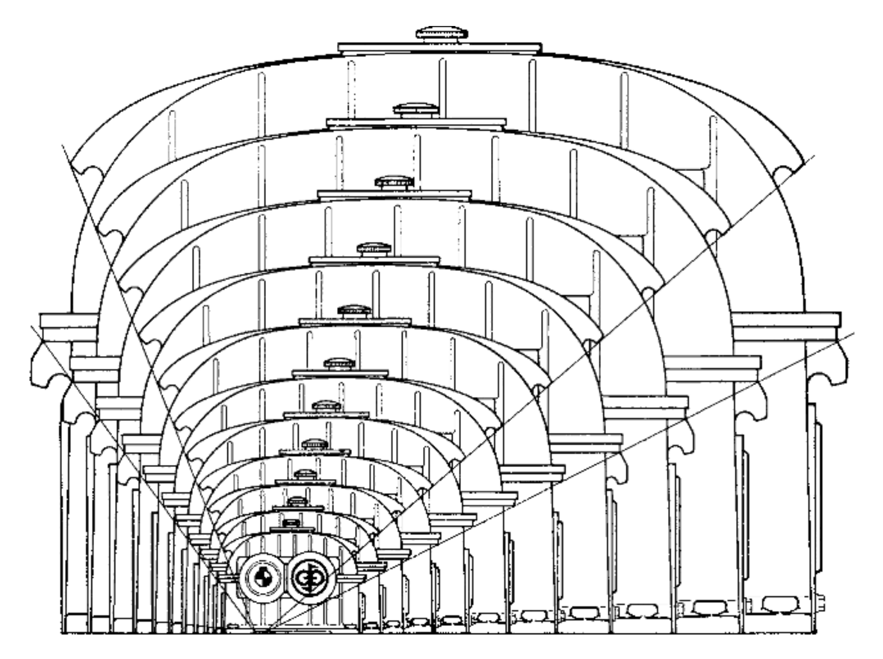

Figure 9.7. Display of a gearbox size range [9.15] (Flender)

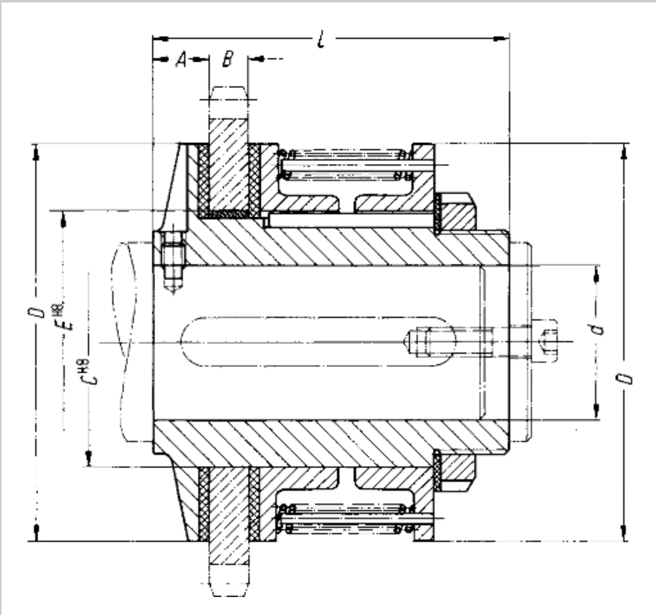

Figure 9.8. Basic design of a torque-limiter (Ringspann KG)

4. *Overriding similarity laws* or *other requirements* may impose a more pronounced deviation from geometric similarity, in which case semi-similar series should be used (see Section 9.1.5).

Once the necessary deviations from geometric similarity have been determined, if necessary by checking drawings of the critical areas, they are entered in the data sheet. Production documents need not be prepared until actually required. To illustrate the size range, say in catalogues or advertisements, displays of the type previously reserved for technical drawings are being increasingly used [9.7, 9.25]. Figure 9.7 shows an example based on a gearbox size range.

Figure 9.8 shows the basic design of a geometrical range of torque-limiters, providing for equal utilisation of materials, paying due heed to overriding standards. If the lining wears, the drop in torque must be kept as small as possible. This is done by means of a large number of peripheral coil springs with relatively flat characteristic curves. All sizes of the torque-limiter fulfil the similarity conditions mentioned in Table 9.3: relationships between forces are kept constant over the

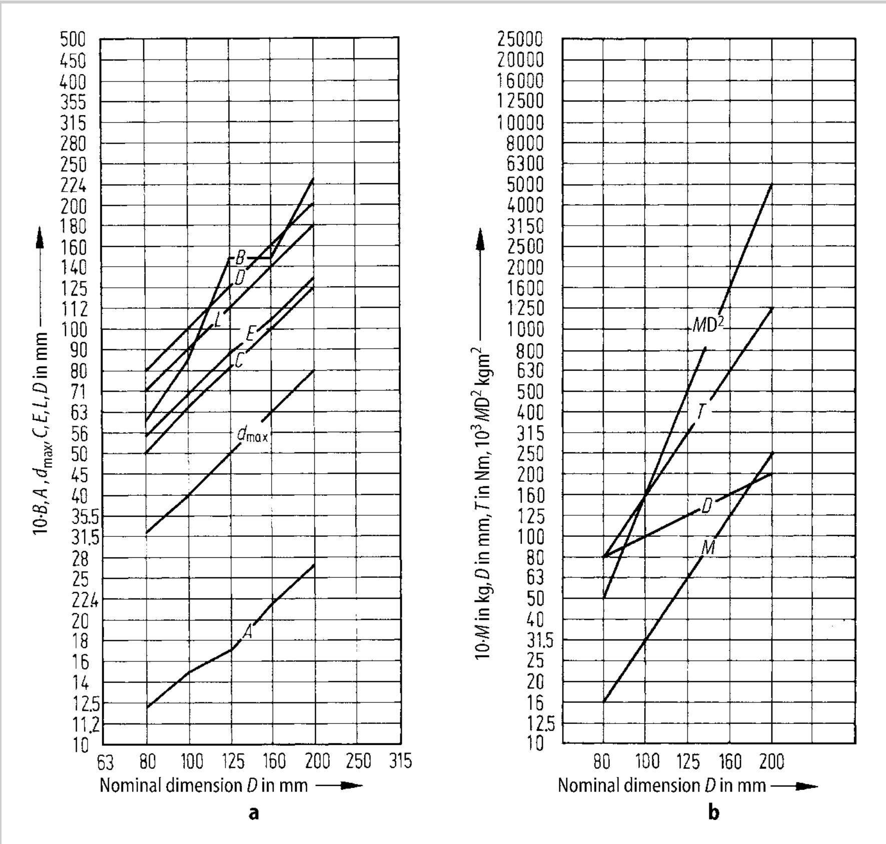

Figure 9.9. Data sheets for torque-limiter shown in Figure 9.8: **a** Dimensions adapted to overriding standards and the sizes of bought-out parts; **b** Main parameters: torque T, mass M and moment of inertia MD^2

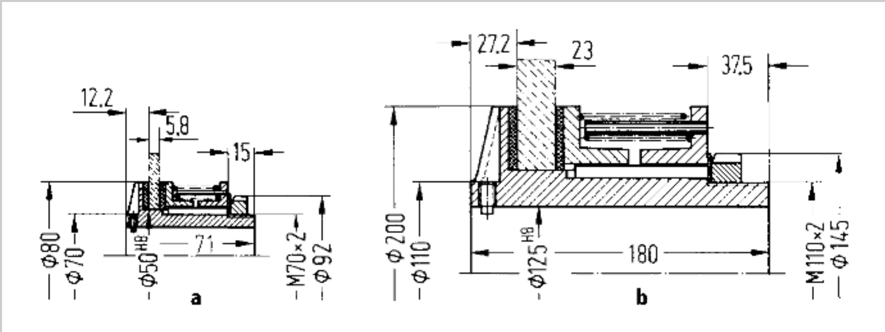

Figure 9.10. Layouts from the size range shown in Figure 9.9 (Ringspann KG): **a** smallest; **b** largest

entire range and the utilisation of the materials is constant. Figures 9.9a and 9.9b show the relevant data sheets. The identifiable deviation of dimension *B* is determined by the overriding standard width of the chain wheels (bought-out parts); the deviation of *A* by the use of standard screws and taps and also by technological factors (wall thickness). Figures 9.10a and 9.10b show the smallest and largest members of the size range respectively.

9.1.5 Semi-Similar Size Ranges

Geometrically similar size ranges based on a decimal-geometric series cannot always be realised. Significant deviations from geometrical similarity may be imposed by the following factors:

- overriding similarity laws
- overriding task requirements
- overriding production requirements.

In all such cases, *semi-similar* size ranges must be developed.

1. Overriding Similarity Laws

Influence of Gravity

If inertia forces, elastic forces and weight act together, and if the latter cannot be neglected, then the relationships derived from the Cauchy condition no longer apply. This, as we have explained, is because, while the inertia and elastic forces at constant speed depend on the length factor ($\varphi_{\mathrm{FI}} = \varphi_{\mathrm{FE}} = \varphi_{\mathrm{L}}^2$), the weight increases as

$$\varphi_{\mathrm{F_w}} = \rho_1 \cdot g \cdot V_1/(\rho_0 \cdot g \cdot V_0) = \varphi_\rho \varphi_{\mathrm{L}}^3 \quad \text{and for} \quad \varphi_\rho = 1 \quad \text{as} \quad \varphi_{\mathrm{F_w}} = \varphi_{\mathrm{L}}^3$$

Table 9.2 shows that, if all other material properties and the speed remain constant, length is the only variable dimension. If it does vary, the relevant dimensionless parameter cannot remain constant—that is, the relationship of the forces must change. Hence with similar cross-sections the stresses change as well and geometric similarity cannot be maintained. This is the case, for instance, with the construction of electrical machines and conveyor systems.

Influence of Thermal Processes

A similar series of problems arises with thermal processes. Constant temperature relationships φ_ϑ only apply when there is thermal similarity, regardless of whether the heat-flow is steady or fluctuating. The first case is represented by the so-called Biot number, $Bi = hL/\lambda$ [9.20], where h is the heat transfer coefficient and λ the coefficient of thermal conductivity of the heated wall. Here too it is obvious that, with approximately equal heat transfer coefficients (the velocity remaining the same) and with the same materials, only the length can vary, and indeed must vary in a size range. As a result the dimensionless parameter governing thermal similarity cannot itself remain unchanged [9.37]. The same is true of fluctuating heating and cooling processes represented by the Fourier number, $Fo = \lambda t/(c\rho L^2)$, where λ is the coefficient of thermal conductivity, c the specific heat and ρ the density of the material. If the material remains the same, the time t and the length L are variable. For the Cauchy number to remain constant, the time must vary as a function of the length. Once again we are left only with the length, which must be variable in a size range. Hence the Fourier number can only remain constant if the time step factor $\varphi_t = \varphi_L^2$, that is, if the time varies as the square of the length.

All other things being equal, therefore, thermal stresses due to temperature variations increase as the square of the wall thickness.

Other Similarity Relationships

If the function of a device is determined by physical processes that do not involve inertia or elastic forces, then the physical relationships must be taken into consideration in all designs based on similarity laws [9.18, 9.34, 9.39, 9.42].

In a plain bearing, for instance, the operating conditions are set by the Sommerfeld number:

$$So = \bar{p}\psi^2/(\eta\omega)$$

where $\bar{p}$ is the mean pressure, ψ the non-dimensional clearance, η the dynamic viscosity and ω the rotational speed.

In a machine that otherwise obeys the Cauchy number, we have

$$\varphi_{So} = \frac{\bar{p}_1\psi_1^2\eta_0\omega_0}{\bar{p}_0\psi_0^2\eta_1\omega_1} = \varphi_{\bar{p}}\varphi_\psi^2\frac{1}{\varphi_\eta}\frac{1}{\varphi_\omega}$$

With elastic forces we have $\varphi_{\bar{p}} = 1$, with weight we have $\varphi_{\bar{p}} = \varphi_L$; for the rest, we have:

$$\varphi_\psi = 1\,, \quad \varphi_\omega = 1/\varphi_L\,, \quad \varphi_\eta = 1 \quad \text{at} \quad \vartheta = \text{constant}\,.$$

With elastic forces, therefore, we have $\varphi_{So} = \phi_L$ with weight $\varphi_{So} = \varphi_L^2$. As the Sommerfeld number increases with the overall size, the bearing becomes increasingly eccentric and, at a given size, may take up the clearance necessary for lubrication.

In a pipe with laminar flow, the loss of pressure is expressed by:

$$\Delta p = f \frac{l}{d} \frac{\rho}{2} v^2 = 32\eta \frac{l}{d^2} v$$

where $f = 64/Re$ in the laminar region, $Re = dv\rho/\eta$, l = length of pipe, d = diameter of pipe, v = velocity in the pipe, ρ = density of the fluid, and η = dynamic viscosity of the fluid.

With η = constant, the pressure loss function becomes:

$$\varphi_{\Delta p} = \varphi_v/\varphi_L$$

Thus, if the pressure loss is to remain constant, the velocity in the pipe must increase in proportion to the size. As a result, the Reynolds number may increase to such an extent that the transition region for turbulent flow is reached, in which case the above equations no longer hold.

Electric AC motors that have a discrete speed depending on the pole number cannot be used to adjust the speed of a finely stepped range of machines (for instance pumps) to maintain a constant Cauchy number. The consequences would be varying stresses and different outputs and the remedy is a suitably adapted semi-similar series.

2. Overriding Task Requirements

The choice of a semi-similar size range may be imposed, not only by similarity laws but also by overriding task requirements. This situation often arises in an ergonomic context. All components with which human beings come into contact in the course of their work—especially the controls, handles, standing and sitting places, and safety features—must fit physiological needs and physical dimensions. In general, none of these components can be changed with the nominal size of the range.

An overriding requirement may also appear for purely technical reasons, inasmuch as inputs and outputs may vary widely in size, as happens with paper and print products.

Figure 9.11 is a schematic representation of a lathe. Here, the size of the human-operated controls cannot be increased with the size of the range; indeed some cannot be altered at all. Thus the operating height must always be adapted to human dimensions, and there are some operations that require an exceptionally long turning length or an exceptionally large turning diameter. In all such cases the machine as a whole must be designed on semi-similar principles, while individual assemblies such as spindle drives, tail-stocks, etc. can be developed as geometrically similar series.

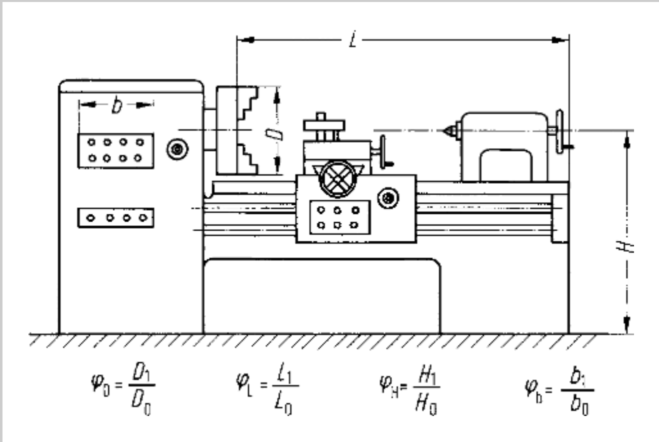

Figure 9.11. Lathe with main dimensions and controls shown schematically; the diameter/length/height ratio may have to be varied to suit particular groups of products, that is $\varphi_D \neq \varphi_L \neq \varphi_H$, but if possible $\varphi_H = \varphi_b = 1$ for ergonomic reasons

3. Overriding Production Requirements

The development of a size range is aimed at high cost-effectiveness. Within the range, especially if it is finely stepped, individual components and assemblies may be more coarsely stepped to provide larger batch sizes for even greater cost effectiveness.

Figure 9.12 is the data sheet of a geometrically similar turbine range consisting of seven sizes. Stuffing boxes and locating bolts are stepped more coarsely than the rest, ensuring greater batch sizes and greater economy. Figure 9.13 shows the increase in batch sizes for an assumed sales projection.

All these examples make it clear that it is not always possible to adhere to geometrically similar size ranges; instead, designers must strive, with the help of similarity laws, to arrive at that size range which provides the highest overall utilisation of the strength of every component. Depending on the physical constraints, each size will have to be individually selected. This is best done with the help of exponential equations, as we shall now go on to show.

4. Adaptation with the Help of Exponential Equations

Exponential equations are a simple means of dealing with the requirements mentioned under the previous three sections and of developing semi-similar size ranges.

As we have pointed out, nearly all technical relationships can be expressed by power functions. When using preferred number diagrams only the exponent is important if one starts from a basic design.

A physical quantity of the k-th member of a size range can often be represented by:

$$y_k = c_k x_k^{p_x} z_k^{p_z}$$

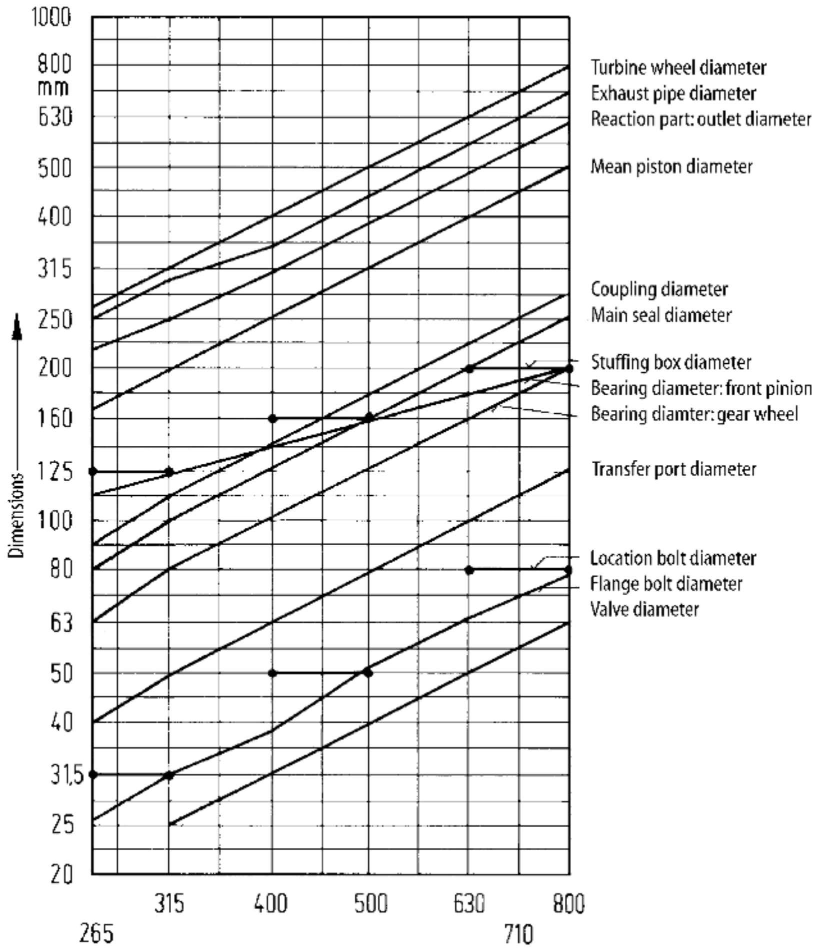

Figure 9.12. Data sheet for turbine size range: main dimensions are geometrically similar, deviations are determined by standards; stuffing boxes and locating bolts are in larger steps than the other components

The dependent variable y and the independent variables x and z can always be expressed by preferred numbers starting from the basic design (Index 0):

$$y_k = y_0 \varphi_L^{y_e k} \; ; \quad x_k = x_0 \varphi_L^{x_e k} \; ; \quad z_k = z_0 \varphi_L^{z_e k}$$

where φ_L is the chosen step factor of the dimension chosen as nominal in the size range, y_0, x_0, z_0 are the appropriate values of the basic design, k is the k-th step, and y_e, x_e and z_e are the associated step exponents. Since c_k is a constant, we have for all elements $c_k = c$:

$$y_k = y_0 \varphi_L^{y_e k} = c \left(x_0 \varphi_L^{x_e k} \right)^{p_x} \left(z_0 \varphi_L^{z_e k} \right)^{p_z}$$

$$y_k = c x_0^{p_x} z_0^{p_z} \cdot \varphi_L^{(x_e k p_x + z_e k p_z)}$$

Sales forecast

Type	265	315	400	500	630	710	800
Number	6	9	9	6	3	2	1

3 locating bolts per turbine

Size	Φ25	Φ31.5	Φ40	Φ50	Φ63	Φ71	Φ80
Number	18	27	27	18	9	6	3

Combined to:

Size	Φ31.5	Φ50	Φ80
Number	45	45	18

Figure 9.13. Sales forecast in respect of turbine size range (Figure 9.12) and the associated bolts. Because of the large step sizes, larger batch sizes are possible

With $y_0 = c x_0^{p_x} z_0^{p_z}$ we have:

$$y_0 \varphi_L^{y_e k} = y_0 \varphi_L^{(x_e k p_x + z_e k p_z)}$$

By equating the exponents, we obtain:

$$y_e = x_e p_x + z_e p_z$$

which is independent of k.

Here y_e, x_e and z_e are the exponents to be determined, and p_x and p_z the physical exponents of x and z. The exponent y_e depends on x_e and z_e.

Let us now consider a practical example: the provision of sprung elastic pipeline supports for a range of geometrically similar valves (see Figure 9.14). The following requirements must be met:

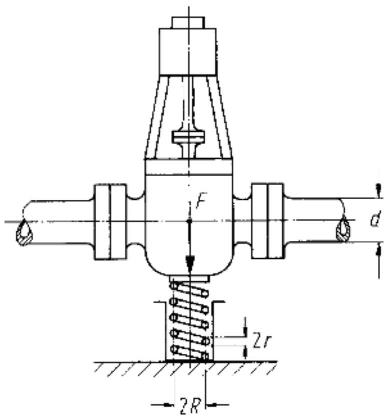

Figure 9.14. Valve supported in pipeline by means of coil springs

- The stress in the spring due to the weight of the valve must be constant throughout the range.
- The stiffness of the spring must increase as the bending stiffness of the pipe.
- The mean spring diameter $2R$ must preserve geometrical similarity with the increasing valve size (nominal dimension d).

What law must the spring wire diameter $2r$ and the number of active coils n obey? First of all the appropriate relationships must be set down, so that the exponential equation can be determined (the subscript e shows that only the exponent of the corresponding quantity is involved):

$$F = Cd^3 \quad (1) \qquad F_e = 3d^3 \quad (1')$$

$$\tau = \frac{F \cdot R}{r^3\pi/2} \quad (2) \qquad \tau_e = F_e + R_e - 3r_e = 0 \quad (2')$$

$$s = \frac{Gr^4}{4nR^3} \quad (3) \qquad s_e = 4r_e - n_e - 3R_e \quad (3')$$

Let d be the independent variable. Since the spring stress must remain constant, the step factor $\varphi_\tau = 1$, and the step exponent $\tau_e = 0$. The stiffness s of the spring must correspond to the bending stiffness of the pipes. According to Table 9.3, this is ensured by $\varphi_s = \varphi_L$. Since the basic dimension d of the valves increases geometrically, $\varphi_s = \varphi_d$, so that the step exponent of s becomes:

$$s_e = d_e \quad (4')$$

The loading is equal to the weight of the valve F; the weight dimension is related to the basic size d by $\varphi_F = \varphi_d^3$. The exponent of F referred to d is therefore:

$$F_e = 3d_e \quad (5')$$

If the mean spring diameter is to increase in geometrical similarity, we must have $\varphi_R = \varphi_d$ or:

$$R_e = d_e \quad (6')$$

Substituting equations (5′) and (6′) into equation (2′) we obtain:

$$3d_e + d_e - 3r_e = 0$$

or

$$r_e = (4/3)d_e \quad (7')$$

Substituting equations (4′), (6′) and (7′) into equation (3′), we obtain:

$$4r_e - n_e - 3d_e = d_e$$
$$n_e = 4r_e - 4d_e = 4(4/3)d_e - 4d_e = (4/3)d_e$$

Result: Spring wire diameter $2r$ and the number of active coils n must increase as $d^{4/3}$. In that case, the step factor is:

$$\varphi_r = \varphi_n = \varphi_d^{4/3}$$

The spread of the individual sizes is shown qualitatively in the data sheet reproduced in Figure 9.15.

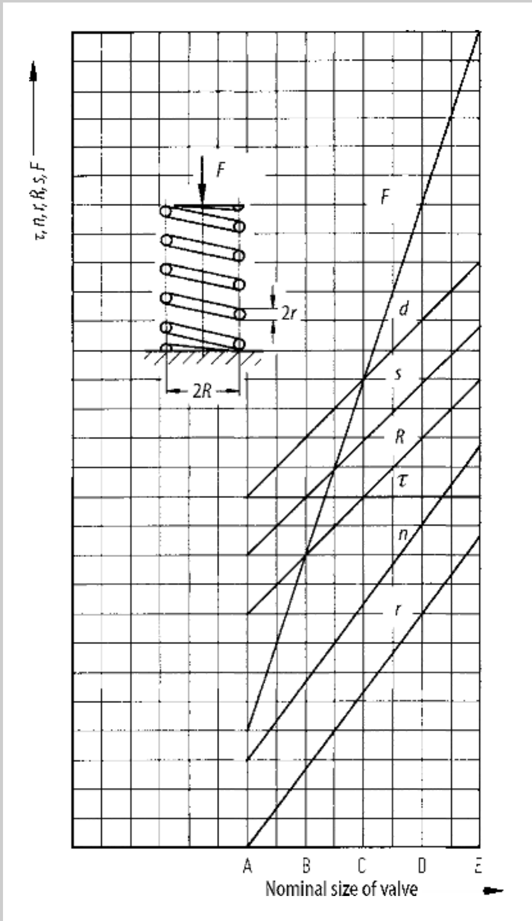

Figure 9.15. Data sheet for semi-similar coil springs

5. Examples

Example 1

A range of high-pressure gear pumps is to consist of six sizes giving delivery volumes ranging from 1.6 to 250 cm^3 per revolution at a maximum operating pressure of 200 bar and a constant input speed of 1500 rev/min. In the preferred number diagram shown in Figure 9.16, the steps laid down for the six sizes are plotted against the delivery volume, gear tooth width and pitch circle diameter. The following relationships are involved:

- The pitch circle diameters d_0 (each pump size has only one) are graded in accordance with R 10 with a step factor of $\varphi_{d_0} = 1.25$, the sizes deviating very slightly from the preferred numbers by virtue of the constant, integral number of teeth and also because the standard values of the modules m differ very slightly from the R 10 series.

- The volume delivered per revolution resulting from the tooth geometry is

$$V = 2\pi\, d_0 m b\,, \quad \text{where } b = \text{gear tooth width}\,.$$

From one size to the next, and at geometrical similarity, the volume delivered therefore increases as:

$$\varphi_V = \varphi_{d_0}\varphi_m\varphi_b = \varphi_L^3 = 1.25^3 = 2$$

that is, the volume delivered doubles from step to step (see Figure 9.16). The pump power $P = \Delta p \cdot \dot{V}$ increases as:

$$\varphi_P = \varphi_{\Delta p}(\varphi_V/\varphi_t)$$

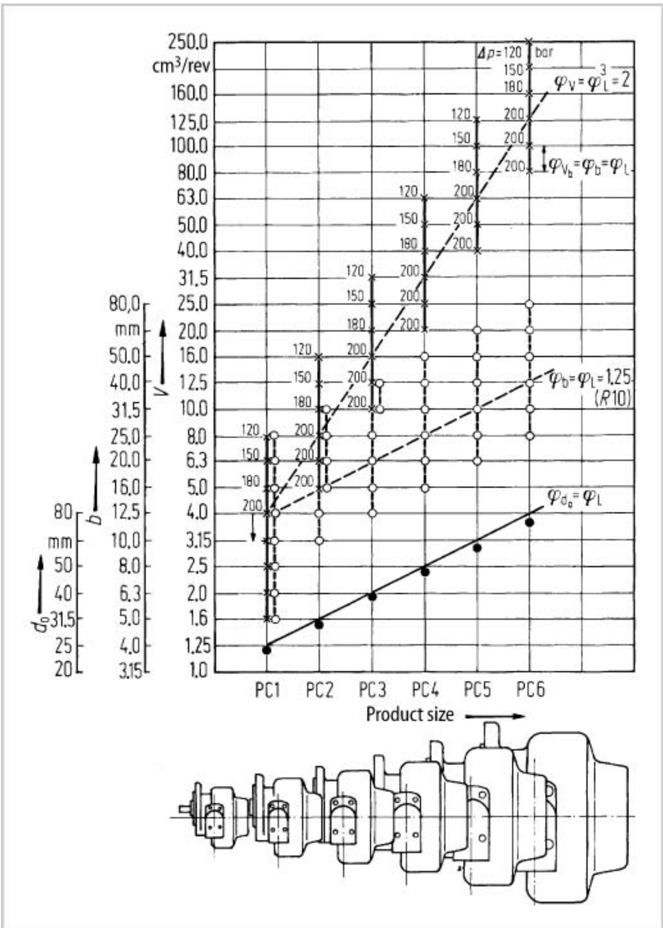

Figure 9.16. Data sheet for a size range of high-pressure gear pumps: V volume delivered per revolution; b gear-tooth width; d_0 pitch circle diameter of gears (Reichert, Hof)

which, with $\varphi_{\Delta p} = 1$ and $\varphi_t = 1$ becomes:

$$\varphi_P = \varphi_V = 2$$

Because of the constant rotational speed, the torque is stepped up accordingly.

- Every pump size, i.e. every pitch circle diameter, has been provided with six tooth widths b, except the smallest size which has eight, so that smaller steps in the volume delivered can be obtained. This means that for each pump size the geometrical volume delivered, $V = 2\pi d_0 mb$, will have a step factor of $\varphi_{V_b} = \varphi_b = 1.25$, d_0 and m being constant and the chosen tooth width step factor being $\varphi_b = 1.25$ (R 10). The power curve for any one pump size then becomes:

$$\varphi_{P_b} = \varphi_{V_b} = \varphi_b = 1.25$$

- To cope with the mechanical stresses (resulting from the increasing torques and the increasing bending moments due to increases in tooth width) with a shaft of constant diameter, the three pumps with the greatest tooth width in each size group must have their output pressure reduced. For overriding economic reasons (identical shaft diameter, identical bearings), the first two pumps of each size group do not have their strengths fully exploited.
- The delivery volumes of the top three pumps in any size group correspond to the bottom three of the next group up. A delivery pressure of 200 bar can therefore be obtained over the entire delivery-volume range.

This particular size range was conceived as a semi-similar series with a small number of housing sizes and several tooth width sets, so that, at the same drive speed and pressure over the entire range (overriding task requirements) and also at constant gear tooth size, constant gearwheel and shaft diameters per housing size (overriding production requirements), the maximum possible range of delivery volumes could be provided.

Example 2

In Figure 9.17 the output P of a size range of electric motors with varying pole numbers (speeds) has been plotted against the various product sizes (shaft heights H). The shaft heights are in accordance with R 20 and have a step factor of $\varphi = 1.12$. The output of the electric motor is governed by $P \sim \omega JBbhtD$, that is, at constant angular velocity ω or speed n, current density J and magnetic flux density B, the output is proportional to the conductor dimensions b, h, t and also to the distance $D/2$ of the conductor from the shaft axis.

The output step factor is therefore given by:

$$\varphi_P = \varphi_L^4 = 1.12^4 = 1.6 \quad \text{(R 5)}$$

In the 4-pole motor (1500 rev/min) the output range is therefore 500–3150 kW. Because power output varies with speed, and also because the dimensions of the conductor, the diameter of the rotors, and the heat removed by ventilation have to be varied, the slower 6-pole version must be reduced by three steps (355 to

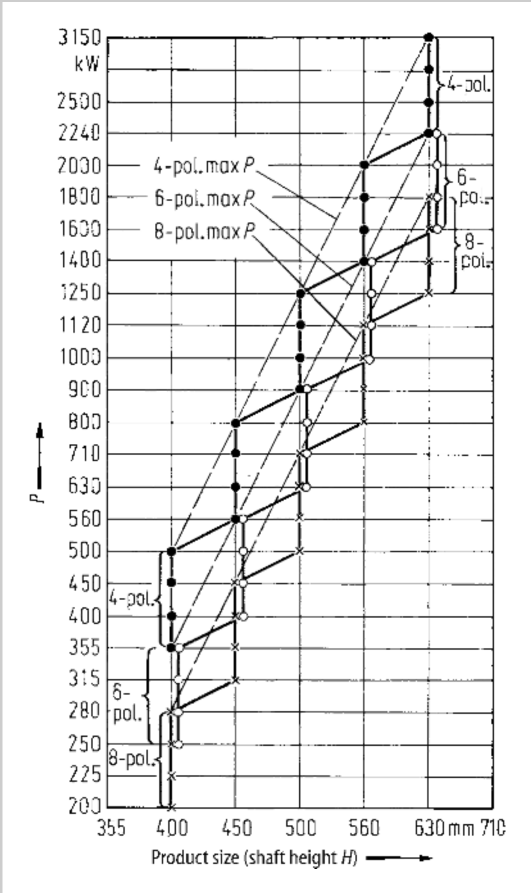

Figure 9.17. Output data sheet for a electric motor size range (AEG Telefunken) [9.1]

2240 kW), and the even slower 8-pole version by a further two steps (280 to 1800 kW).

To provide marketable and finer output steps and also to satisfy the overriding production requirements, four outputs are provided per shaft height or motor size, so that the output curve assumes the form of a stepped line. Smaller outputs are obtained by varying the size of the electrically active parts and fitting them into the same size of housing. In contrast to what happened in Example 1, the outputs for the different size groups (fixed pole number) do not overlap, although this has been done with other motor designs so as to maintain certain performance properties, e.g. efficiency.

Figure 9.18 shows the welded housings of this motor range in greatly simplified form. The stepped sizes of several important dimensions are entered in a data sheet (see Figure 9.19). It can be seen that the shaft height *H*, the housing height *HC* and the distance between the foundation bolts *B* and *A* are all stepped up by the factor $\varphi_L = \varphi_H = 1.12$. The values of *H*, *HC* and *B* follow the R 20 series, whereas *A* and *DB*

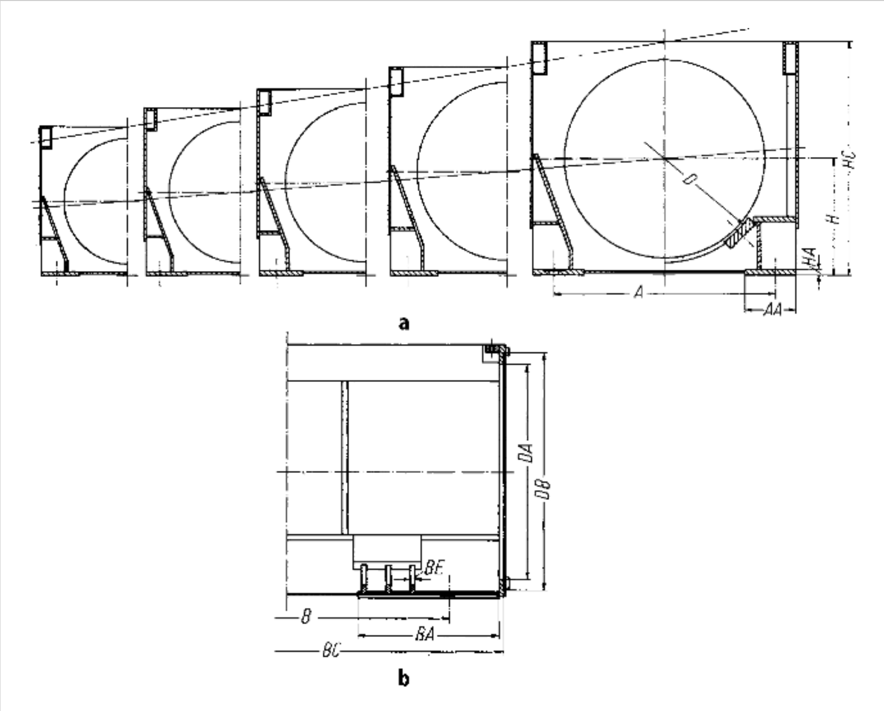

Figure 9.18. Housing for the electric motor size range (simplified) shown in Figure 9.17 (AEG Telefunken): **a** cross sections; **b** elevation

follow the same series, but with their positions slightly shifted. Just one housing length *BC* is provided for the four outputs per shaft size (see Figure 9.18). This is possible because different sizes of the electrically active parts can be fitted easily into one housing size. Without this separation of the housings from the electrical components, the layout would not be economic and several housing lengths would have to be provided for each shaft height [9.30].

Because of overriding similarity laws on the electrical side (for instance in respect of the windings) the housing length step factor φ_{BC} cannot be kept constant over the entire range of shaft heights. Figure 9.19 shows the increase in step factor for *BC* with increasing shaft height, the step size only approaching R 20 for the last two housings of the range.

Let us now look at a few detailed measurements of this housing design. The baseplate dimensions *AA* and *BA* have been graded by a single step factor which lies between R 20 and R 40. This was done to save material while maintaining the minimum dimensions needed to assemble the fixing bolts. The baseplate thickness *HA* has been stepped in accordance with the usual semi-finished material dimensions, but by and large follows R 20. For the strengthening ribs an equal thickness *BE* is provided for four housing sizes. Only for the largest housing are thicker ribs required.

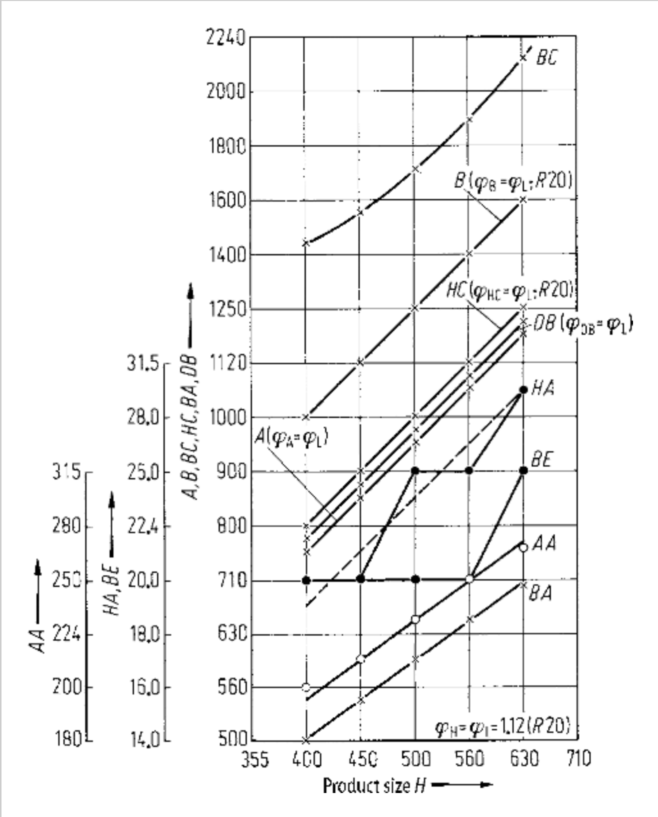

Figure 9.19. Data sheet for housing dimensions of the electric motor size range in Figure 9.17. (symbols as in Figure 9.18)

Because of overriding similarity laws, overriding task requirements and overriding production requirements, individual dimensions and nominal sizes may have to be stepped in accordance with laws that differ from those leading to geometric similarity. In every case, however, designers must, in the first instance, aim at size ranges based on the appropriate similarity laws and the preferred number series and only deviate from them after careful consideration of the particular task and the costs involved.

9.1.6 Development of Size Ranges

Size-range development can be summed up as follows:

1. Prepare the basic design for the range. This can be completely new or derived from an existing product.
2. Determine the physical relationships (exponents) in accordance with similarity laws, using Table 9.3 for geometrically similar product ranges, or using exponential equations for semi-similar product ranges. Put down the results as preferred number diagrams in the form of data sheets.

3. Determine the step sizes and the scope of application, and add them to the data sheets.
4. Adapt the theoretically obtained ranges to satisfy overriding standards or technological requirements and record the deviations on the data sheets.
5. Check the product range against scale layouts of assemblies paying particular attention to critical areas for extreme dimensions.
6. Improve and complete what documentation may be needed to determine the range and prepare production documents (at the time they are needed).

The need for developing a semi-similar size range may not always appear from the requirements list or from a first survey of the physical relationships, but may only become clear during an actual development. Section 9.1.5 describes how the individual components and dimensions can be determined during the development of semi-similar size ranges using exponential equations. The number of parameters and the number of equations to be solved may be quite large in complex applications. For that reason Kloberdanz [9.26] has developed a computer-aided size range program. After formulating the physical relationships involved and adding the constraints, the program automatically determines the scaling rules and represents the results in the form of preferred number diagrams and data sheets. These can then be adapted interactively to other constraints such as company standards and stock lists.

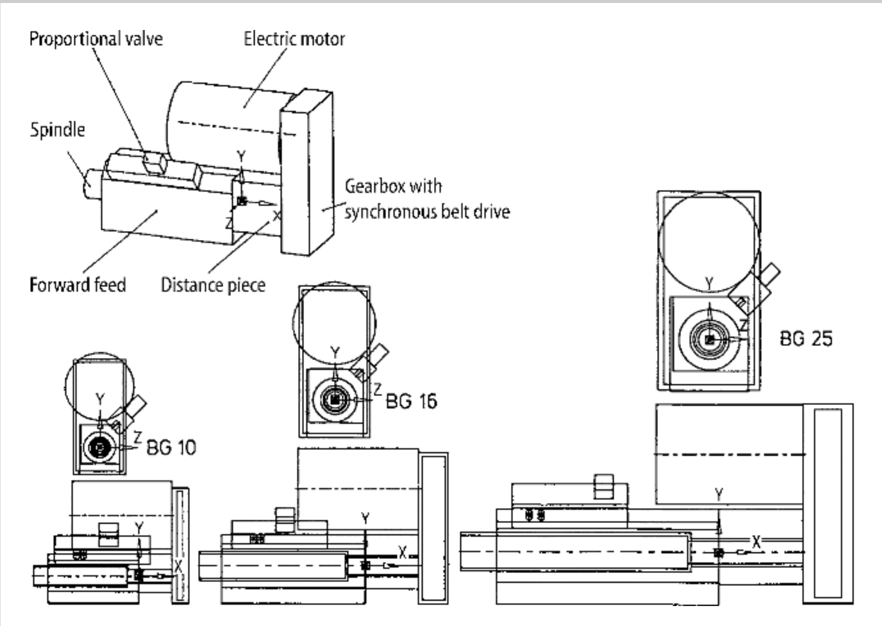

Figure 9.20. Example of computed-aided development of a semi-similar size range of hydropneumatic forward feed units, after [9.26, 9.38]

Using parametric macros, the scaling rules are used to generate automatically preliminary geometrical layouts of sequential designs for a semi-similar size range (see Figure 9.20). After the final size range has been determined, the details can then be defined using single part macros [9.8, 9.26].

9.2 Modular Products

In Section 9.1 we discussed the features and design potential of size ranges. Their aim is the rationalisation of product development by the implementation of the *same* function with the same principle solution and, if possible, with the same properties over a wide range of sizes.

Modular systems provide rationalisation in a different situation. If a product is to fulfil *different* functions, then many variants will have to be provided, at great cost in design and production. Rationalisation is, however, possible if the particular *function variant* at any one time is based on a combination of fixed individual parts and assemblies (function units), and this is precisely what a modular system sets out to achieve.

By *modular products* we refer to machines, assemblies and components that fulfil various overall functions through the combination of distinct function units (building blocks) or modules.

Because such modules may come in various sizes, modular products often involve size ranges. The modules should be produced by similar methods whenever possible. Since in a modular system the overall function results from a combination of building blocks, the development of modular products demands the elaboration of a corresponding function structure and this calls for greater design effort during the conceptual and embodiment phases than does the development of a pure size range.

A modular system can provide a favourable technical and economic solution whenever all or some function variants of a product series are required in small batch sizes only, and whenever they can be based on a single or only a few basic modules, along with additional modules.

Besides fulfilling a variety of functions, modular systems can also serve to increase the production batch size of identical parts for use as building blocks in a variety of products. This additional objective, which greatly helps to rationalise the production procedure, is attained by the breakdown of the product into module-like units, as was the done for differential construction described in Section 7.5.8. Which of the two objectives is paramount depends largely on the product and on the task it has to perform. With a wide-ranging overall function, what matters most is the resolution (divisibility) of the product into function-oriented modules. On the other hand with a small number of overall function variants, a production-oriented resolution is the paramount consideration.

Often, modular development is only initiated when what was originally conceived as an individual or size-range development is expected to yield a large number of variants. To that end, product series that have already been marketed are often redesigned as a modular system. The disadvantage here is that the products are more or less predetermined. Whereas the advantage is that their essential properties have already been tested so that an expensive new development can be dispensed with.

9.2.1 Modular Product Systematics

Modular product systematics are discussed in [9.10,9.11,9.29]. Basing ourselves on these findings, we shall first of all examine the principles and the most important concepts, and merely add a few amplifications [9.4].

Modular product systems are built up of separable or inseparable units, i.e. *modules*. We must distinguish between *function modules* and *production modules*. Function modules help to implement technical functions independently or in combination with others. Production modules are designed independently of their function and are based on production considerations alone. Function modules in the narrower sense have been divided into equipment, accessory, connecting and other modules [9.10, 9.11]. This division is neither clear-cut nor adequate for the development of modular systems.

1. Classification of Modules

For the classification of function modules it seems advantageous to define the various types of function that recur in modular systems and can be combined as subfunctions to fulfil different overall functions (overall function variants), see Figure 9.21.

Basic functions are fundamental to a system. They are not variable in principle. A basic function can fulfil an overall function simply or in combination with other functions. It is implemented as a basic module which may come in one or several sizes, stages and finishes. Basic modules are "essential modules".

Auxiliary functions are implemented by locating or joining *auxiliary modules* that are kept in step with the basic modules and are usually "essential modules".

Special functions are complementary and task-specific subfunctions that need not appear in all overall function variants. They are implemented by *special modules* that are additions to or accessories for the basic modules. They are "possible modules".

Adaptive functions are necessary for adaptation to other systems and to boundary conditions. They are implemented by *adaptive modules* whose dimensions are not fully fixed in advance and hence allow for unpredictable circumstances. Adaptive modules may be "essential modules" or "possible modules".

Customer-specific functions not provided for in the modular system will recur time and again even in the most careful development. Such systems are implemented by *non-modules* which have to be designed individually for specific tasks. If they are used, the result is a *mixed system*, that is, a combination of modules and non-modules.

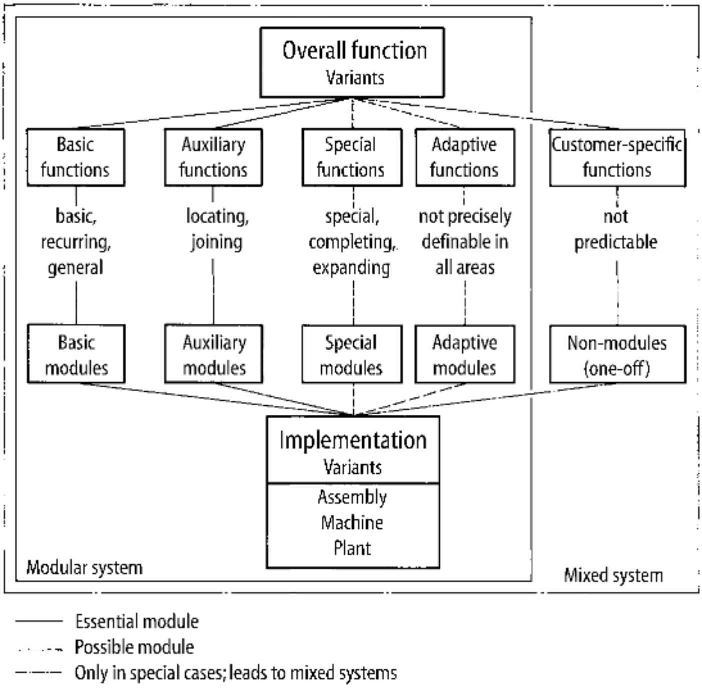

Figure 9.21. Function and module types in modular and mixed product systems

By the *importance of a module* we refer to its ranking within a modular system. Thus, function modules can be ranked as essential modules or as possible modules [9.14].

A production-oriented characteristic is the *complexity of a module*. Here we distinguish between *macro modules* which, as assemblies, can be subdivided into components, and *micro modules* that are components themselves.

A further aspect of module characterisation is their *type of combination*. Designers should always aim for technically advantageous combinations of similar modules. In practice, however, the combination of similar with different modules, and also with customer-specific non-modules, is often unavoidable. The latter, as mixed systems, can meet market requirements very economically.

For the characterisation of modular systems we can also consider their *resolution*—in other words, the extent to which a particular module can be broken down into individual parts for functional or production reasons. For the modular system as a whole, the resolution defines the number of individual units and their possible combinations.

2. Concretisation of Modules

One-off products, such as turbines, pumps and compressors, often demand significant variations in performance and efficiency. They require their working zones, for example blade passages and cylinder dimensions, to be adapted. However, many parts remain identical, for example the bearings, seals, and input and output sections. In such cases a division into modules is advantageous (see Figure 1.9, working step 4 and Figure 7.1, working step 3). The overall product is thus developed as a combined approach, that is, as a size range partially made up from modules (see Figure 9.22). The modules are generated in suitable step sizes. For the manufacturer, these modular systems do not really exist until, based on specific requirements, the appropriate sets of drawings are combined as modules into an overall machine (see Figure 9.23). Such a "fictitious" modular product is not only useful for the product development department; it can also provide the basis for fixed production modules that can be used to prepare production plans and software for CNC machines. Another use of the modules is to plan the optimum stock of casting patterns. These patterns can be divided into modules that are combined, where necessary, into more complex castings, such as housings. Depending on the need, the level of concretisation can be selected between having product modules available either in software (and paper) or in hardware.

For the application of closed modular systems, their *range* and *potential* can be expressed by *combinatorial plans* with a finite and predictable number of variants. Such plans make it possible to choose desired combinations directly. By contrast, open modular systems contain a great multiplicity of combinatorial possibilities, which cannot be fully planned or represented (see Figure 9.32). A *specimen plan* provides examples of typical applications of the modular system.

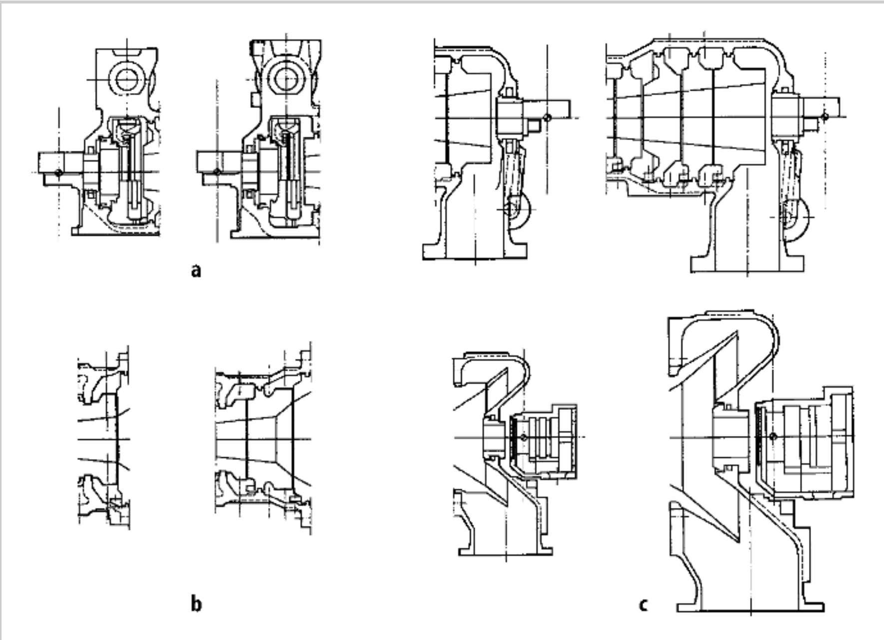

Figure 9.22. Modules for an industrial turbine size range generated using geometric sections (Siemens): **a** Entry section; **b** Middle section; **c** Exit section

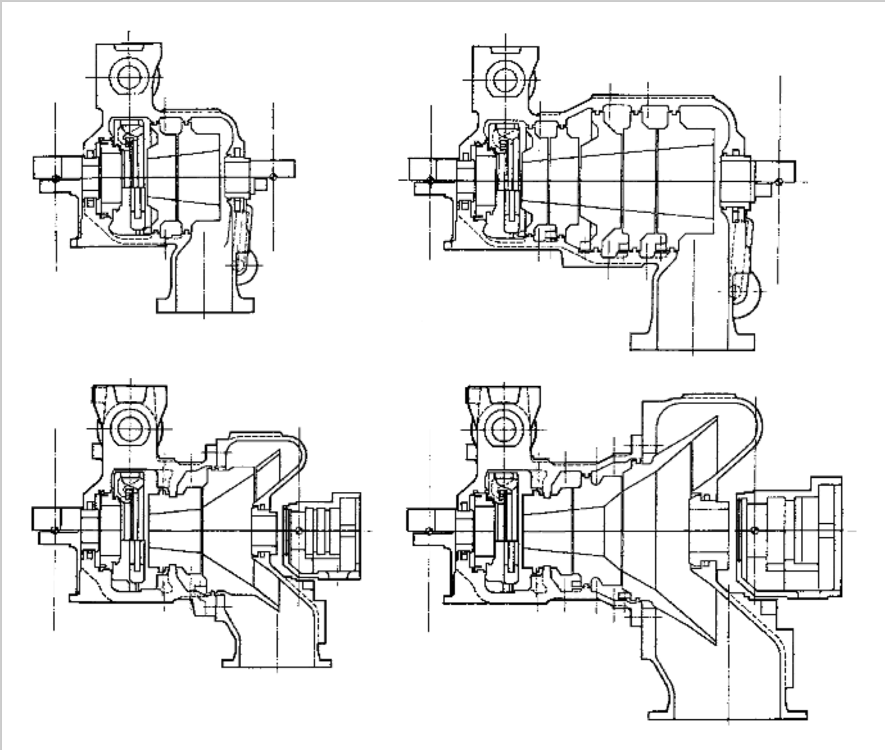

Figure 9.23. Complete turbine design for different pressure and flow requirements produced by combining the modules shown in Figure 9.22 (Siemens)

The above-mentioned concepts of module development are summarised in Table 9.5.

9.2.2 Modular Product Development

In what follows the development of modular products will be presented in accordance with the steps listed in Figure 4.3.

1. Clarifying the Task

In their formulation of demands and wishes, for instance with the help of the checklist (see Figure 5.3), designers must pay careful attention to the clarification of the various tasks to be performed by the product series. A characteristic demand of the specification of a modular product is that it must fulfil several overall functions. This results in the *variants of the overall function* that a specific modular product has to fulfil.

Of particular importance for the economic analysis and application of modules is data about the market expectations of particular variants. Friedewald [9.17]

Table 9.5. Concepts of modular systematics

Classifying criteria	Distinguishing features
Types of module	– Function modules • Basic modules • Auxiliary modules • Special modules • Adaptive modules • Non-modules – Production modules
Importance of modules	– Essential modules – Possible modules
Complexity of modules	– Large modules – Small modules
Combination of modules	– Similar modules only – Different modules only – Similar and different modules – Modules and non-modules
Resolution of modules	– Number of parts per module – Number of units and their possible combinations
Concretisation of modules	– Software/paper modules only – Mix of hardware and software modules – Hardware modules only
Application of modules	– Closed system with combinatorial plan – Open system with specimen plan

speaks of the quantification of function variants for the technical and economic optimisation of modules. Whenever the implementation of rarely demanded variants increases the overall cost of the modular system, an attempt must be made to remove such variants. The more searching these analyses are before the actual development is begun, the greater are the chances of arriving at a cost-effective solution. However, the reduction of types by the removal of infrequently demanded and costly function variants cannot be finalised until the elaborated solution concept or even the embodiment design provides reliable information about the cost of the different variants and also about the influence of every individual variant on the cost of the modular system as a whole.

2. Establishing Function Structures

The establishment of function structures is of particular importance in the development of modular systems. With the function structure—that is, the splitting up of the required overall function into subfunctions—the structure of the system is already laid down, at least in principle. From the outset, designers must try to subdivide the overall function variants into a minimum number of similar and recurring subfunctions (basic, auxiliary, special and adaptive functions, see Figure 9.21). The function structures of the overall function variants must

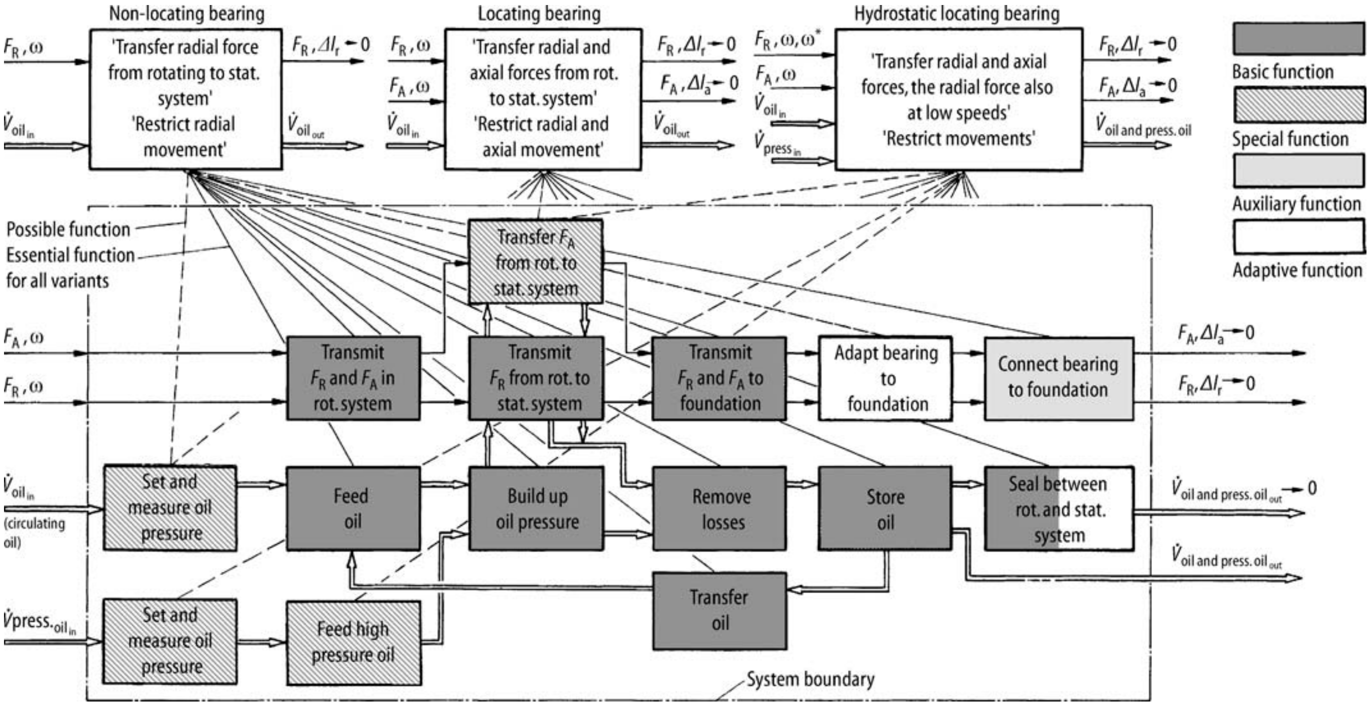

Figure 9.24. Function structure for a modular bearing system, after [9.23]

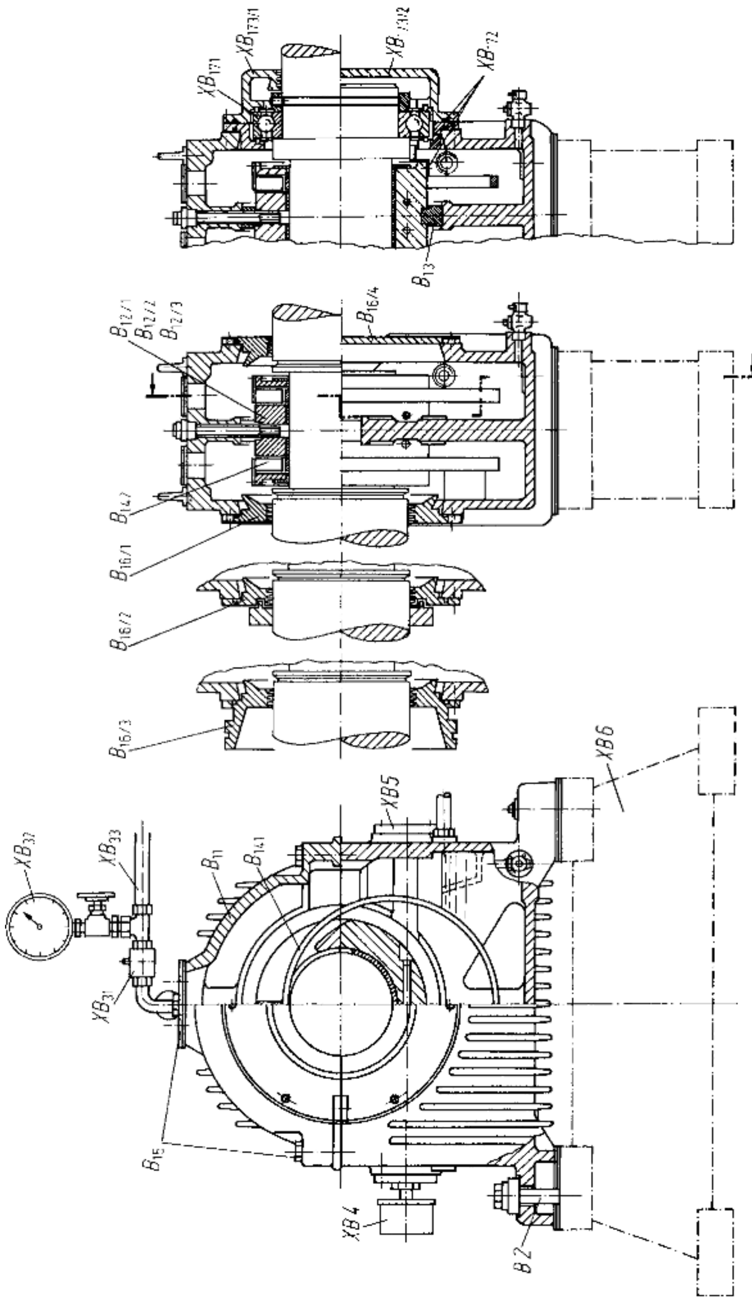

Figure 9.25. Layout of the modular bearing system shown in Figure 9.24 (AEG Telefunken)

be logically and physically compatible, and the subfunctions determined by them must be interchangeable. To that end, it is useful if, depending on the particular task, the overall function can be achieved by essential modules and by additional task-specific possible modules.

Figure 9.24 shows the function structure for the modular bearing system discussed in [9.3, 9.23]. The most frequently demanded overall functions, namely "non-locating bearing", "locating bearing" and "hydrostatic locating bearing", together with the appropriate basic, special, auxiliary and adaptive functions, are represented. By means of the subfunction "seal between rotating and stationary systems", we can show that it is often more cost-effective to combine several functions into one complex function; thus in the present case, the sealing function was combined with an adaptive function to satisfy various interface conditions. The production module "shaft seal", which performs this complex function, was accordingly specified as an unfinished one that could be completed during production as: (1) a simple line seal, (2) as a line seal with an additional labyrinth, or (3) as a seal with an additional coupling adapter (see Figure 9.25). It should also be stressed that there are special functions (special modules) that occur in at least one overall function variant (here: "transfer axial force F_A from rotating to stationary system"), others that represent possible modules for all overall function variants (here: "set and measure oil pressure"), and yet others that only become necessary at a certain size (here: "feed high pressure oil").

In the setting up of function structures the following objectives should be borne in mind:

- Aim for the implementation of the required overall functions by the combination of the minimum number of easily implementable basic functions.
- Try to divide the overall functions into basic functions and if necessary into auxiliary, special and adaptive functions in accordance with Figure 9.21, in such a way that variants in high demand are predominantly built up with basic functions; and more rarely demanded variants with additional special and adaptive functions. For very rarely demanded function variants, mixed systems with additional functions (non-modules) are often more cost-effective.
- Try to combine several subfunctions into a single module if this increases cost-effectiveness. Such combinations are particularly recommended for the implementation of adaptive functions.

3. Searching for Working Principles and Concept Variants

The next step is to find working principles for the implementation of the various subfunctions. To that end, designers should, above all, look for such principles as provide variants without changes in working principle and basic design. As a rule, it is advantageous to stipulate similar types of energy and similar physical working principles for the individual function modules. Thus it is more cost effective and technically advantageous, in the combination of subsolutions into overall solutions (solution variants), to implement various drive functions with a single type of energy rather than provide a single modular system with separate electrical, hydraulic and mechanical drives.

A satisfactory production solution is also ensured by the implementation of several functions by a single unfinished module that can be completed in various ways depending on the requirements.

However, so complex are the technical and economic factors involved that it is impossible to lay down hard and fast rules. Thus, in the case of the bearing system (see Figure 9.25) it seems technically and economically advantageous to provide the bearing shell with lateral locating surfaces for taking up small axial forces. With larger axial forces, however, rolling bearings must be provided instead; it would be a mistake to try, for purely theoretical reasons, to transfer the radial and axial forces over the entire size range by means of plain bearings. The plain bearing system must be designed during the conceptual phase with two alternative lubrication systems (free ring or fixed ring) because their respective advantages and disadvantages can only be determined by later experiments [9.23]. The design of the ultimately chosen modular bearing system is shown in Figure 9.25.

4. Selecting and Evaluating

If several concept variants have been found during the previous steps, each must now be evaluated with the help of technical and economic criteria so that the most favourable solution concept can be selected. Experience has shown that, since the properties of any one variant are not yet sufficiently clear at this stage, such selections are very difficult to make.

Thus, in the case of the bearing system, preliminary evaluations have to be made even in the conceptual phase, for instance as to whether the axial forces should be taken up by plain or rolling bearings. However, the final choice of lubricating system can only be taken after the building of prototypes and experimentation with them.

Apart from the determination of the technical rating of individual concept variants, economic factors are of crucial importance in the design of modular systems. To come to grips with them, designers must estimate the production costs of the individual modules and their relative effect on the cost of the modular system as a whole. To that end, they will first of all determine the expected "function costs" of the subfunctions or of the modules fulfilling them. At a low level of concretisation, which is characteristic of the conceptual phase, they cannot usually hope to come up with more than very rough estimates. Since basic modules appear in all sorts of variants, they will select such solution principles as provide the most cost-effective basic modules. Special and adaptive modules take second place in the minimisation of costs.

For minimising the costs of a modular system, not only the modules themselves but also their interaction must be taken into account; in particular, the influence of special, auxiliary and adaptive modules on the *cost of the basic modules*. The influence of the cost of every overall function variant on the cost of the modular system as a whole must be fully determined. This may prove a complex task. Thus, in the bearing system we have been considering, the function variant “cool oil internally” would greatly influence the cost of the basic module “bearing housing”, because the dimensions of the special module “water cooler” determine the dimensions of the housing and hence the overall cost. If there is only a small demand for this variant, then it is certainly more cost-effective to fit the oil cooler to the outside of the housing and to put up with the extra cost of an oil pump.

In short, the layout of the basic modules must be adapted to the function variants with the highest expected demand. To that end, the influence of the remaining modules is of great importance. In [9.27, 9.28] a method using Neural Nets is proposed to identify and assess such complex relationships.

If it is impossible to provide a marketable adaptation of the basic concept, the least cost-effective function variants should be eliminated from the modular system. It will often be more economical to replace unusual variants, which render the overall system more expensive, by making individual adaptions than to impose such adaptions on the whole modular system. An alternative is the use of mixed systems.

5. Preparing Dimensioned Layouts

Once a solution concept has been selected, the individual modules must be designed in accordance both with their functions and their production requirements. In the design of modular systems, production and assembly considerations are of paramount economic importance. By paying heed to the embodiment design guidelines laid down in Sections 7.5.8 and 7.5.9, designers must try to provide basic, auxiliary, special and adaptive modules with the maximum number of similar and recurring parts and the minimum number of unfinished parts and production processes.

When selecting step sizes, designers should aim at the optimum resolution of modules (modularity), and to that end they may well adopt the differential construction approach. The determination of the optimum number of modules is, however, a complex task, for it is influenced by the following factors:

- Requirements and quality must be maintained and the propagation of errors must be taken into account (see Section 7.4.5: the principle of fault free design). Thus the greater the number of individual components, the greater the number of fits, and this may have untoward repercussions on the function, for instance on the vibration of a machine.
- Overall function variants must be created by simple assembly of modules (individual parts and assemblies).
- Modules may only be broken down to the extent that functions and quality permit and costs allow.
- In modular products marketed as overall systems, variants of which clients can assemble themselves by combinations of the modules [9.33], the most common modules must be designed for equal wear and tear and for easy replacement.
- In determining the most efficient modularity with regard to costs and production times, designers must pay special heed to the costs, not only of the design itself,

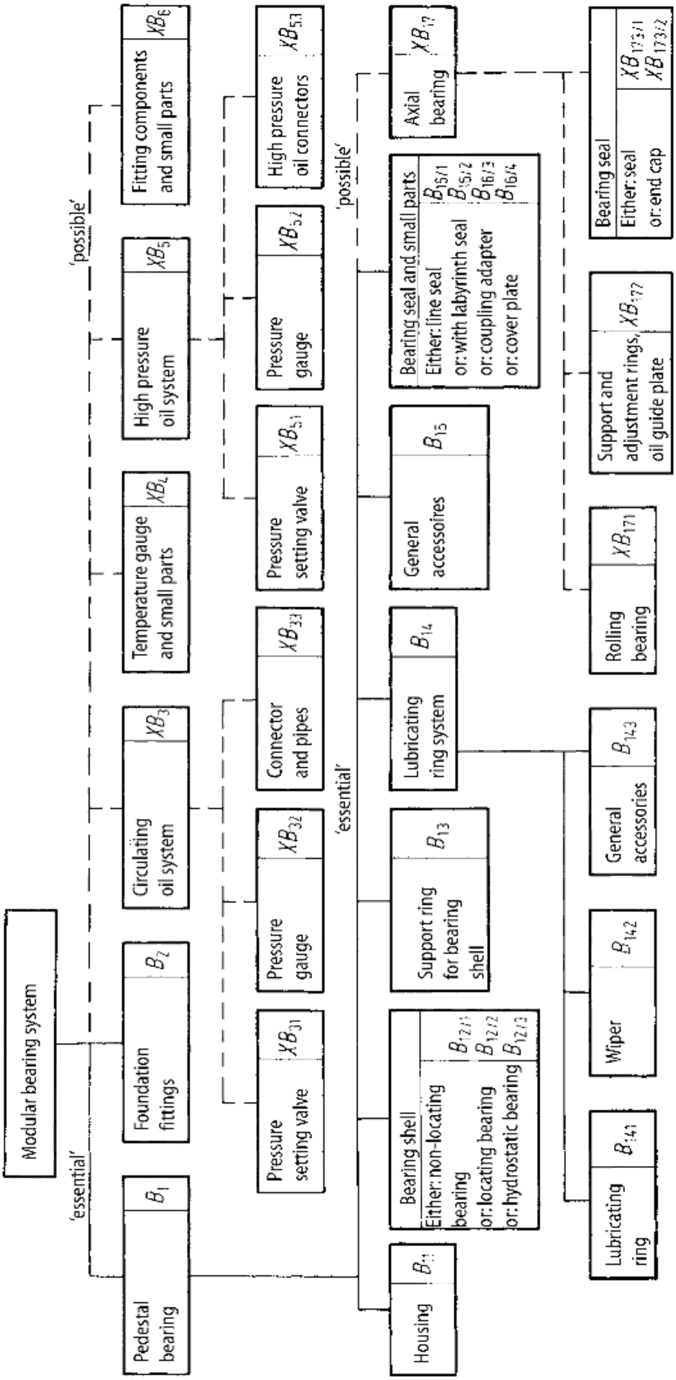

Figure 9.26. Family tree of the modular bearing system in accordance with Figures 9.24 and 9.25 (prefix *X* indicates possible modules)

but also of production, including production planning, production processes, assembly, handling and distribution.

Figure 9.25 shows the scale layout of the bearing system we have been discussing. In Figure 9.26 the structure of the overall function variants (see Figure 9.24) is shown in the form of a family tree. In both these figures, only the most important assemblies and individual parts of the bearing system have been entered; the actual modularity is greater. If the function structure, which only shows the main function variants, is compared with the final modular structure, it becomes clear

Table 9.6. Modules in bearing system shown in Figure 9.26

Modules	Nos.	Types	Functions
Housing	B_{11}	Basic module	'Transmit F_R and F_A to foundation', 'Remove losses', 'Store oil'
Bearing shell	$B_{12/1}$	Basic module	'Transmit F_R from the rotating to the stationary system', 'Build up oil pressure'
	$B_{12/2}$	Variant of $B_{12/1}$	additionally: 'Transfer F_A from the rotating to the stationary system'
	$B_{12/3}$	Variant of $B_{12/1}$	additionally: 'Transfer hydro-static oil pressure to shaft'
Support ring between housing and bearing shell	B_{13}	Auxiliary module	'Connect bearing shell with housing'
Lubricating ring	B_{141}	Basic module	'Transfer oil'
Wiper	B_{142}	Basic module	'Feed oil'
General accessories	B_{143}	Basic module	'Control oil level' and 'Remove oil'
General accessories	B_{15}	Basic module/ auxiliary module	'Accessory and connecting functions'
Bearing seal and small parts	$B_{16/1}$	Basic module	'Seal between rotating and stationary systems'
	$B_{16/2}$	Basic module/ adaptive module	additionally: 'adapt to labyrinth seal'
	$B_{16/3}$	Basic module/ adaptive module	additionally: 'Provide coupling adapter'
	$B_{16/4}$	Special module	'Seal housing in the absence of shaft'
Foundation fittings	B_2	Auxiliary module	'Connect bearing to foundations'
Pressure setting valve	XB_{31}	Special module	'Set pressure for circulating oil'
Pressure gauge	XB_{32}	Special module	'Measure oil pressure'
Connectors and pipes	XB_{33}	Auxiliary module	'Transfer circulating oil'
Temperature gauge and small parts	XB_4	Special module	'Measure temperature'
Pressure setting valve	XB_{51}	Special module	'Set pressure for high pressure oil'
Pressure gauge	XB_{52}	Special module	'Measure oil pressure'
High pressure oil connectors	XB_{53}	Auxiliary module	'Feed high pressure oil'
Fitting components and small parts	XB_6	Adaptive module	'Adapt bearing to foundation'
Rolling bearing	XB_{171}	Special module (for large axial forces)	'Transfer F_A from the rotating to the stationary system'
Support and adjustment rings, oil guide plate	XB_{172}	Auxiliary module	'Connect rolling bearing with housing', 'Supply oil to rolling bearing'
Bearing seal	$XB_{173/1}$	Special module	'Seal between rotating and stationary systems in case of rolling bearing variant'
	$XB_{173/2}$	Special module	'Seal housing in the absence of shaft'

that in the given modular system several functions are fulfilled by a single module or its variants. Table 9.6 shows the modules used and their assigned functions.

6. Preparing Production Documents

Production documents must be prepared in such a way that the execution of orders can be based on the simple, and if possible computer-aided, combination and further elaboration of modules for the required overall function variants.

Drawings require an appropriate part-numbering system and classification, two prerequisites of the optimum combination of modules (individual parts and assemblies).

The combination of individual modules into product variants must be recorded in the parts list. To build up a parts list, designers can refer to the so-called variant parts list [9.14] which is based on the structure of the product and in which a distinction is made between essential modules and possible modules.

Particularly suited to the numeration of drawings and parts lists is the method of parallel encoding, which assigns identification numbers for the unequivocal and unmistakable description of components and assemblies, and classification numbers for the function-oriented recording and retrieval of these components and assemblies. The classification number is of particular importance in a modular system, because it helps to identify functional and other similarities between components.

9.2.3 Advantages and Limitations of Modular Systems

For the *manufacturer*, modular systems provide *advantages* in nearly all areas of the company:

- Ready documentation is available for tenders, project planning and design. Design is done once and for all, though it may be more costly for that very reason.
- Additional design effort is needed for unforeseeable orders only.
- Combinations with non-modules are possible.
- Overall scheduling is simplified and delivery dates can be improved.
- The execution of orders by the design and production departments can be cut short through the production of modules in parallel; in addition parts can be supplied quickly.
- Computer-aided execution of orders is greatly facilitated.
- Calculations are simplified.
- Modules can be manufactured for stock with consequent savings.
- More appropriate subdivision of assemblies ensures favourable assembly conditions.

- Modular product technology can be applied at successive stages of product development, for example, in product planning, in the preparation of drawings and parts lists, in the purchase of raw materials and semi-finished materials, in the production of parts, in assembly work, and also in marketing.

For the *user* there are the following *advantages*:

- short delivery times
- better exchange possibilities and easier maintenance
- better spare parts service
- possible changes of functions and extensions of the range
- almost total elimination of failures thanks to well-developed products.

For the *manufacturer* the *limit* of a modular system is reached whenever the subdivision into modules leads to technical shortcomings and economic losses:

- Adaptations to special customer wishes are not as easily made as they are with individual designs (loss of flexibility and market orientation).
- Once the system has been adopted, working drawings are made on receipt of orders only, with the result that the stock of drawings may be inadequate.
- Product changes can only be considered at long intervals because once-and-for-all development costs are high.
- The technical features and overall shape are more strongly influenced by the design of modules and the modularity than they would be by individual designs.
- Production costs are increased, for example because of the need for accurate locating surfaces and production quality must be higher because re-machining is impossible.
- Increased assembly effort and care are required.
- Since the interests of both the users and the producers have to be taken into consideration, the determination of an optimal modular system may prove very difficult.
- Rare combinations needed to implement unusual requirements may prove much costlier than tailor-made designs.

For the *user* there are such *disadvantages* as:

- Special wishes cannot be met easily.
- Certain quality characteristics may be less satisfactory than they would be with special-purpose designs.
- Weights and structural volumes of modular products are usually greater than those of specially designed products, and so space requirements and foundation costs may increase.

Experience has shown that, while modular production helps to make significant reductions in general overheads (administrative staff costs in particular), the effect on production and material costs can be less significant, because, as mentioned earlier, greater weights and volumes tend to be involved. Only if a modular system is developed with the express intention of rendering every function variant more cost-effective than a specially designed product can there be a significant reduction in overall costs.

9.2.4 Examples

Gearboxes

Gearboxes are another familiar example of modular systems. They involve a multiplicity of market-determined function variants, for instance, the attachment of different input and output devices, various shaft positions and different gear ratios. However, the basic overall construction structure is known and fixed. Several examples can be found in [9.21, 9.22, 9.43].

Modular Tram System

We will now use the example of a modular tram system to illustrate how the right selection of module parameters, in combination with an appropriate design strategy making use of CAx tools, can produce a high degree of flexibility and, at the same time, reduce costs.

The outer shape of a tram is, apart from visual aspects, determined by the required transportation capacity and the existing infrastructure of the operator. The *length* of the tram is mainly determined by the required number of passengers to be carried. The *width* is determined by the maximum allowable values set out in transport regulations and by the infrastructure, e.g. the existing distances between tracks in the case of twin-track layouts. The arrangement of the tram, that is, the *number* and *length* of the tram sections, and the configuration of the chassis are also determined by the infrastructure. Relevant issues here are, among others, the radius of the curves in the tracks, the buildings along the route, proximity of pavements, etc.

Because the abovementioned influences on the external shape of a tram differ for each operator and the required transportation tasks, a very large number of tram concepts have been generated over time. In this example, the task was to cover all existing tram applications with a very limited number of different tram sections, i.e. modules (basic modules) with not more than three widths and two lengths. After an extensive market analysis and a study of the trams produced in the past, the three basic modules shown in Figure 9.27 were defined. These are an end module, a chassis module and a middle module.

The end module is in two variants, with a driver cabin and without one; the chassis module with a driven variant and non-driven one; and the middle module in two lengths. The longer variant permits two different door arrangements. All modules come in three widths. The modules are shown in Figure 9.28.

The design of the body shell is based on a strict systematic approach. It can be represented using a parametric 3-D modeller and modified within predetermined

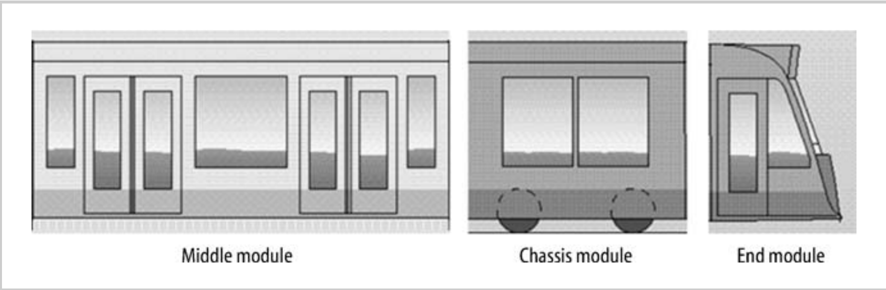

Figure 9.27. Basic modules of a modular tram

parameter ranges. The lengths of the individual design elements of the modules, such as the linking cross members, the roof supporting members, etc., have a clear geometric interdependency. By setting the parameters for the external dimensions of the modules, such as module length and width, number of doors, etc., the dimensions of the remaining elements of the module follow directly. Figure 9.29 shows, as an example, the body shell of the middle module.

The end module is a special module. The body shell of the tram consists of aluminium and extruded profiles that are bolted together. To realise the market requirement for different end module designs, the structure of the end module was produced using a GRP sandwich construction. The interfaces to the body shell, however, remain unchanged for each particular class of tram width. The resulting high flexibility and cost effectiveness, along with a wide range of configuration options, was partly due to the coupling of CAD and CAM. The 3-D

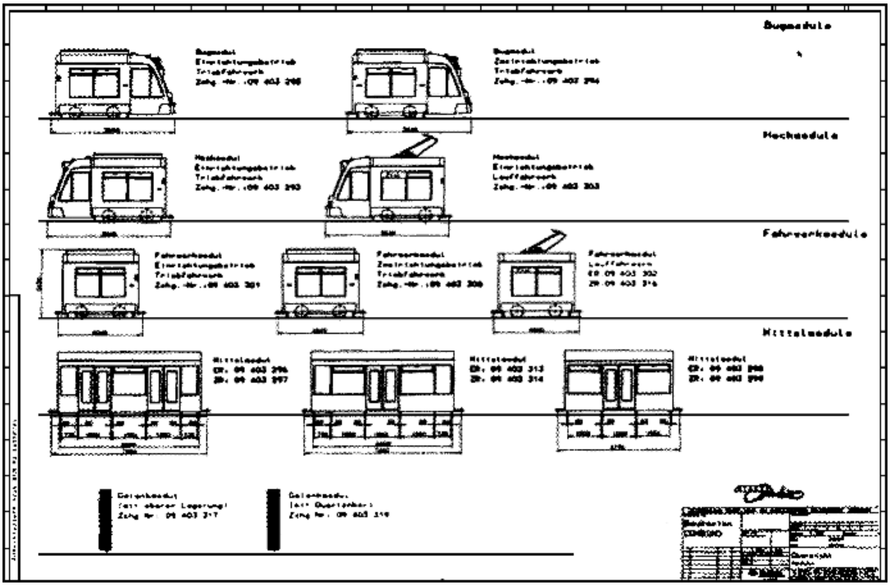

Figure 9.28. Modular tram system

CAD data for the end module can be sent directly to form milling machines that produce the foam cores for the GRP sandwich structure. It is essential that such possibilities, in addition to the previously mentioned structural and visual imperatives of the body shells, are taken into account when planning such modular products.

The selected tram modularisation only allows three sensible tram types of different lengths, namely a three, five and seven section tram. In Figure 9.30 the trams of the series are shown.

The basic configuration of the trams can be recorded as standard product structures in a Production Planning System (PPS). The design strategy behind the modules can be described in a Configuration Management System (CMS). This system can be used in the following way. In a first step, using the appropriate requirements, the structure of the tram, with three, five or seven sections, is selected. The parameters of the tram are then entered into the CMS. This system retrieves from the digital archive the required drawings, along with their ID numbers, and enters these at the appropriate positions in the product structure. In a second step, the assemblies and components that are not pre-defined, i.e. the customer-specific ones, are designed as special modules or non-modules using a conventional design approach. In this way, the product structure is completed (see Figure 9.31). More details of the approach adopted for this modular design task can be found in [9.32].

Further examples taken from hydraulics, pneumatics and machine tool construction can be found in the literature [9.2, 9.19, 9.29, 9.41].

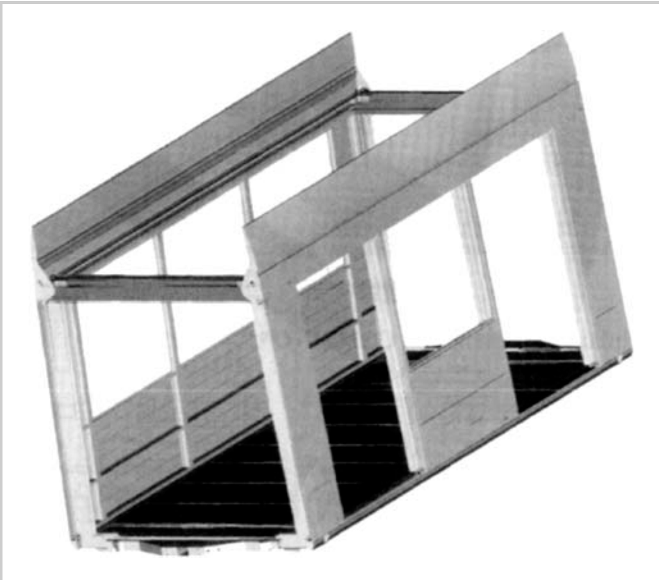

Figure 9.29. The parameterised body shell of the middle module

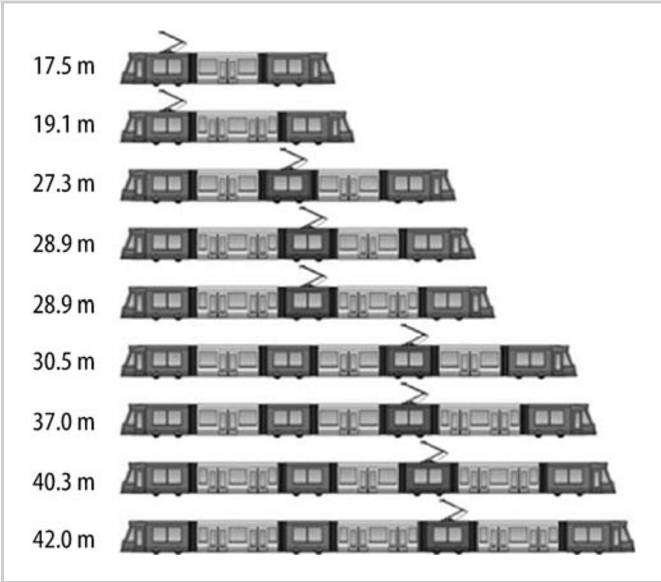

Figure 9.30. The trams of the COMBINO series: closed modular system [9.32]

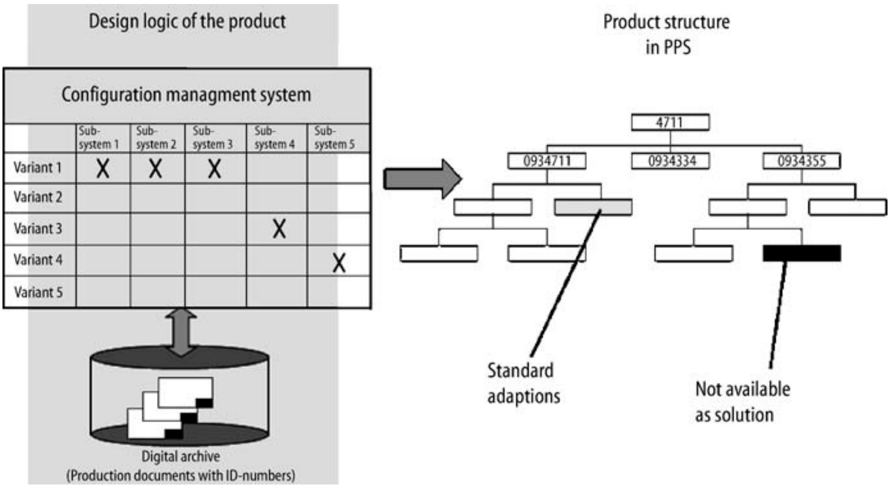

Figure 9.31. Configuration management system and product structure [9.32]

Modular Conveyor System

While all the systems discussed above are examples of "closed" modular systems, Figure 9.32 shows the modules and a specimen plan of an "open" modular system. The fixed modules are shown under *a* and a sample combination under *b*.

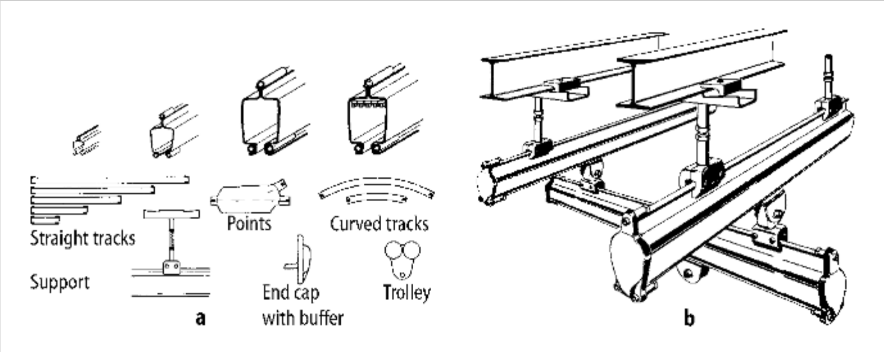

Figure 9.32. Open modular system for conveyors (Demag, Duisburg), **a** fixed modules **b** sample combination

9.3 Recent Rationalisation Approaches

9.3.1 Modularisation and Product Architecture

According VDI Guideline 2221 (see Section 1.2.3) after identifying the principle solution it has to be divided into modules. This results in a construction structure (see Figure 2.13), often referred to as a *product architecture* [9.44].

The product architecture is a scheme showing the relationship between the function structure of a product and its physical configuration. The particular importance of the product architecture is described by Ulrich [9.44]. According to Göpfer [9.45] the development of a product architecture is an essential task of product development and involves the transformation of a functional description of a product into a physical one. The relationships between these two descriptions characterise the product architecture, see Figure 9.33.

A product architecture can be used to describe the modularity of a product, which can be classified according the functional and physical independence of its components. A component is functionally independent if it fulfils exactly one

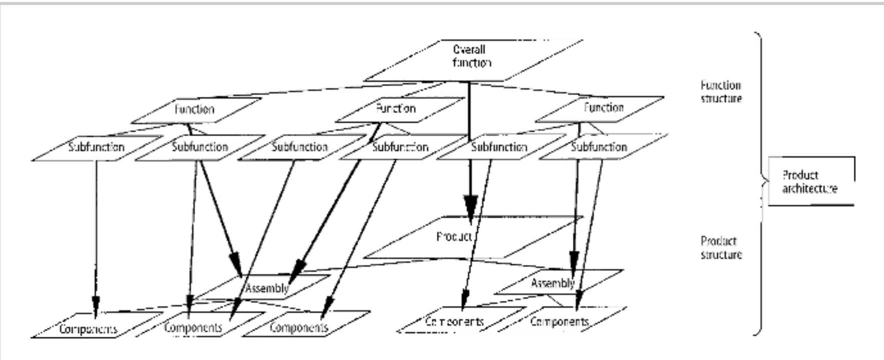

Figure 9.33. Product architecture [9.45]

subfunction. There is therefore and unambiguous relationship between function and component. In terms of product modularisation, a component is physically independent when it represents a coherent unit before the product is assembled. This means, for example, that it can be tested independently of the rest of the product. The objective of product modularisation is not the maximisation of modularity, which would mean an unnecessary increase of interfaces, but optimising the opportunities to meet different objectives.

Based on the previous descriptions, the terms related to product modularisation can be defined as follows:

Modularity is the degree of purposeful structuring of the product architecture.

Modularisation is the purposeful structuring of a product in order to increase its modularity. The aim is to optimise an existing product architecture to meet product requirements [9.46] or to rationalise production processes.

Modules are units that can be described functionally and physically and are essentially independent [9.46].

9.3.2 Platform Construction

The concept of platform construction comes from the automotive industry [9.47]. Platform construction is an approach for developing variant-rich products with short cycle times. It utilises the rationalisation potential of identical structures and components in a planned manner [9.48, 9.49]. A platform product consists of a basic variant-neutral product platform and product-specific additions (design elements) [9.48]. The product platform is determined from a functional perspective and is the lowest common denominator of a product series. A characteristic of platform construction is that the similarity between the products sharing a common product platform cannot easily be recognised from the appearance of the products [9.50].

Platform construction and modular construction are not identical. This is essentially because, unlike modular construction, the product variants based on a platform construction are not principally configured out of predefined modules.