11 Design for Minimum Cost

11.1 Cost Factors

It is important to identify cost factors as early and as accurately as possible in the design process. This is true for all types of design, including the development of size ranges and modular products. It is well known that the majority of costs have been committed when the principle solution has been selected and its embodiment completed. During the production and assembly stages there are relatively few opportunities to reduce costs. It is important, therefore, to start cost optimisation as early as possible since any design changes that have to be made during production are usually very costly. This might prolong the design process, but overall it is more economical than a retrospective drive to reduce costs [11.17].

In some of the examples in this chapter values for currency are given in Monetary Units (MU), with 1 MU approximately equivalent to 0.5 Euro.

The *overall cost* of producing a product can be divided into direct costs and indirect costs (overheads). *Direct costs* are those costs that can be allocated directly to a specific cost carrier, for example material and labour costs for producing a specific component [11.6]. *Indirect costs* are those costs that cannot be allocated directly, for example the costs of running the stores and illuminating the workshop.

Some costs depend on the number of items ordered, the degree of facility utilisation or the batch size. Material costs, production labour costs and consumable materials costs, for example, increase with higher turnover. In a cost calculation these are *variable costs*. *Fixed costs* are those that are incurred in a certain period and do not change, for example, management salaries, rent of space and interest on borrowings.

The *manufacturing cost* (see Figure 11.1) is the total of the costs for material and production including additional costs such as for production tooling and fixtures, and for design, development, models and tests as far as they relate to a specific product. Manufacturing cost therefore consists of fixed and variable costs. For decision making during the design process, however, only variable costs are of interest [11.35]. This is because they are influenced directly by designers, for example, by the choice of material types, production times, batch sizes, production processes and assembly methods. Of interest, therefore, are the variable manufacturing costs which comprise direct costs and indirect costs (overheads).

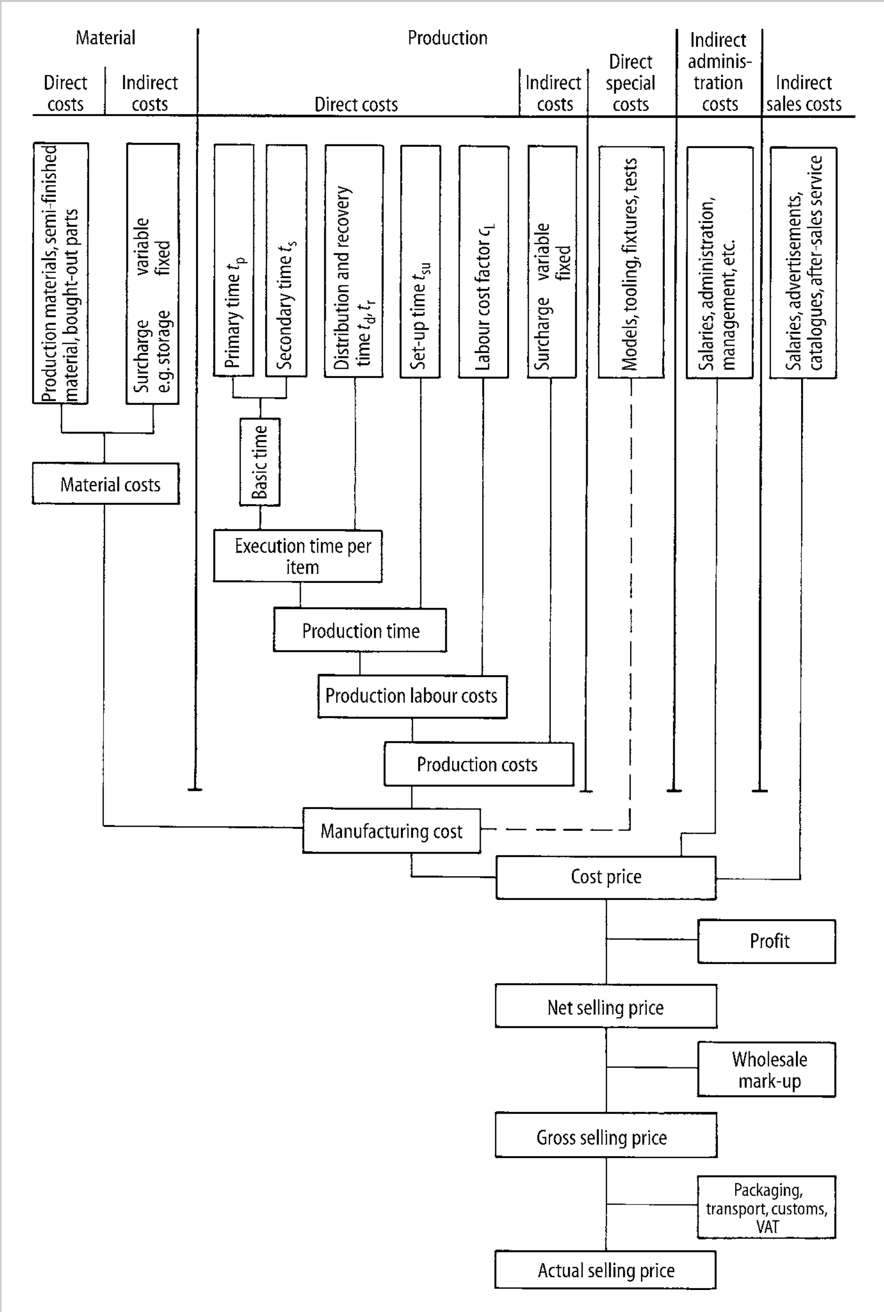

Figure 11.1. Cost sources and cost structure

Variable and fixed indirect costs are taken into account differently in different companies. Usually they are combined with the direct costs by using multiplication factors, such as a factor of 1.05 to 1.3 for indirect material costs, a factor 1.5 to 10 (or higher) for indirect production labour costs; and also by additions based on machine utilisation. The choice depends on the production processes and types of machine tool. When the factors are high or when machine utilisation is considered, it is useful to check whether it is possible, at least in theory, to reduce costs by using another production process. This avoidance strategy, however, increases the specific multiplication factors if the organisational structure does not change. This suggests a modification to the factory planning to take into account the modified product and production structure.

Concluding from what has been said, variable overheads are usually taken into account through multiplication factors on the direct costs and in this way they influence the manufacturing cost. In general designers can limit themselves to calculating variable direct costs when comparing the costs of solution variants.

At an early stage it is important to make rough cost estimates rather than detailed calculations, which should only be undertaken when really necessary. New methods to identify costs early in the design process will be discussed in the following sections.

11.2 Fundamentals of Cost Calculations

In Section 11.1 the *variable part* of the manufacturing cost ($VMfC$) was recommended as a basis for decision making. It comprises direct material costs ($DMtC$) and production labour costs (PLC), including assembly costs. All costs for production and assembly operations have to be added:

$$VMfC = DMtC + \sum PLC \tag{1}$$

The *direct material costs* are determined by the weight W or volume V and the specific cost c, that is cost per unit weight or volume, as follows:

$$DMtC = c_W \cdot W = c_V \cdot V \tag{2}$$

The *direct production costs* can be calculated from the times needed for the individual production processes and assembly operations multiplied by a labour cost factor c_L (see Figure 11.1). The production time is based on the primary time t_p, secondary time t_s and set-up time t_{su}, as well as distribution and recovery time. The last two times are generally taken into account as a constant factor on the basic time t_b, which is the sum of primary and secondary times and results in a time per unit. For the calculation of costs, therefore, primary, secondary and set-up times are important. Using the labour cost factor, the following simplified equation for a particular production operation can be used:

$$PLC = c_L(t_p + t_s + t_{su}) \tag{3}$$

For a more precise calculation, taking into account variable production overheads, see [11.21, 11.22, 11.36, 11.37].

We have indicated that the *manufacturing cost* is the sum of direct and indirect costs. Direct costs are usually linked to the type of product, for example the primary time for turning [11.31] which can be calculated from:

$$t_{\mathrm{p}} = \frac{D \cdot \pi \cdot L \cdot i}{v_{\mathrm{c}} \cdot f \cdot 1\,000} \text{ minutes} \tag{4}$$

with:

D = diameter in mm
L = length in mm
i = number of cuts
v_{c} = cutting speed in m/min
f = feed in mm/revolution.

The individual cost terms, for example turning cost (Equation (4)), can thus be represented by exponential functions consisting of variables x with exponents p and constants K. The generic form of a cost equation, e.g. manufacturing cost, would be as follows:

$$VMfC = \sum_{i=1}^{n} K_{\mathrm{i}} \cdot \prod_{j=1}^{m} x_{\mathrm{ij}}^{p_{\mathrm{ij}}} \tag{5}$$

with m equal to the number of variables x_{j} in cost term i and with n equal to the number of cost terms. In the case of three influencing variables, this results in:

$$VMfC = \sum_{i=1}^{n} K_{\mathrm{i}} \left(x_{\mathrm{i1}}^{p_{\mathrm{i1}}}\right) \cdot \left(x_{\mathrm{i2}}^{p_{\mathrm{i2}}}\right) \cdot \left(x_{\mathrm{i3}}^{p_{\mathrm{i3}}}\right) \tag{6}$$

The variable direct costs of the manufacturing cost for a turned component, for example, comprise the direct material costs and the turning costs. For t_{P} Equation (4) is used:

$$VMfC = \frac{\pi}{4} D^2 \cdot L \cdot c_{\mathrm{V}} + \left(\frac{D \cdot \pi \cdot L \cdot i}{v_{\mathrm{c}} \cdot f \cdot 1\,000} + t_{\mathrm{s}} + t_{\mathrm{su}}\right) c_{\mathrm{L}} \tag{7}$$

in which the following approximations are made:

$D \approx D_{\mathrm{raw}}$ (Diameter of raw material)
$L \approx L_{\mathrm{raw}}$ (Length of raw material).

The variable terms of the manufacturing cost considered here can thus be represented as power series of different orders. When adding up several production operations, an equivalent number of cost terms in the power series is created using Equations (1) and (5) as appropriate.

For *cost estimations* based on quick or all-inclusive calculations, it is too much effort to determine the direct costs strictly according to their individual dependencies. A better way is to define *relative costs* that are more generic and have long-term validity (see Section 11.3.1). It is also possible to estimate costs based on the *share of the material costs* (see Section 11.3.2). This method is only valid when comparing items (components, assemblies) of similar size. Recently cost profiles in several companies have been analysed statistically. Using *regression analysis*, researchers have attempted to correlate variable costs and influencing factors (see Section 11.3.3).

To determine the regression function, a power series is selected whose exponents and coefficients are determined in such a way that the resulting equation deviates as little as possible from the findings. The selected exponents and coefficients generally do not represent the real dependencies, but only mathematical relations. In [11.25] it is shown that very different regression functions can provide good approximations for the same set of circumstances.

In cases where one influence dominates and this has been identified and introduced into the regression function by selecting the relevant variables, it is likely that this influence represents physical reality. When it is possible to relate back all cost factors to only one characteristic variable x, for example diameter or weight, the cost function can be reduced to a simple equation of the following form:

$$VMfC = a + bx^p \quad (8)$$

For an example see Section 11.3.3.

Extrapolation using *similarity relationships*, on the other hand, is based on the physical relationships involved in the particular technology and uses power series with the appropriate exponents taken from the equations for material costs, primary times, secondary times and times per item. The coefficients of the cost terms are derived from company-specific data using a reference item (basic design or operation element) (see Section 11.3.4). The reason for developing this procedure was to make designers more aware of existing dependencies so that they can make more goal-directed decisions. The application of similarity relationships requires the availability of a sufficiently similar item, e.g. part, assembly or production operation.

In the case of *geometric similarity* (see Section 9.1.4), very simple cost-growth laws with polynomials of maximum order 3 can be set up based on a geometric reference length. For *semi-similar variants* (see Section 9.1.5) (most geometric magnitudes remain constant, but some deviate from geometric similarity) the cost-growth laws consist of many terms comprising all geometric and material variables that are involved. They have the form of power series with functions that can have fractional exponents. They are often called differential cost-growth laws. They achieve relatively high precision and only require a reasonable effort to apply.

Much effort is currently going into the identification of costs at an early stage through making available such methods in combination with computer support, including CAD and Knowledge-Based Systems [11.10].

In the following sections, the different methods are explained in more detail. Which method should be used depends on the available time, required precision and the available data.

11.3 Methods for Estimating Costs

11.3.1 Comparing with Relative Costs

In this method prices or costs are related to a reference value. For this reason, the results are valid for much longer than when absolute costs are used. In [11.7] principles are described for creating relative cost catalogues. Catalogues for materials, semi-finished materials, and bought-out parts are common. The *relative material costs* c^* are usually based on a standard size of channel-section steel (USt 37-2) and can be calculated from the following equation, which uses the specific material costs c^*_{W} or c^*_{V} derived from weight and volume respectively:

$$c^*_{\mathrm{W,V}} = \frac{c_{\mathrm{W,V}}}{c_{\mathrm{W,V}}(\text{reference value})}$$

It has to be noted that the resulting value is magnitude dependent. VDI Guideline 2225 Part 2 [11.34] therefore gives values for small, medium and large dimensions of all common materials. Material utilisation depends on the goals to be achieved. When strength requirements dominate, a different material has to be selected than when stiffness requirements dominate.

Figure 11.2 lists the relative material costs c^* for some materials with medium dimensions including the relation with tensile strength σ_{T} (strength requirement) and with Young's modulus E (stiffness requirement). The cost relation for machining based on [11.28] is also listed. This shows, for example, that in the case of tempered steels and case hardened steels strength increases generally faster than the material cost. This indicates the economic advantages of using these materials. For stressed shapes that have to be stiff, grey cast irons and plastics are substantially more expensive than steel. However the relations listed in Figure 11.2 change substantially in favour of cast or plastic parts when the shapes are complex and when there are additional corrosion resistance or surface finish requirements. In the case of highly alloyed materials, for example, obtaining a good surface finish can require very expensive machining.

Of particular interest are casting costs. In principle the overall cost is based on total weight, but the weight per item, number to be produced and item complexity play a role. Our own investigation [11.25] for steel castings resulted in the relationships shown in Figure 11.3. This figure shows that for steel castings specific cost reduces with increasing item weight, that is $\varphi_{\mathrm{c}} = \varphi_{\mathrm{W}}^{-0.12}$, so that the material costs increase by $\varphi_{\mathrm{M}} = \varphi_{\mathrm{W}}^{0.9}$, and not by $\varphi_{\mathrm{M}} = \varphi_{\mathrm{W}}^{1}$ (see cost-growth laws in Section 11.3.4).

For *semi-finished materials*, Figure 11.4 shows that shape has little influence on specific price provided they are produced by rolling. Drawn materials are considerably more expensive (factor ≈ 1.6). Closed sections cost about twice as much for the same weight. Figure 11.4 also shows the material utilisation advantages of particular sections when subjected to bending moments. For carrying bending moments, the required sectional area, that is weight per unit length, of some sections is considerably smaller and therefore cheaper.

The relative costs of *bought-out parts* vary strongly with size (see also cost-growth laws in Section 11.3.4). Rieg [11.27] developed a procedure for determining and representing these costs. Figure 11.5 gives an example of such a relative cost diagram for rolling element bearings. A particular deep groove ball bearing from series 60 with $d = 50$ mm is used as a reference ($\varphi_{\mathrm{d}} = 1$). The price of this bearing was 24.8 MU ($\varphi_{\mathrm{P}} = 1$). The current price for a deep groove ball bearing 6007 with $d = 35$ mm is 18.33 MU. To find the price for bearing 6036 with $d = 180$ mm the procedure is as follows:

	Name No	Density ρ g/cm³	Young's modulus E N/mm²	Yield strength σ_Y N/mm²	Tensile strength σ_T N/mm²	Strain to failure σ_F %	E/E_{St37}	σ_T/σ_{St37}	C^*_W	C^*_V	$\frac{C^*_W}{\sigma_T/\sigma_{TSt37}}$ 7	$\frac{C^*_W}{E/E_{St37}}$	Relative costs for machining
General construction steels DIN 17100	USt37-2 1.0112	7.85	$2.15 \cdot 10^5$	215...235	360...440	25	1	1	1	1	1 - 0,82	1	1
	St50-2 1.0532	7.85	$2.15 \cdot 10^5$	275...295	490..590	20	1	1.36...1.64	1.1	1.1	0.81 - 0.67	1.1	1
Cold drawn DIN 1652	St37-2K+G 1.0161	7.85	$2.15 \cdot 10^5$	195...215	330...440	25	1	0.92...1.22	1.6	1.6	1.75 - 1.31	1.6	1
Machining steels DIN 1651	10S20K+N 1.0721	7.85	$2.10 \cdot 10^5$	195..225	340...350	25	0.98	0.94...0.97	1.9	1.9	2.01 - 1.95	1.94	0.73
	9SMn28K+N 1.0715	7.85	$2.10 \cdot 10^5$	205...235	350...370	23	0.98	0.97...1.03	1.8	1.8	1.85 - 1.75	1.89	
	45S20K+N 1.0727	7.85	$2.10 \cdot 10^5$	305...335	570...700	14	0.98	1.58...1.94	2	2	1.26 - 1.03	2.05	
Tempering steels DIN 17200	Ck35V 1.1181	7.85	$2.15 \cdot 10^5$	295...420	490...770	22...17	1	1.36...2.14	1.6	1.6	1.18 - 0.75	1.6	0.91
	Ck45V 1.1191	7.85	$2.15 \cdot 10^5$	380	630...780	17	1	1.75...2.17	1.78	1.78	1.02 - 0.82	1.78	1.05
	34Cr4V 1.7033	7.85	$2.15 \cdot 10^5$	470	700...850	15	1	1.94...2.36	2.13	2.13	1.1 - 0.9	2.13	1.43
	42CrMo4V 1.7225	7.85	$2.15 \cdot 10^5$	650	900...1100	12	1	2.30...3.05	2.24	2.24	0.9 - 0.73	2.24	1.73
	50CrV4V 1.8159	7.85	$2.15 \cdot 10^5$	700	900...1100	12	1	2.50...3.05	2.25	2.25	0.9 - 0.74	2.25	2.09
	C35K+N 1.0501	7.85	$2.15 \cdot 10^5$	275	490...590	22	1	1.36...1.64	1.7	1.7	1.25 - 1.04	1.7	
	Ck35K+V	7.85	$2.15 \cdot 10^5$	325...410	540...790	20...16	1	1.50...2.19	1.85	1.85	1.23 - 0.84	1.85	

Figure 11.2. Characteristic values and relative material costs c^* for some materiels (Reference Ust 37.2 with $\sigma_T = 360$ N/mm²)

Case hardening steels DIN 17210	C15 1.0401	7.85	$2.15 \cdot 10^5$	355...440	590...890	14...12	1	1.64...2.47	1.1	1.1	0.67 - 0.45	1.1	0.86
	Ck15 1.1141	7.85	$2.15 \cdot 10^5$	355...440	590...890	14...12	1	1.64...2.47	1.4	1.4	0.85 - 0.57	1.4	
	16MnCr5G 1.7131	7.85	$2.15 \cdot 10^5$	440...635	640...1190	11...9	1	1.78...3.30	1.7	1.7	0.96 - 0.51	1.7	1.14
Nitriding steels DIN 17211	34CrAlNi7V 1.8550	7.85	$2.15 \cdot 10^5$	590	780...980	13	1	2.17...2.72	2.6	2.6	1.2 - 0.95	2.6	2.0
	41CrAlMo7V 1.8509	7.85	$2.15 \cdot 10^5$	635...735	830...1130	14...12	1	2.30...3.14	2.6	2.6	1.13 - 0.83	2.6	
	31CrMoV9 1.8519	7.85	$2.15 \cdot 10^5$	700	900..1050	13	1	2.50...2.92					2.0
Stainless steels DIN 17440	X20Cr13 1.4021	7.70	$2.10 \cdot 10^5$	440...540	640...940	18...8	0.99	1.78...2.61	3.14	3.2	1.8 - 1.2	3.21	1.25
	X12CrNi188 1.4300	7.80	$2.03 \cdot 10^5$	220	500...700	50	0.94	1.39...1.94	8.45	8.4	6.08 - 4.35	8.95	
Casting materials without cores and recesses	GG - 25 0.6025	7.35	$1.30 \cdot 10^5$		250		0.60	0.69	2.0	1.2	2.88	3.3	1.24
	GS - 45 1.0443	7.85	$2.15 \cdot 10^5$	225	445...590	22	1	1.24...1.64	1.8	1.8	1.46 - 1.1	1.8	1.45
Non-ferrous metals	AlMg3F23 3.3535.26	2.66	$0.70 \cdot 10^5$	140	230	9	0.33	0.64	10.0	3.4	15.65	30.7	0.36
Light metals	AlMg5F26 3.3555.26	2.64	$0.72 \cdot 10^5$	150	250	8	0.33	0.69	11.6	3.9	16.70	34.6	
	AlMgSi1F32 3.2315.72	2.70	$0.7 \cdot 10^5$	250	310	10	0.33	0.86	8.72	3.0	10.13	26.8	0.51
Non-metals	Woven laminate Hgw 2088	1.25	$7 \cdot 10^3$		50		0.033	0.14	62.8	10	452.2	1928	(0.4)
	Glass fibre reinforced polyester HM 2472	1.60	$10 \cdot 10^3$		100		0.046	0.28					(0.71)
	Nylon 66 PA 66	1.14	$2 \cdot 10^3$		65		0.009	0.18	22.72	3.3	125.8	2442	(0.27)

Figure 11.2. (continued)

$$d = 35\ \text{mm} \quad \varphi_d = 35/50 = 0.7 \quad \text{from Figure 11.5: } \varphi_{P_{6007}} = 0.61$$
$$d = 180\ \text{mm} \quad \varphi_d = 180/50 = 3.6 \quad \text{from Figure 11.5: } \varphi_{P_{6036}} = 28$$
$$P_{6036} = P_{6007} \quad (\varphi_{P_{6036}}/\varphi_{P_{6007}}) = 18.33(28/0.61) = 841\ \text{MU}$$

Diagrams for screws, circlips, connectors and valves are given in [11.26, 11.27]. Figure 11.6 shows a cost comparison for different threaded connectors based on [11.5]. As described in Sections 11.3.4 and 11.3.5, the cost relations can vary with size and this can be seen in Figure 11.6.

Relative cost data has to be applied with caution, taking into account all the relevant circumstances [11.1]. When comparing and selecting items, not only must the cost relations be assessed but also the required functions, the application conditions and the space requirements. Extrapolations are generally are not allowed. It is not sufficient simply to compare the costs of items without considering their effect on the rest of the design.

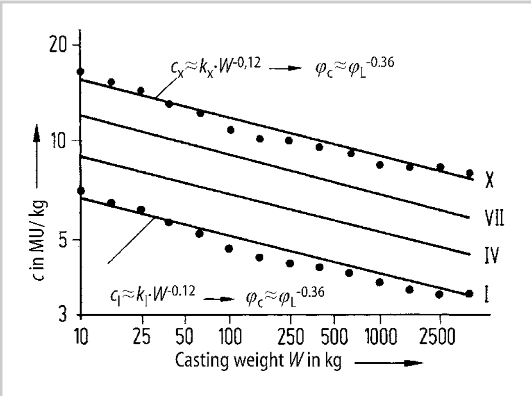

Figure 11.3. Costs for steel castings depending on weight per casting and level of complexity, after [11.27]. Level I: Solid castings without cores and recesses; Level IV: Solid castings with simple cores and recesses; Level VII: Hollow castings (cored) with simple webs and recesses; Level X: Hollow castings (cored) with complex cores

Section	Round 100 DIN 1013	Square 85 DIN 1014	L160 × 17 DIN 1028	Pipe 159×5.6 DIN 2448	U 160 DIN 1026	I 160 DIN 1025
H/*A* in mm	12.5	14.1	20.8	37	48.3	54
I/*A* in mm²	625	601	2374	2944	3854	4323
c_w^* rolled	1	1.02	1.06	1.6 - 2.1	1	1
c_w^* drawn	1.6	1.6		2.8		

Figure 11.4. Specific material costs c_w^* for semi-finished materials. The reference first moment of area is $H \approx 10^5$ mm³ (the first moment of area of round 100 and of square 85). H/A: ratio of first moment of area/section area. I/A: ratio of second moment of area/section area

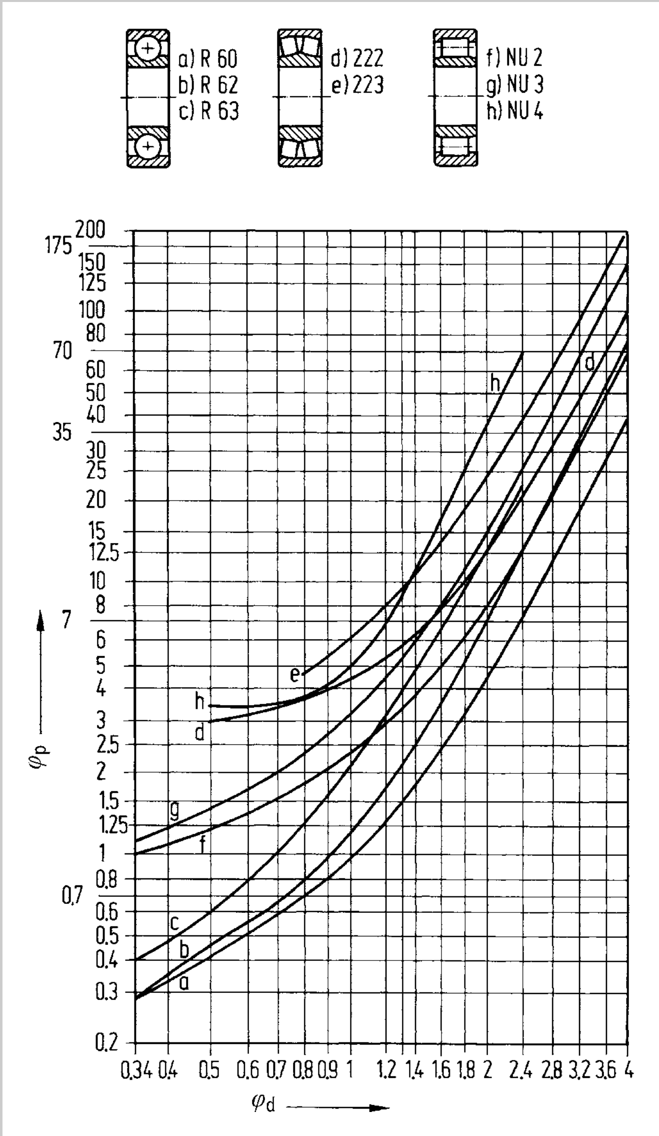

Figure 11.5. Relative costs for rolling element bearings, after [11.27]. Reference: a deep groove ball bearing from series 60 with $d = 50$ mm ($\varphi_d = 1$) and $P = 24.80$ MU ($\varphi_P = 1$)

11.3.2 Estimating Using Share of Material Costs

If in a particular application area the ratio *m* of material costs *MtC* to the manufacturing cost *MfC* is known and almost identical, it is possible to estimate the manufacturing cost after determining the material costs, $MfC = MtC/m$. This procedure is described in VDI Guideline 2225 [11.33]. The procedure cannot be used,

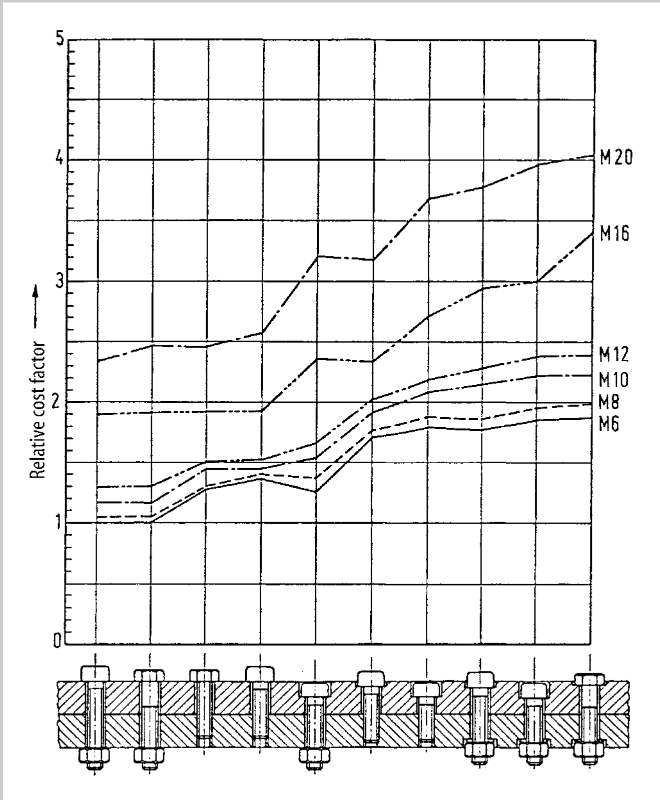

Figure 11.6. Relative cost factors for threaded connections using cap screws and hexagonal bolts, M6 to M20, class 8.8, after [11.5, 11.6]

however, when the cost structure changes, in particular with large size changes (see cost estimation using similarity relations in Section 11.3.4 and cost structures in Section 11.3.5).

11.3.3 Estimating Using Regression Analysis

Based on a statistical analysis of data, the relation between costs or prices and the characteristic parameters (output, weight, diameter, shaft height, etc.) are determined. The results can be presented graphically for each of these parameters. Regression analysis is used to find a relation that determines the regression equation using regression coefficients and exponents. Using this equation the costs can be calculated within certain limits. The effort needed to set up the equation can be considerable and usually involves computer support. The regression equation should be built up in such a way that parameters that may change, such as hourly labour rates, are represented as individual terms, or in the form of relative costs, so that they can be updated easily.

An example is the regression equation of Pacyna [11.23] for the cost of hand-moulded grey iron castings:

$$C = 7.1479 \cdot B^{-0.0782} \cdot V^{0.8179} \cdot D^{-0.1124} \cdot T^{0.1655} \cdot P^{0.1786} \cdot N^{0.0387} \cdot \sigma_{\mathrm{T}}^{0.2301} \cdot F^{1.0000}$$

in MU per unit, with:

C = *DMtC*, direct material costs of the cast item
B = batch size
V = material volume in litres
D = dimension ratio (see Figure 11.7)
T = wall thickness ratio (see Figure 11.7)
P = packing ratio (see Figure 11.7)
N = number or cores (without cores = 0.5)
σ_{T} = tensile strength in N/mm^2
F = factor of difficulty (normal = 1, main range 0.9 to 1.4).

This equation might need updating. Further guidelines for this procedure and examples of regression calculations can be found in [11.11–11.13] and in VDI Guideline 2235 [11.35].

Regression analyses can also be used to set up more easily maintainable *cost functions* by introducing simplifications and similarity considerations (see Section 11.3.4). The following example from Klasmeier [11.18] shows the calculation

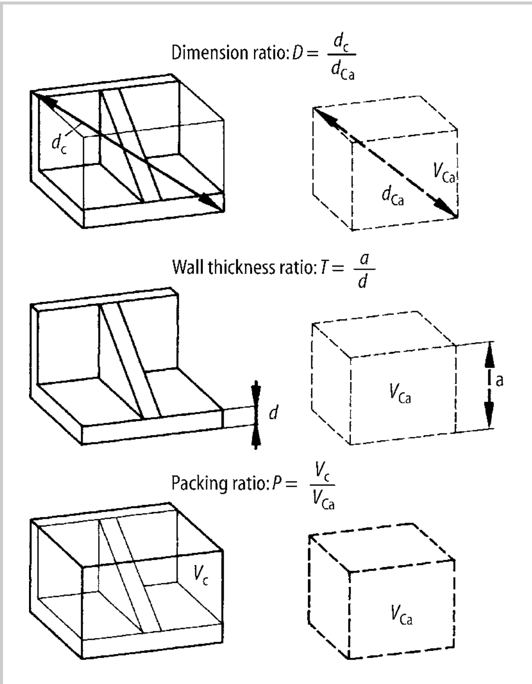

Figure 11.7. Shape characteristics for casting [11.23]. The reference shape is a cube with casting volume V_{Ca}

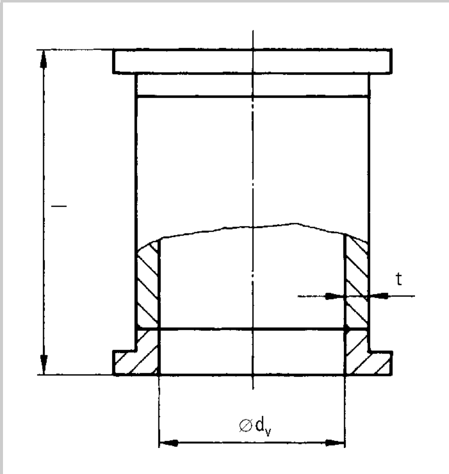

Figure 11.8. Geometric parameters of a pressure vessel for a high-voltage switch. Inner diameter of the vessel d_v. Length of the vessel l. Wall thickness of the vessel t. Nominal pressure NP

of the costs for a pressure vessel for a high-voltage switch. The influencing parameters on the variable costs are shown in Figure 11.8.

The regression equation for welded pressure vessels is:

$$VMfC = a + b \cdot d_v^{1.42} \cdot NP^{0.94} \cdot l^{0.21} \cdot t^{0.17}$$

The factors a and b cannot be given because they are commercially sensitive.

We will now derive a specific simple cost function. Based on electro-technical laws: Voltage V is proportional to the distance between electrodes e, which in turn is proportional to the inner vessel diameter d_v, thus

$$V \propto e = k_1 \cdot d_v$$

Where k_1 takes into account the conductor dimensions and the safety distance with constant gas pressure and constant temperature.

For thin-walled vessels, such as the one discussed here, the standard thin-walled formula can be applied. Because the calculated wall thickness based on the required strength remains below the prescribed minimum wall thickness, we can take $t = t_{min}$ = constant. We can also take l = constant, because the allowable voltage is independent of the vessel length. In this way we can base the cost function simply on the variable parameter voltage:

$$VMfC = a_1 + b_1 \cdot V^{1.42}$$

11.3.4 Extrapolating Using Similarity Relations

1. Basic Design as Reference

When geometrically similar or semi-similar components are available in a size range or as variants of known components, it is useful to determine the cost-growth laws using similarity relations [11.27]. The step size of the variable manufacturing cost φ_{VMfC} is equal to the ratio of the variable cost of the *sequential design* $VMfC_{\mathrm{s}}$ (cost to be calculated) to the variable cost of the *basic design* $VMfC_0$ (known cost) and is calculated using a similarity analysis (see Section 9.1.1):

$$\varphi_{\mathrm{VMfC}} = \frac{VMfC_{\mathrm{s}}}{VMfC_0} = \frac{DMtC_{\mathrm{s}} + \sum PLC_{\mathrm{s}}}{DMtC_0 + \sum PLC_0}$$

The basic design (Index 0) is selected such that it can represent the largest possible size range. When the size of this design places it roughly in the centre of the range, the extrapolation errors are minimised. For the extrapolation to be valid, the sequential design should have sufficient similarity to the basic design in terms of production facilities, production processes etc.

The ratio of direct material costs to the manufacturing cost, and the ratio of the individual production costs or times (for example drilling, turning, grinding, etc.) to the manufacturing cost are calculated for the basic design and result in the following:

$$a_{\mathrm{m}} = \frac{DMtC_0}{VMfC_0}\,; \quad a_{\mathrm{P_k}} = \frac{PLC_{\mathrm{k}0}}{VMfC_0} \quad \text{for the } k\text{-th production operation}\,.$$

The ratios defined in this way are part of the variable manufacturing costs and represent the cost structure of the basic design (see Section 11.3.5).

When the cost-growth laws of the individual terms are known, the overall cost-growth law is:

$$\varphi_{\mathrm{VMfC}} = a_{\mathrm{m}} \cdot \varphi_{\mathrm{DMtC}} + \sum_k a_{\mathrm{P_k}} \cdot \varphi_{\mathrm{PLC_k}}$$

When the length is the dependent characteristic parameter, this can be written generically as follows:

$$\varphi_{\mathrm{VMfC}} = \sum_i a_{\mathrm{i}} \cdot \varphi_{\mathrm{L}}^{x_{\mathrm{i}}}\,, \quad \varphi_{\mathrm{L}} = \frac{L_{\mathrm{s}}}{L_0} \quad \text{(see Section 9.1.1) with} \sum_i a_{\mathrm{i}} = 1 \text{ and } a_{\mathrm{i}} \geq 0$$

This procedure is not company specific. The results can be made company specific through the introduction of coefficient a_{i} derived from the basic design. This also ensures the use of up-to-date knowledge.

Determining exponents x_{i} that depend on the appropriate dimensions (characteristic parameter length) is easy for *geometrically similar components*. According to [11.27] one can use integer exponents for making *quick estimates*. This results in the following polynomial:

$$\varphi_{\mathrm{VMfC}} = a_3 \cdot \varphi_{\mathrm{L}}^3 + a_2 \cdot \varphi_{\mathrm{L}}^2 + a_1 \cdot \varphi_{\mathrm{L}}^1 + \frac{a_0}{\varphi_{\mathrm{z}}} \quad \text{with} \quad \varphi_{\mathrm{z}} = \frac{z_{\mathrm{s}}}{z_0}$$

with z = batch size.

For material costs one can usually apply $\varphi_{\mathrm{DMtC}} = \varphi_{\mathrm{L}}^3$. For production operations Figure 11.9 can be used [11.26, 11.27].

Machine types	Processes	Exponents calculated	Exponents rounded	Accuracy
Universal lathe	External and internal turning Threading Parting Groove turning Chamfer turning	2 ≈1 ≈1.5 ≈1	2 1 1 1	+ + + + +
Vertical boring and turning mill	External and internal milling	2	2	+ +
Radial drill	Drilling Threading Counter sinking	≈1	1	0
Drilling and milling machine	Turning Drilling Milling	≈1	1	0
Groove milling machine	Key groove milling	≈1.2	1	+
Universal cylindrical grinding machine	Surface grinding	≈1.8	2	+ +
Disc saw	Sawing section	≈2	2	0
Guillotine shears	Cutting sheet metal	1.5...1.8	2	+
Plate bending machine	Bending sheet metal	≈1.25	1	+
Press	Straightening section	1.6...1.7	2	+
Chamfering machine	Chamfering sheets	1	1	+ +
Flame cutting machine	Cutting sheets	1.25	1	+ +
MIG arc and manual electric arc welding	I-welds V, X, fillet, corner welds	2 2.5	2 2	+ + + +
Annealing		3	3	+ +
Sand blasting (depending on using weight or surface in the calculation)		2 o. 3	2 o. 3	+ +
Assembling		1	1	+ +
Tacking before welding		1	1	+ +
Trimming or cleaning by hand		1	1	+ +
Enamelling or coating		2	2	+ +

Figure 11.9. Exponents for the time per item for various production operations for geometrically similar items, after [11.26, 11.27]; Legend: ++ accurate; + less accurate ++; 0 large deviations possible

The terms a_i are calculated from the basic design and assigned to the individual integer exponents. The cost-growth law for the example shown in Figures 11.10 and 11.11 with $\varphi_z = 1$ becomes:

$$\varphi_{\mathrm{VMfC}} = 0.49 \cdot \varphi_L^3 + 0.26 \cdot \varphi_L^2 + 0.20 \cdot \varphi_L + 0.05$$

A geometrically similar variant that is twice as large with $\varphi_L = 2$ would give a cost increase with step size $\varphi_{\mathrm{VMfC}} = 5.41$.

This procedure can also be used for a more *precise extrapolation* and for *semi-similar variants* as shown in the following example of a drive shaft (see Fig-

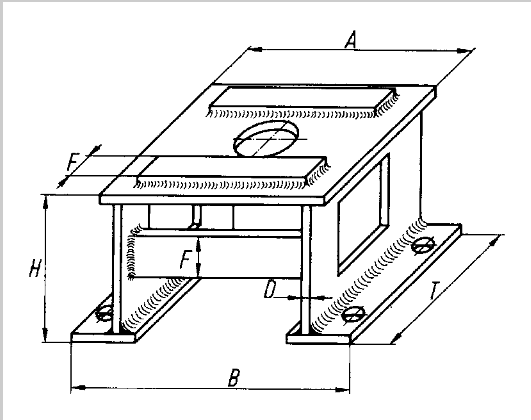

Figure 11.10. Basic design (welded) for geometrically similar series [11.27]

Operations		Costs increase with φ_L^3	Costs increase with φ_L^2	Costs increase with φ_L	Constant costs
material		800			
flame cutting	joining			60	15
chamfering	joining			35	
tacking	joining			105	
welding	joining		500		
annealing		80			
sand blasting		40			
marking out	machining			40	
horizontal boring	machining			100	70
radial drilling	machining			30	15
1890 MU $= C_0$		Σ_3 (=920)	Σ_2 (=500)	Σ_1 (370)	Σ_0 (100)
		Σ_3/C_0 $a_3=0.49$	Σ_2/C_0 $a_2=0.26$	Σ_1/C_0 $a_1=0.20$	Σ_0/C_0 $a_0=0.05$

Figure 11.11. Calculation scheme for determining cost contributions a_i to the basic design

ure 11.12). The product is a friction-welded shaft journal, with main dimensions *d* and *l*, with two drop-forged disc-shaped elements welded together to form a cylinder. The component is finally turned to size.

The characteristic parameters cylinder diameter *D* and length *B* can be selected independently. The shaft journal diameter *d* and the journal length *l* have to be chosen in proportion to the cylinder diameter *D*.

The relations between the times and each of the individual geometric parameters was based on an analysis of the primary and secondary times according to [11.24, 11.26, 11.27]. For turning, for example, the primary time is determined by the area of the surface to be turned, represented by the diameter and length of the component. The secondary time is constant for this size range. The welding costs, however, increase in relation to the seam thickness *t*, with $\varphi_t^{1.5}$, and linearly with the welding length *l*, that is with φ_l^1 [11.24]. The preparation cost for welding depends not only on the number of components but also on the square root of the weight which gives $\varphi_W^{0.5}$ or $\varphi_D \cdot \varphi_B^{0.5}$.

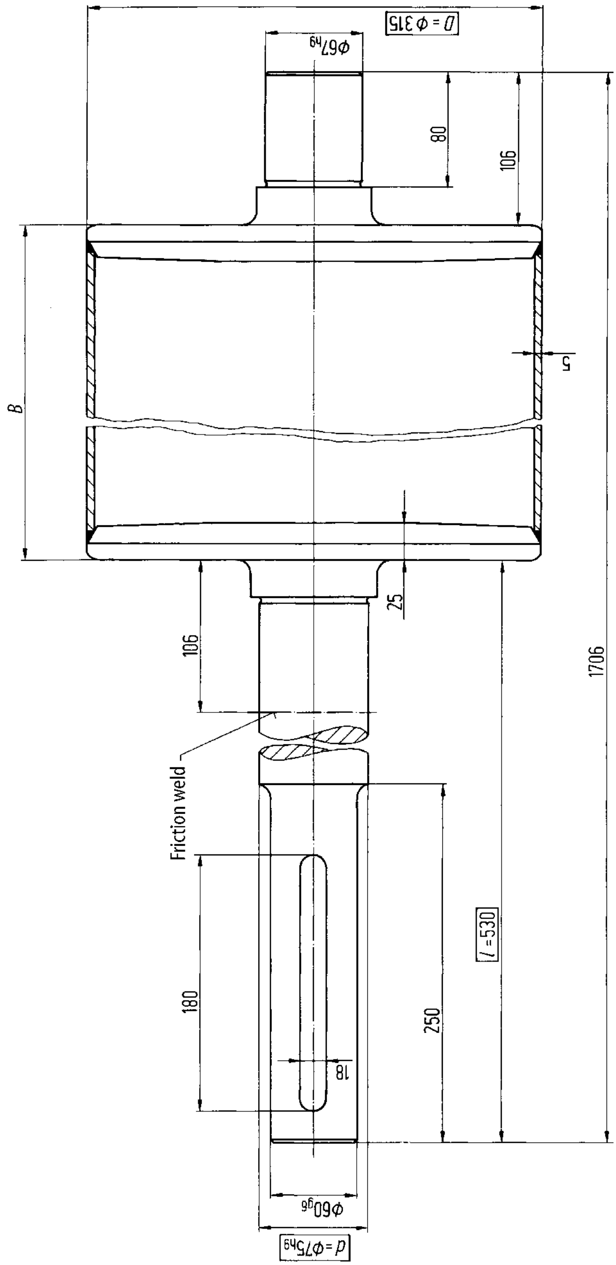

Figure 11.12. Drive shaft (basic design)

Materials, production operations	Cost contributions	Cost growth laws
Materials		
Cylinder	0.164	$\varphi_{cWC} \cdot \varphi_D^2 \cdot \varphi_B$
Disc and journal	0.222	$\varphi_{cWJ} \cdot \varphi_d^2 \cdot \varphi_l$
Constant part	0.070	
Production operations		
Preparing for welding	0.049	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B^{0.5}$
Welding	0.081	$\varphi_{cL} \cdot \varphi_D^{2.5}$
Trimming, cleaning	0.011	$\varphi_{cL} \cdot \varphi_D$
Turning, cylinder axial	0.054	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B$
Turning, journal axial	0.097	$\varphi_{cL} \cdot \varphi_d \cdot \varphi_l$
Turning, journal radial	0.038	$\varphi_{cL} \cdot \varphi_d^2$
Turning (constant)	0.114	φ_{cL}
Milling	0.016	$\varphi_{cL} \cdot \varphi_d \cdot \varphi_l$
Milling (constant)	0.021	φ_{cL}
Surface treating	0.021	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B$
Preparing for surface treatment	0.032	$\varphi_{cL} \cdot \varphi_D \cdot \varphi_B^{0.5}$
Cutting	0.001	$\varphi_{cL} \cdot \varphi_D$
Cutting (constant)	0.009	φ_{cL}
	1.000	

Figure 11.13. Cost contribution for the basic design of the drive shaft (see Figure 11.12); $D = 315$ mm, $B = 1000$ mm, φ_{cW} = step size of the specific material costs, φ_{cL} = Step size of the labour costs

Figure 11.13 lists the cost contributions of the individual operations for a basic design with $D = 315$ mm and $B = 1000$ mm.

When the terms that have the same relations and parameters are brought together, the general form of the differential growth law for our example becomes:

$$\begin{aligned}\varphi_{VMfC} &= 0.164 \cdot \varphi_{cWC} \cdot \varphi_D^2 \cdot \varphi_B + 0.222 \cdot \varphi_{cWJ} \cdot \varphi_d^2 \cdot \varphi_l + \varphi_{cL}(0.081 \cdot \varphi_D^{2.5} \\ &\quad + 0.075 \cdot \varphi_D \cdot \varphi_B + 0.113 \cdot \varphi_d \cdot \varphi_l + 0.038 \cdot \varphi_D^2 + 0.081 \cdot \varphi_D \cdot \varphi_B^{0.5} \\ &\quad + 0.012 \cdot \varphi_D + 0.144) + 0.07\end{aligned}$$

The diagram in Figure 11.14 for the total cost range of the available variants is based on the use of $\varphi_D = \varphi_B = \varphi_d = \varphi_l$ for geometric similarity of the cylinder dimensions, and the use of $\varphi_D = \varphi_d = \varphi_l$ = constant with φ_B being variable for semi-similar variants. The terms φ_{cL} and φ_{cWJ} are constant for all sizes, whereas φ_{cWC} increases with 1.25 when $D = 355$ mm because of a price supplement due to a smaller batch size.

The cost curve for the variable manufacturing costs for a component or assembly size range is, even when drawn using a double logarithmic scale, curved and not linear (see Figure 11.14). The reasons are that the direct costs always include constant parts, such as set-up costs for a specific batch size, and that some costs increase with high powers, such as material costs which increase with the third power of the characteristic parameter length.

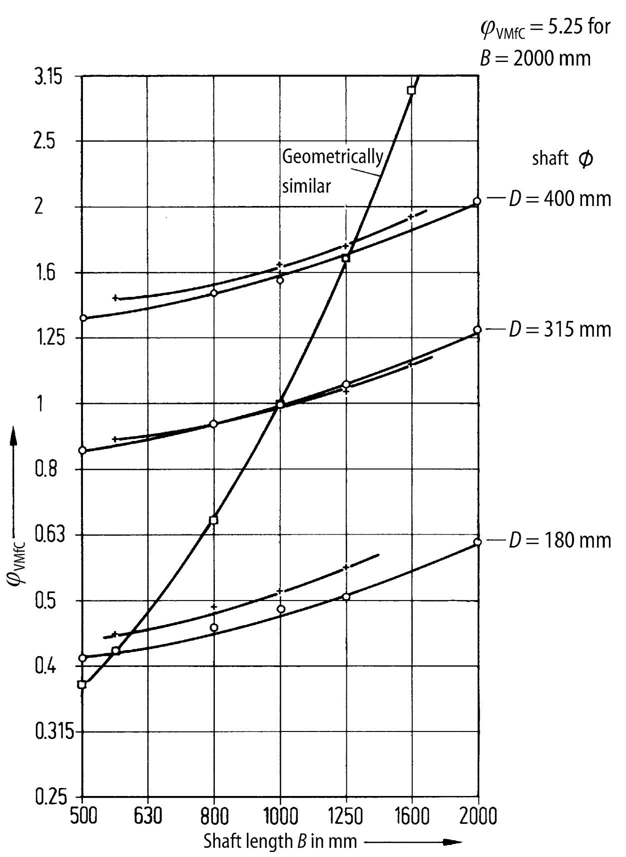

Figure 11.14. Relative manufacturing costs for geometically similar and semi-similar drive shafts as shown in Figure 11.12. Basic design $D = 315$ mm, $B = 1000$ mm. Curves indicated "+" are calculated in the conventional way

The comparison between a conventional calculation and an extrapolation using cost-growth laws shows that the latter gives a sufficiently precise estimate of the costs. The estimation of the manufacturing cost is quite accurate because the large number of individual terms balance out the errors. The error is, in general, smaller than ±10%. The individual operations, however, can have larger errors [11.16, 11.27]. Further examples can be found in [11.18, 11.24, 11.26, 11.27].

2. Operation Element as Reference

According Beelich [11.24] a so-called *operation element* representing a specific production process can be used instead of a basic design. The main idea is to define a normalised, relatively simple element that has be subjected to all the essential partial operations of the specific production operation, for example turning, grinding, welding, etc. The cost of a real component is extrapolated from this simple element. The normalisation involves setting all dimension-determining geometric parameters equal to 1 so that specific production times result. For the operation element, the required production times are determined from the specific technology involved.

The next step is to determine the cost-growth law of this operation element as described before, only now using the step size $\varphi_i = X_{iP}/X_{iO}$ (X_{iP} = parameter of the actual component or part, and X_{iO} = parameter of the operation element).

The use of operation elements is particularly advantageous when one main production operation is involved. On the other hand, operation elements for various different production operations allow extrapolation into complex components and assemblies.

For the production operation "manual electric arc welding" Beelich [11.24] describes the *generation of an operation element*. An analysis of this operation resulted in the following times for the various partial operations.

Times to combine, align and clamp parts into a welding assembly can be determined based on Ruckes [11.29] as follows:

$$t_{wr} = C_r \cdot \alpha \cdot \sqrt{W} \cdot \sqrt{x}$$

with: α = factor of difficulty (see Figure 11.15)
W = overall weight
x = number of parts.

The primary time for seam welding can be calculated from the time necessary to fill a specific seam volume with a specific volume of electrode as follows [11.24]:

$$t_{ws} = C_p \cdot t^{1.5} \cdot l$$

with:
t = seam thickness (= plate thickness for a V-weld)
l = seam length.

Type and shape of the seam		V-weld 60°	Fillet weld 90°
Type of construction	Shape of the part Length of the seam		
2D	Tank shape Long seam	1	2
3D	Plate, sheet metal Short seam	1.5	2.5
	Sections such as U, L Pipe	2	3
	Sections such as T, I	2.5	4

Figure 11.15. Factor of difficulty α for normal tolerances and basically right angles. (In case of higher precision and oblique angles, the factors have to be increased by 1 to 2 points.)

The secondary times for changing electrodes and initiating the welding sequence (t_{wci}), and for removing slag and cleaning the seam (t_{wrc}) relate to the number of electrodes n_e and the number of weld runs n. Both parameters can be linked and compared with the volumes and cross-sections of seams and electrodes [11.24]. Analyses also revealed the influence of the factor of difficulty α. It was considered useful to include this factor as a square root:

$$t_{wci} + t_{wrc} = C_s \cdot \sqrt{\alpha} \cdot t^{1.5} \cdot l$$

The material costs of the welding material can be calculated from the specific weld seam weight W_s^* and the specific cost factor c_W:

$$MC_w = W_s^* \cdot t^2 \cdot l \cdot c_W$$

This results in the following formula for the total production cost of welding in MUs:

$$PC_w = c_L \left[C_r \cdot \alpha \cdot \sqrt{W} \cdot \sqrt{x} + \left(C_p + C_s \cdot \sqrt{\alpha} \right) t^{1.5} \cdot l \right] + W_s^* \cdot t^2 \cdot l \cdot c_W$$

For the operation element "manual electric arc welding" (see Figure 11.16), the welding costs can be calculated with the following normalised data and company-specific production times:

$\alpha = 1$ $\quad c_L = 1$ MU/min (labour cost)

$W = 1$ kg $\quad c_W = 10$ MU/kg (specific material cost)

$$\left.\begin{array}{ll} x = 1 & C_r = 1\ \text{min/kg}^{0.5} \\ t = 1\ \text{mm} & C_p = 0.8\ \text{min/mm}^{1.5} \cdot \text{m} \\ l = 1\ \text{m} & C_s = 1.2\ \text{min/mm}^{1.5} \cdot \text{m} \end{array}\right\} \text{Specific production times}$$

$W_s^* = 0.0095\ \text{kg/mm}^2 \cdot \text{m}$

(W_s^* is the specific seam weight with a raised seam of $k_{rs} = 1.21$)

$PC_{w0} = 3.095$ MU

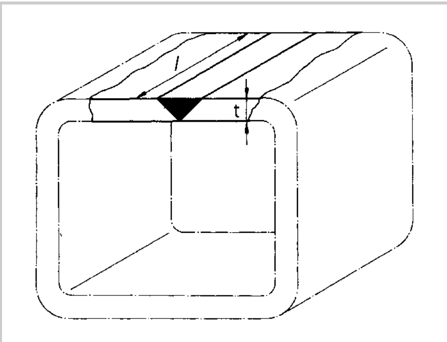

Figure 11.16. Operation element "manual electric arc welding"

With this information, the cost terms for operation element 0 can be calculated as follows:

$$a_r = \frac{PC_{wr0}}{PC_{w0}} = \frac{1}{3.095} = 0.32$$
$$a_{sp} = \frac{PC_{ws0}}{PC_{w0}} = \frac{0.8}{3.095} = 0.26$$
$$a_{ss} = \frac{PC_{wci0} + PC_{wrc0}}{PC_{w0}} = \frac{1.2}{3.095} = 0.39$$
$$a_m = \frac{MC_{w0}}{PC_{w0}} = \frac{0.095}{3.095} = 0.03$$

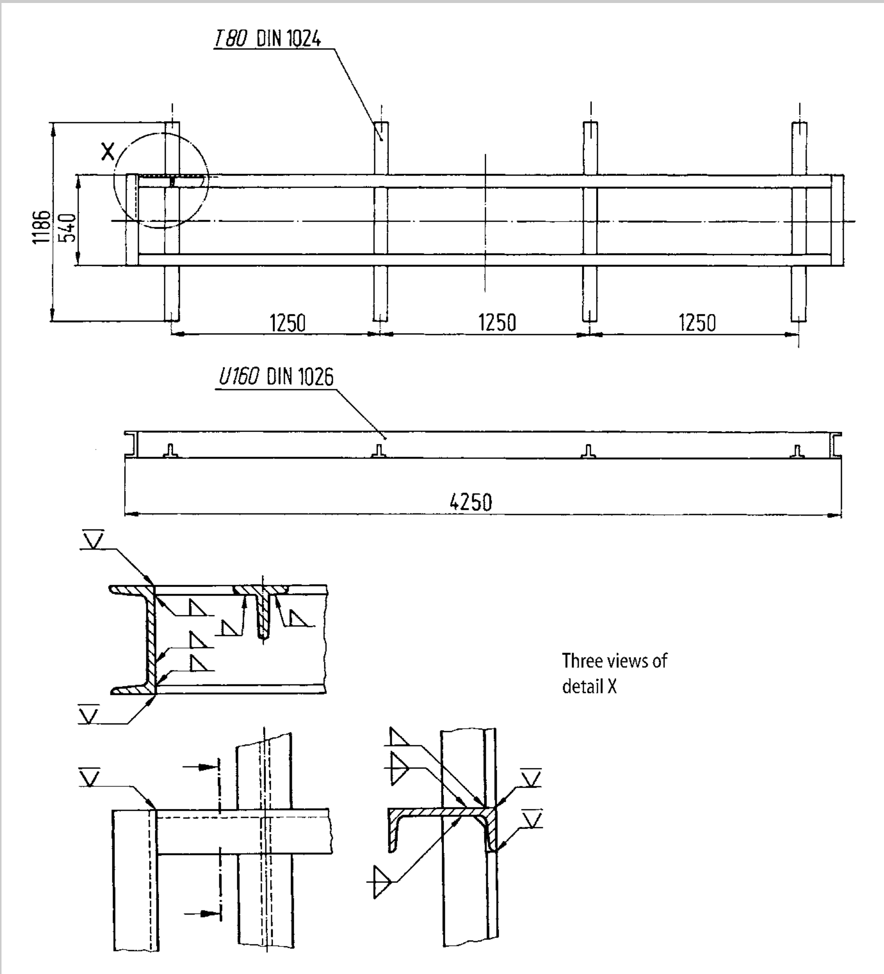

Figure 11.17. Assembly "welded frame"

The resulting cost-growth law for the operation element "manual electric arc welding" thus becomes:

$$\varphi_{\mathrm{PC_W}} = \varphi_{\mathrm{c_L}} (\underbrace{0.32 \cdot \varphi_\alpha \cdot \varphi_{\mathrm{W}}^{0.5} \cdot \varphi_{\mathrm{x}}^{0.5}}_{\substack{\text{preparing:}\\\text{combining}\\\text{aligning}\\\text{clamping}}} + (\underbrace{0.26}_{\substack{\text{welding:}\\\text{seam}\\\text{welding}}} + \underbrace{0.39 \cdot \varphi_\alpha^{0.5}}_{\substack{\text{changing electrodes,}\\\text{initiating welding}\\\text{sequence, removing}\\\text{slag}}}) \cdot \varphi_{\mathrm{t}}^{1.5} \cdot \varphi_{\mathrm{l}}) + \underbrace{0.03 \cdot \varphi_{\mathrm{t}}^{2} \cdot \varphi_{\mathrm{l}} \cdot \varphi_{\mathrm{c_W}}}_{\substack{\text{welding}\\\text{material}}}$$

With this formula the cost of components that have to be welded can be extrapolated using the relevant parameter values to determine step sizes φ.

As an example of how to use this operation element, the cost of the welded frame shown in Figure 11.17 has to be estimated. The welding costs can be calculated with the data for the assembly and the step sizes related to the operation element as shown in Figure 11.18. When the values are substituted into the above equation separately for V-welds and fillet welds, the step size is:

$$\varphi_{\mathrm{PC_W}} = 163.67 \quad \text{(see Figure 11.19)}$$

The manufacturing cost for the production operation "manual electric arc welding" thus becomes:

$$MfC = PC_{\mathrm{w0}} \cdot \varphi_{\mathrm{PC_W}} = 3.095 \cdot 163.67 = 506\,\mathrm{MU}$$

As the equation shows, the thickness of the weld has a large influence. If the V-weld, for example, could be reduced from 10 to 8 mm, this would result in a considerable cost saving, since φ_{W} would be 8 rather than 10. Because of the exponents 2

	Table for welded frame						
Production operations Materials		Labels		Dimen-sions	Data from the welded assemblies	Data for the operational elements	Step sizes φ
Preparing for welding		Weight of the assembly	W	kg	226	1	226
		Number of parts	x		16	1	16
		Factor of difficulty	α		3	1	3
		Labour cost factor	c_L	MU/min	1	1	1
Seam welding	Fillet weld	Seam thickness	a	mm	4	1	4
		Seam length	l_f	m	4.52	1	4.52
		Factor of difficulty	α		3	1	3
	V-weld	Sheet thickness	t	mm	10	1	10
		Seam length	l_V	m	2.44	1	2.44
		Factor of difficulty	α		2	1	2
Welding material		Specific material costs	c_W	MU/kg	10	10	1
Data: 1/85		Author: BI					

Figure 11.18. Table for calculating step sizes

Production operations Materials		Growth laws	Calculations	Stepsizes φ $t=100$mm	$t=8$mm
Preparation		$\varphi_r = 0.32 \cdot \varphi_{cL} \cdot \varphi_\alpha \cdot \varphi_W^{0.5} \cdot \varphi_x^{0.5}$	$0.32 \cdot 1 \cdot 3 \cdot 226^{0.5} \cdot 16^{0.5}$	57.73	57.73
Welding	Fillet weld	$\varphi_s = (0.26 + 0.39 \cdot \varphi_\alpha^{0.5}) \cdot \varphi_t^{1.5} \cdot \varphi_l \cdot \varphi_{cL}$	$(0.26 + 0.39 \cdot 3^{0.5}) \cdot 4^{1.5} \cdot 4.52 \cdot 1$	33.83	33.83
	V- weld		$(0.26 + 0.39 \cdot 2^{0.5}) \cdot 10^{1.5} \cdot 2.44 \cdot 1$	62.62	44.81
Welding material	Fillet weld	$\varphi_m = 0.03 \cdot \varphi_t^2 \cdot \varphi_l \cdot \varphi_{cW}$	$0.03 \cdot 4^2 \cdot 4.52 \cdot 1$	2.17	2.17
	V-weld		$0.03 \cdot 10^2 \cdot 2.44 \cdot 1$	7.32	4.68
			$\varphi_{PC_W} =$	163.67	143.22

Figure 11.19. Calculating the step size for the welding costs of the operation element for the welded assembly in Figure 11.17

and 1.5 respectively, the values of φ_W and φ_M are lower (see Figure 11.19) and the manufacturing cost is reduced significantly:

$$MfC = 3.095 \cdot 143.22 = 443 \text{ MU}$$

11.3.5 Cost Structures

In the previous discussion it became clear that the *cost structure* changes with the overall dimensions and with semi-similar variants. Dominating are the cost terms that increase with φ_L^3 and φ_L^2 such as material costs and surface finish costs. Figure 11.20 shows the change in manufacturing cost structure in relation to overall dimensions and batch size based on Ehrlenspiel [11.12]. With increasing batch size, the one-off costs and the terms that are independent of the dimensions, which

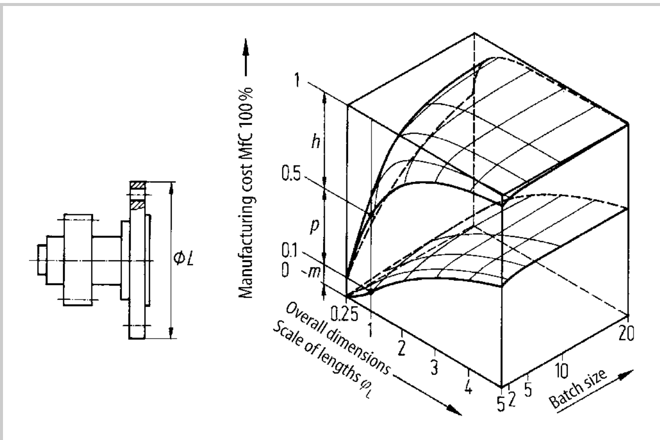

Figure 11.20. Manufacturing cost structure for gear boxes depending on overall dimensions, or length step size φ_L, and batch size, after [11.11, 11.35]. m = material costs contribution, p = production costs contribution, o = costs that occur only once (set-up costs)

are mainly the set-up costs, are reduced. Figure 11.21 shows the cost structure in relation to the overall dimensions for the example shown in Figure 11.10. This figure shows that when the overall dimensions vary from $\varphi_L = 0.4$ to $\varphi_L = 2.5$, i.e. with a factor 6.25, the cost structure changes from an emphasis on production costs to an emphasis on material costs. Cost structures for cast items can be found in [11.14].

Without knowledge of the cost structure, that is, without knowledge of the contributions of direct material costs and production labour costs to the variable

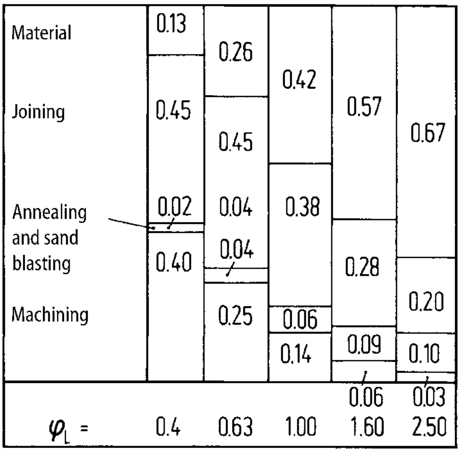

Figure 11.21. Cost structure for the example in Figure 11.10, showing a large change in the contributions of the various factors when the overall dimensions change

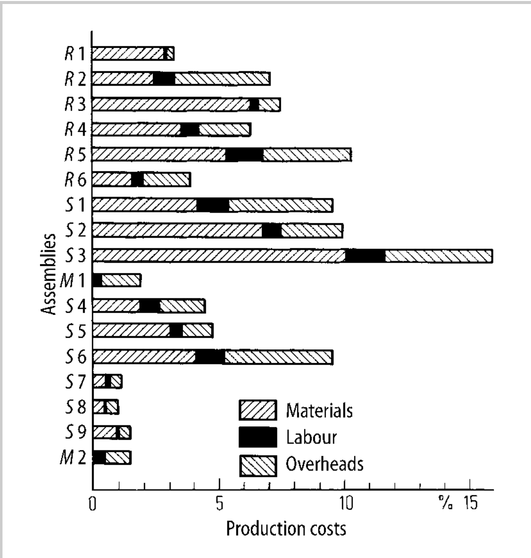

Figure 11.22. Cost structure of a synchronous generator, after [11.19] (Siemens). Examples $R1$: rotor shaft; $R2$: rotor body; $S3$: stator housing; $S5$: bearing; $S6$: spider; $M2$: mountings, etc.

manufacturing costs, designers cannot identify the measures that would lead to cost reduction. Therefore it is important to provide the appropriate data. For original designs, estimates based on rough calculations or similarity relations are useful. For adaptive designs, useful data are final calculations from previous designs.

Figure 11.22 shows an example of the cost distribution for a synchronous generator [11.19]. This shows, for example, that it is not advantageous to redesign rotor shaft $R1$ to reduce production labour costs and indirect production costs. A weight reduction or a more suitable choice of material, however, could lead to substantial cost reductions because of the high contribution of material costs. The situation is different for stator housing $S3$ because the high contribution of indirect production costs indicates advantages in changing the production process by modifying the design.

11.4 Target Costing

The market price and operating costs are the most important criteria for a customer when selecting between competing products and processes. An unfavourable cost situation in the market is often an important reason for new or further developments, even if a product's existing properties are satisfactory. The primary development goal will then be to reduce the manufacturing cost in order to improve the market situation. In such a case, project management will attempt to fulfil specific cost requirements from the start by establishing target costs [11.3, 11.30]. The development process focusing on this type of cost management proceeds more or less as follows.

Following a market analysis (see Section 3.1.4), an attractive selling price is established that is in line with customer expectations and compares favourably with competing products. Taking into account profit and internal overheads (see Figure 11.1), the acceptable but allowable manufacturing cost is estimated. As far as possible and where identifiable the overall manufacturing cost is broken down into the different functional groups or assemblies to enable target costs for individual subsystems to be set. A comparison with the manufacturing cost of the existing product then shows which individual cost elements have to be reduced. If necessary, operating costs are included in an appropriate way.

Compared to conventional product development, the manufacturing cost is not determined retrospectively, in the sense of a cost evaluation, but given as target costs for the subsystems to control the development of solutions [11.4, 11.9]. The derived permissible manufacturing cost is thus an important development goal. Similar to Value Analysis (see Section 1.2.3 and [11.8, 11.32, 11.38]), existing functions, features and construction methods are questioned. If possible, functional improvements, performance gains and material reductions, etc. should be considered to increase the product's attractiveness while at the same time lowering costs.

Opportunities for cost reduction can, in particular, be found in those subsystems (function groups or assemblies) that contribute significantly to the overall cost, and that offer the potential for considerable cost reduction through changing, for example, the task, the principle solution, the embodiment, the materials, the production processes and the assembly methods. The main priority remains the fulfilment of customer expectations regarding the combination of functionality, reliability and attractiveness for a favourable price and low operating costs. Ehrlenspiel gives in [11.9, 11.15] an instructive example for the original development of a concrete mixer based on target costing.

It will be clear, that Target Costing can only be successful when applied by a *development team* that includes all those involved in the product creation process, similar to the approach adopted for Simultaneous Engineering (see Section 4.3) or Value Analysis (see Section 1.2.3). The application of the methods of cost estimation and minimisation proposed in this chapter facilitates the realisation of the target costs at an early stage, e.g. during the search and selection of solutions.

An interesting application of Target Costing for modular systems is proposed in the dissertation of Kohlhase [11.20]. For the individual modules and for their combinations, the projected permissible costs are determined by splitting the target cost. These costs comprise production costs and recurring process costs. Using neural nets, the reciprocal influences are captured and taken into account. If sufficient data are available, it is possible to determine economic module combinations based on the demands.

11.5 Rules for Minimising Costs

In addition to the statements made in Sections 7.5.8 and 7.5.9, the following general rules to minimise costs can be stated [11.11, 11.13, 11.35]:

- Aim for low complexity, that is, a low number of parts and few production processes.
- Aim for small overall dimensions to reduce material costs, because these costs increase disproportionately with size, most frequently diameter.
- Aim for large numbers (large batch sizes) to spread the once-only costs, because, for example, set-up costs can be spread, high performance production processes can be used, and benefits of repetition can be exploited.
- Aim for minimising precision requirements, that is, specify, where possible, large tolerances and rough surface finishes.

In applying these rules one has to take into account the task and the size of the artefact.

With respect to costs, it has been shown that the economic viewpoint does not have to contradict the environmental viewpoint, in fact they can be mutually supportive [11.2]. This is particularly true when energy and material reducing measures are taken into account during the search for solutions and their embodiment. This results both in a reduction of costs and a reduction of resources and environmental load. This is illustrated with the following checklist.

Save energy by:

- avoiding energy transformations (see Section 6.3: establishing function structures)
- reducing flow losses
- reducing friction losses (see Section 7.4.1: principle of balanced forces)
- using waste energy (see Section 7.4.3: principle of self-help)
- using machine sizes suitable for the process
- dividing the system into subsystems to achieve a higher overall efficiency
- using machine components with reduced losses.

Save material by:

- selecting suitable materials (see Section 11.3.1: relative costs)
- adopting tension/compression force transfer (see Section 7.4.1: principle of short and direct force transmission paths)
- selecting the best sections for the loading (see Section 11.3.1: relative costs)
- distributing and channelling flows effectively (see Section 7.4.2: principle of division of tasks)
- increasing speed
- adopting integral construction and function integration (see Section 7.3.2: simplicity and Section 7.5.7: design for production)
- avoiding overdesign while maintaining safety (see Section 7.3.3: safety, fail-safe principle)
- producing components using material-saving processes such as casting, forging, deep drawing, etc.