In all cases procedural plans should be applied in a flexible manner and adapted to the particular problem situation. At the end of each main working and decision step, the overall approach should be assessed and adjusted if necessary.

The four main phases are outlined below.

1. Planning and Task Clarification

The product development task is given to the engineering department by the marketing department, or a special department responsible for product planning, see also Sections 3.1 and 5.1.

Irrespective of whether the task is based on a product proposal stemming from a *product planning* process or on a specific customer order, it is necessary to clarify the given task in more detail before starting product development. The purpose of this *task clarification* is to collect information about the requirements that have to be fulfilled by the product, and also about the existing constraints and their importance.

This activity results in the *specification of information* in the form of a *requirements list* that focuses on, and is tuned to, the interests of the design process and subsequent working steps (see Section 5.2). The conceptual design phase and subsequent phases should be based on this document, which must be updated continuously (this is indicated by the information feedback loop in Figure 4.3).

2. Conceptual Design

After completing the task clarification phase, the conceptual design phase determines the principle solution. This is achieved by abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure. Conceptual design results in the specification of a *principle solution* (concept).

Often, however, a working structure cannot be assessed until it is transformed into a more concrete representation. This concretisation involves selecting preliminary materials, producing a rough dimensional layout, and considering technological possibilities. Only then, in general, is it possible to assess the essential aspects of a solution principle and to review the objectives and constraints (see Section 2.1.7). It is possible that there will be several principle solution variants.

The representation of a principle solution can take many forms. For existing building blocks, a schematic representation in the form of a function structure, a circuit diagram or a flow chart may be sufficient. In other cases a line sketch might be more suitable, and sometimes a rough scale drawing is necessary.

The conceptual design phase consists of several steps (see Chapter 6), none of which should be skipped if the most promising principle solution is to be found. In the subsequent embodiment and detail design phases it is extremely difficult or impossible to correct fundamental shortcomings of the solution principle. A lasting and successful solution is more likely to spring from the choice of the most appropriate principles than from exaggerated concentration on technical details.

This claim does not conflict with the fact that problems may emerge during the detail design phase, even in the most promising solution principles or combinations of principles.

The solution variants that have been elaborated must now be evaluated. Variants that do not satisfy the demands of the requirements list have to be eliminated; the rest must be judged by the methodical application of specific criteria. During this phase, the chief criteria are of a technical nature, though rough economic criteria also begin to play a part (see Sections 3.3.2 and 6.5.2). Based on this evaluation, the best concept can now be selected.

It may be that several variants look equally promising, and that a final decision can only be reached on a more concrete level. Moreover, various form designs may satisfy one and the same concept. The design process now continues on a more concrete level referred to as embodiment design.

3. Embodiment Design

During this phase, designers, starting from a concept (working structure, principle solution), determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. Embodiment design results in the specification of a *layout*.

It is often necessary to produce several *preliminary layouts* to scale simultaneously or successively in order to obtain more information about the advantages and disadvantages of the different variants.

After sufficient elaboration of the layouts, this design phase also ends with an evaluation against technical and economic criteria. This results in new knowledge on a higher information level. Frequently, the evaluation of individual variants may lead to the selection of one that looks particularly promising but which may nevertheless benefit from, and be further improved by, incorporating ideas and solutions from the others. By appropriate combination and the elimination of weak spots, the best layout can then be obtained.

This *definitive layout* provides a means to check function, strength, spatial compatibility, etc., and it is also at this stage (at the very latest) that the financial viability of the project must be assessed. Only then should work start on the detail design phase.

4. Detail Design

This is the phase of the design process in which the arrangement, forms, dimensions and surface properties of all of the individual parts are finally laid down, the materials specified, production possibilities assessed, costs estimated, and all the drawings and other production documents produced [4.28] (see also [4.26]). The detail design phase results in the *specification of information* in the form of *production documentation*.

It is important that designers should not relax their vigilance at this stage, otherwise their ideas and plans might change out of all recognition. It is a mistake to think that detail design poses subordinate problems lacking in importance or

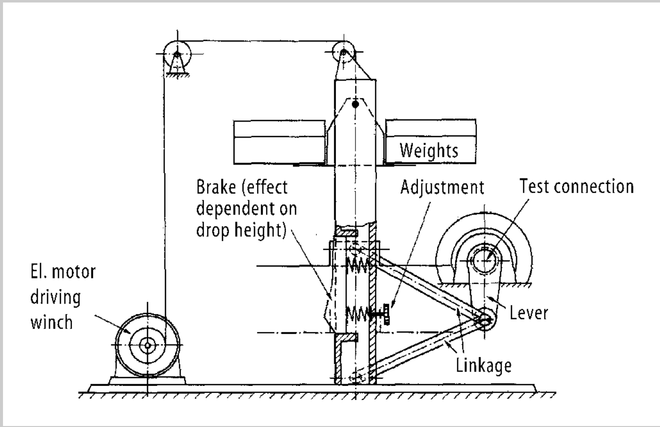

Figure 6.49. Concept variant V_1

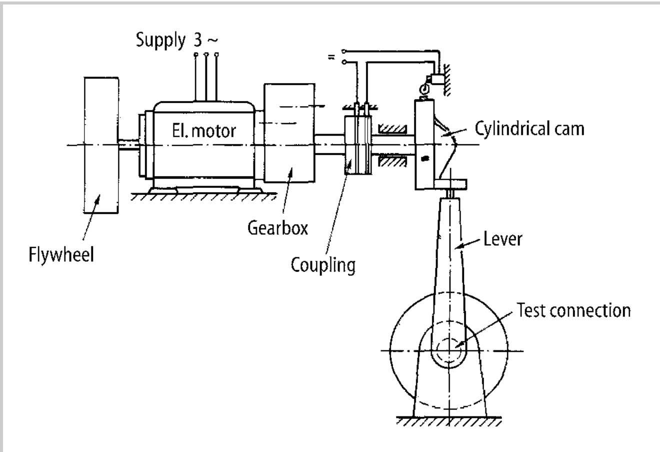

Figure 6.50. Concept variant V_2

- Tangential velocity of the cylindrical cam:

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

- Angular velocity and rpm of cylindrical cam:

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

- Period of revolution:

$$t_{\mathrm{r}} = \frac{2\pi}{\omega} = 3.14 \text{ s}$$

Since the switching times of the electromagnetically operated clutches used to connect and disconnect the cam drive are in the region of a few tenths of a second, there with rough designs). In many cases it suffices, while keeping the overall perspective in mind, to evaluate only those aspects that show marked differences from one another. Once that has been done, their relationship to the whole, of course, must be examined; for example the relationship between part costs and total costs.

- The manufacturing costs (materials, labour and overheads) can be determined (see Chapter 11). If a particular solution introduces subsidiary costs, such as operating costs, and demands special investment, then—depending on the point of view (the producer's or the user's)—these factors must be allowed for, if necessary by amortisation. In addition, optimisation can help to achieve a minimisation of production and operating costs.

If the calculation of manufacturing costs is omitted, then the economic rating can only be evaluated qualitatively, as it was in the conceptual phase. In the embodiment phase, however, costs should, in principle, be determined more concretely (see Chapter 11).

As we mentioned in Section 3.3.2, the first step is to establish the *evaluation criteria*. They are derived from:

- the requirements list:
  - desirable improvement on minimum demands (how far exceeded)
  - wishes (fulfilled, not fulfilled, how well fulfilled)
- the technical properties (to what extent present and fulfilled).

The comprehensiveness of the evaluation criteria can be tested against the headings of the checklist (see Figure 7.148), which is specially adapted to the level of embodiment attained.

At least one significant evaluation criterion must be considered for each heading, although sometimes more will be needed. A heading may only be ignored if the corresponding properties are absent from, or identical in, all the variants. This approach avoids subjective over-valuation of individual properties. It must be followed by the procedural steps outlined in Section 3.3.2. The economic feasibility should be established by this stage at the latest.

In the embodiment phase, the search for weak spots, errors and disturbing influences, along with their elimination, is essential, in particular when evaluating the final layout.

7.7 Example of Embodiment Design

The *conceptual design phase* involves a process that focuses mainly on functions and working structures and results in principle solutions (concepts).

In the *embodiment design phase*, the emphasis is on determining the construction structures of the individual assemblies and components. In VDI 2223 and in Chapter 4 (Figure 4.3) and Chapter 7 (Figure 7.1) of this book, a systematic approach is proposed that has been tested in practice. The variations in approach

Headings	Examples
Function, Working principle	Fulfilment in accordance with the selected working principle: efficiency, risk, susceptibility to disturbances
Layout design	Space requirements, weight, arrangement, fits, scope for modifications
Form design	Material utilisation, durability, deformation, strength, operating life, wear, shock resistance, stability, resonance
Safety	Direct safety methods, industrial safety, protection of the environment
Ergonomics	Human–machine relationship, workload, handling, aesthetics
Production	Risk-free methods, setting-up time, heat treatment, surface treatment, tolerances
Quality control	Quality standards, testing possibilities
Assembly	Unambiguous, easy, comfortable, adjustable, upgradable
Transport	Internal and external transportation, means of despatch, packing
Operation	Handling, operational behaviour, corrosion properties, consumption of resources
Maintenance	Servicing, checking, repair and exchange
Recycling	Disassembly, reuse potential, reprocessing potential
Costs	Evaluated separately (economic rating)
Schedules	Production schedule and completion date

Figure 7.148. Checklist for evaluating embodiment designs

and methods needed to deal with different tasks and problems are greater in embodiment design than in conceptual design. Embodiment design, characterised by a further elaboration of the selected principle solution, requires a more flexible approach, extensive knowledge of the relevant domain and greater experience.

Explaining embodiment design using examples for different tasks would require too much space. It would also be misleading because such examples might suggest that the specific approach described is the only correct one. The example used in the rest of this chapter is based on the principle solution discussed in Chapter 6. Its only purpose is to show how the main embodiment steps of Figure 7.1 are executed and linked together.

The embodiment task is the concretisation of the principle solution for the impulse-loading test rig for shaft–hub connections (see Section 6.6.2). That section described the clarification of the task and the setting up of the requirements list (see Figure 6.43); the identification of the essential problems through abstraction (see Table 6.2); the establishment of function structures (see Figures 6.44 and 6.45); the search for working principles (see Figure 6.46); the combination of working principles into working structures (see Figure 6.47); the selection of suitable working structures (see Figure 6.48); their concretisation into principle solution variants (see Figures 6.49 to 6.52); and the evaluation of these solution variants (see Figures 6.55 and 6.56). We now continue with the embodiment design of this example following the steps shown in Figure 7.1.

Steps 1 and 2: Identifying Embodiment-Determining Requirements and Clarifying Spatial Constraints

The following items from the requirements list were identified as determining the embodiment features:

- Determining layout:

  test connection held in position

  loading applied to stationary shaft in one direction only

  hubside load take-off variable

  torque input variable

  no special foundation.

- Determining dimensions:

  diameter of shaft to be tested $\leq$100 mm

  adjustable torque $T \leq 15\,000$ Nm (maintained for at least 3 s)

  adjustable torque increase $\mathrm{d}T/\mathrm{d}t = 1.25 \times 10^3$ Nm/s

  power consumption ≤ 5 kW.

- Determining material:

  shaft and hub: 45C.

- Other requirements:

  production of the test rig in own workshops

  bought-out and standard parts wherever possible

  easy to disassemble.

The requirements list did not contain specific spatial constraints.

Step 3: Identifying Embodiment-Determining Main Function Carriers

The basis for this step was function structure variant No 4 (see Figure 6.45) and the principle solution variant V_2 (see Figure 6.47). Table 7.6 lists the *main function carriers* used in the selected solution variant to fulfil the various subfunctions, along with their main characteristics. The function carriers that determined the embodiment are:

- the test specimen
- the lever between the cylindrical cam and the shaft of the test specimen
- the cylindrical cam.

The other main function carriers are:

- the electric motor
- the flywheel

Table 7.6. Main function carriers

Functions	Function carriers	Characteristics
Transform energy; increase energy component	Electric motor	Power P_M Speed n_M Run-up time t_M
Store energy	Flywheel	Moment of inertia J_F Speed n_F Torque transmitted T_{CL}
Release energy	Clutch	Torque transmitted T_{CL} Maximum speed n_{CL} Response time t_{CL}
Increase energy component	Gearbox	Power P_G Maximum output torque T_G at output speed n_G Gear ratio R_G
Control magnitude and time	Cylindrical cam	Power P_{CAM} Torque T_{CAM} Speed n_{CAM} Diameter D_{CAM} Cam angle α_{CAM} Rise h_{CAM}
Transform energy into torque	Lever	Length l_L Stiffness s_L
Load test specimen	Test specimen	Torque T Rate of torque increase $\mathrm{d}T/\mathrm{d}t$
Take up forces and torque	Frame	

- the clutch
- the gearbox
- the frame.

Step 4: Developing Preliminary Layouts and Form Designs for the Main Function Carriers

Figure 7.149 shows a preliminary layout drawing for the three embodiment-determining function carriers.

The embodiment of the test specimen in line with DIN 6885 and of the transmission lever, modelled and analysed as a cantilever, were relatively straightforward. The development and embodiment of the cylindrical cam, however, required a more detailed kinematic and dynamic analysis based on specific items in the requirements list.

A more precise analysis showed that the initial estimates undertaken in the conceptual phase of the cylindrical cam's performance were insufficient to proceed directly to embodiment. The following analysis therefore had to be carried out before determining the main dimensions.

Figure 7.150 shows that:

Torque on the shaft: $T = s_L \cdot h_{CAM} \cdot l_L$

Torque increase: $dT/dt = \pi \cdot D_{CAM} \cdot n_{CAM} \cdot \tan \alpha_{CAM} \cdot s_L \cdot l_L$

Hold time: $t_L = \dfrac{U_{CAM}}{2\pi \cdot D_{CAM} \cdot n_{CAM}} = \dfrac{1}{2 \cdot n_{CAM}}$

The equation for the torque increase is only valid if the lever movement is parallel to the cam track. In order to minimise friction, a roller follower was required (see Figure 7.151), so the actual torque increase was lower than calculated and also varies. We therefore used the average increase in our calculations (see Figure 7.152).

If, in line with the requirements list, the average torque increase dT/dt is used, then the calculation of dT/dt should not involve the full circumferential speed v_X, but instead the effective circumferential speed v_X^*, thus:

$$v_X^* = K \cdot v_X$$

The correction K depends on:

- the cam angle α_{CAM}
- the diameter of the roller follower d
- the rise of the cylindrical cam h_{CAM}.

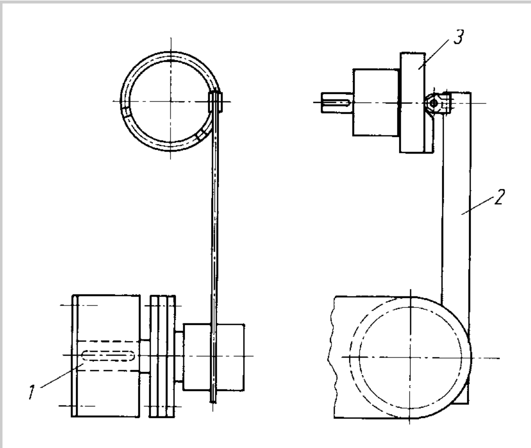

Figure 7.149. Main function carriers that determine the layout: *1* test connection; *2* transmission lever; *3* cylindrical cam

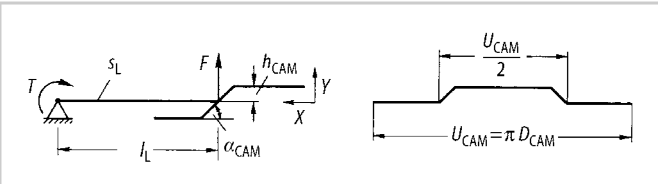

Figure 7.150. Geometric constraints for the cylindrical cam and lever. s_L is the stiffness of the lever

The correction K was derived from Figure 7.153:

$$x = \frac{h_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}}$$

$$x = d/2 \cdot \left(\sin \alpha_{\mathrm{CAM}} - \frac{1 - \cos \alpha_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}} \right)$$

$$K = \frac{v_{\mathrm{X}}^{*}}{v_{\mathrm{X}}} = \frac{x}{x + \Delta x}$$

The formula is only valid when $d/2 \cdot (1 - \cos \alpha_{\mathrm{CAM}}) \leq h_{\mathrm{CAM}}$, for example:

$$K = \frac{\frac{h_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}}}{\frac{h_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}} + d/2 \cdot \left(\sin \alpha_{\mathrm{CAM}} - \frac{1 - \cos \alpha_{\mathrm{CAM}}}{\tan \alpha_{\mathrm{CAM}}} \right)}$$

To obtain a value for K, the following estimates were made:

- cam angle $\alpha_{\mathrm{CAM}} = 10 \ldots 45°$

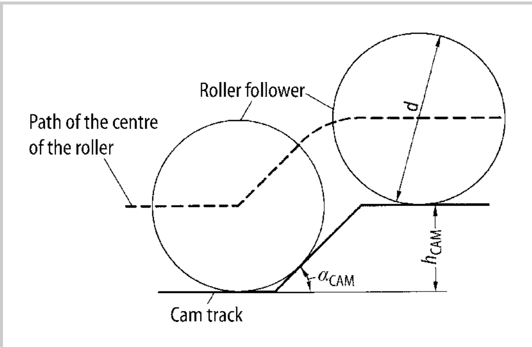

Figure 7.151. Cam path and lever movement

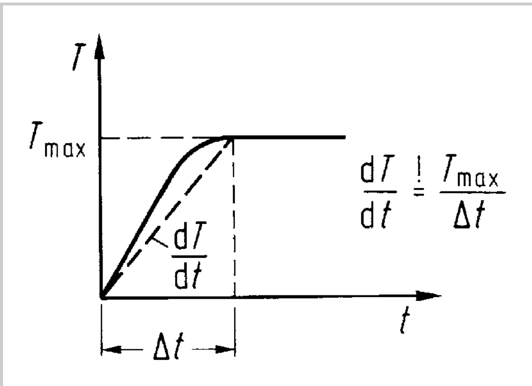

Figure 7.152. Torque increase

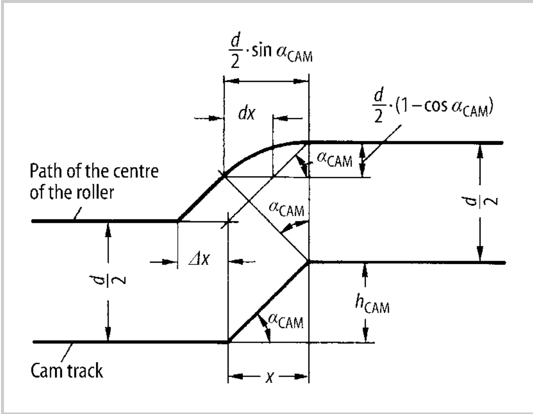

Figure 7.153. Derivation of correction K

- the diameter of the roller follower $d = 60$ mm
- the rise of the cylindrical cam $h_{CAM} = 7.5$ mm and 30 mm, respectively.

Table 7.7 contains the values of K obtained from the above formula.

After converting the cylindrical cam speed n_{CAM} and using the calculated correction value K, the formula including torque increase $\mathrm{d}T/\mathrm{d}t$ became:

$$n_{CAM} = \frac{\frac{\mathrm{d}T}{\mathrm{d}t}}{K \cdot \pi \cdot D_{CAM} \cdot \tan \alpha_{CAM} \cdot s_L \cdot l_L}$$

The speed controller range C

$$C = \frac{n_{CAM\max}}{n_{CAM\min}}$$

was determined as follows.

If the diameter of the cylindrical cam D_{CAM}, the stiffness s_L and the length l_L of the lever are considered constant for this solution concept, the above formula can be used to calculate the extremes of the speed n_{CAM} in relation to the other parameters $\mathrm{d}T/\mathrm{d}t$, K and α_{CAM} (see Table 7.8).

B is a constant that includes units and the other constants (π, D_{CAM}, s_L, l_L).

Table 7.7. Reference values for K corrections

h_{CAM} mm	α_{CAM}	45°	40°	30°	20°	10°
7.5	K	0.41	0.45	0.62	0.79	0.94
30.0	K	0.71	0.76	0.87	0.94	0.98

Table 7.8. Determination of $n_{CAM_{min}}$ and $n_{CAM_{max}}$

	dT/dt	α_{CAM}	K	n_{CAM}
Minimum	20	10	0.98	$116 \cdot B$
Maximum	125	45	0.41	$305 \cdot B$

The speed control range C therefore became:

$$C = \frac{305 \cdot B}{116 \cdot B} = 2.6$$

This meant that:

- The function "control magnitude and time" could not be fulfilled by the cylindrical cam alone.
- The function structure had to change if we wished to maintain the principles underpinning the concept.
- The cylindrical cam had to have an adjustable drive with a speed control range of approximately $C = 2.6$.

Figure 7.154 shows the adapted function structure variants (see Figure 6.45). The subfunction "adjust speed" was added. This could, for example, be realised by a continuously adjustable drive motor. Several variants were possible (4/1 to 4/3).

The quantitative developments of the cylindrical cam based on these formulae resulted in the following values for the main characteristics: spring stiffness of the lever $s_L = 700$ N/mm; lever length $l_L = 850$ mm; cylinder diameter $D_{CAM} = 300$ mm; cam angle $\alpha_{CAM} = 10 \ldots 45°$; constant $B = 0.107\ \text{min}^{-1}$ (see Table 7.8); speed range for the required rate of torque increase ($dT/dt_{min} = 20 \times 10^3$ Nm/s, $dT/dt_{max} = 125 \times 10^3$ Nm/s), $n_{CAM} = 12.4 \ldots 32.6\ \text{min}^{-1}$ for a control range $C = 2.6$.

The requirements for the adjustable torque increase dT/dt could therefore be realised with the selected values.

This was not the case for the required hold time for the maximum torque. This value was $t_L = 0.5 \cdot n_{CAM} = 2.4 \ldots 0.92$ s, which was lower than the required value of 3 s. After a discussion with the client, the requirement was reduced to $t_L \geq 1$ s, which could be realised by using slightly more than half of the circumference of the cylindrical cam.

Before a scale layout for the main function carriers that determine the embodiment could be drawn, the following issues had to be resolved:

- What spatial layout of the test specimen and the cylindrical cam should be used?
- To what extent should auxiliary function carriers be considered?

It was decided that the test specimen should be positioned horizontally, and as a consequence the cylindrical cam should rotate about a vertical axis for the following reasons:

- Easy exchange of test specimen and cylindrical cam (design for assembly).

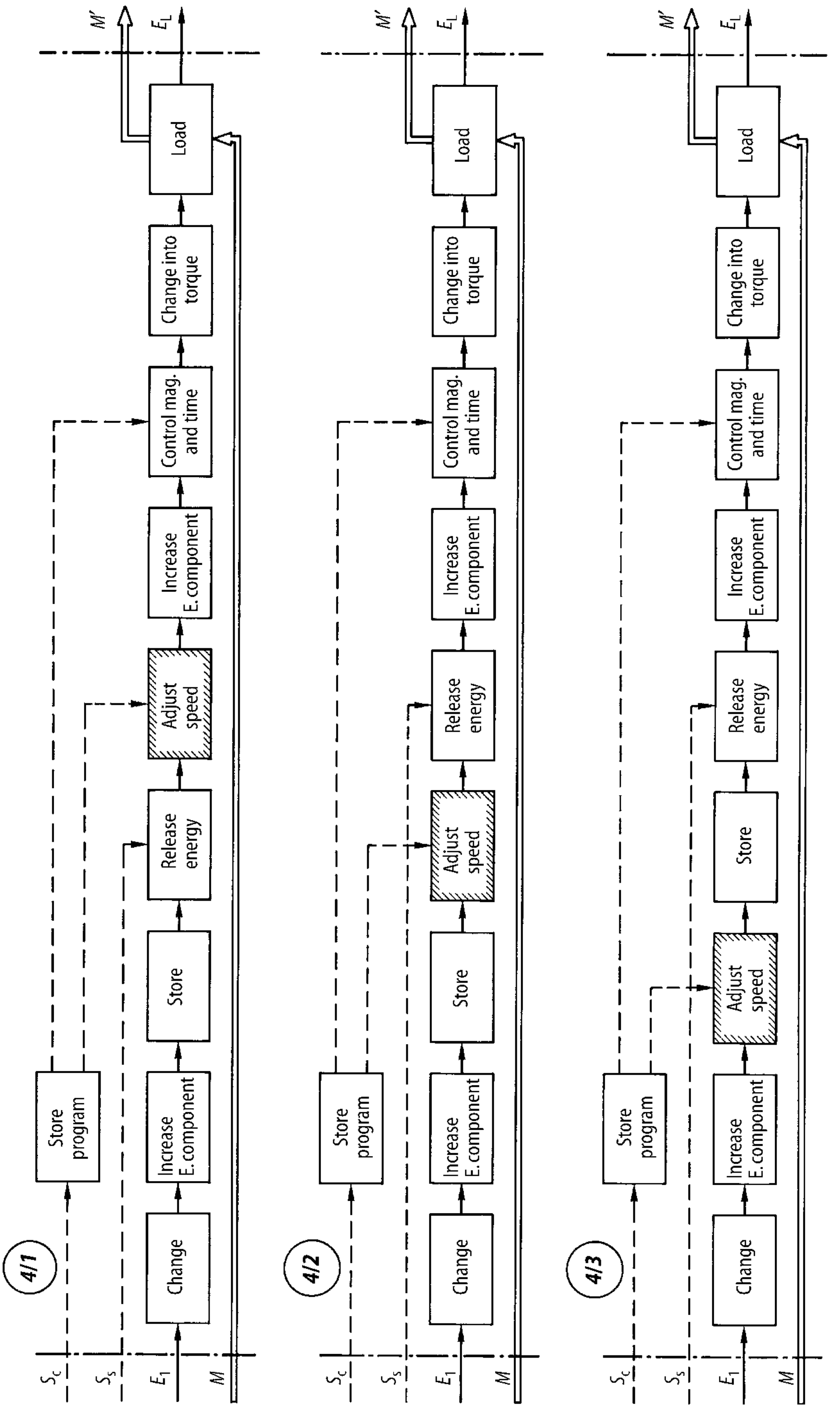

Figure 7.154. Function structure variants for function structure 4, after Figure 6.45

- Easy access to the test specimen for measurements (design for ergonomics).
- Smooth transmission of the clamping forces of the test specimen into the foundation (short and direct force transmission paths).
- Easy resetting of the test rig for different types of specimen, in particular larger specimens (design for minimum risk).

The need for auxiliary function carriers was then assessed and the space requirements determined on the basis of experience. It was found that:

- A separate bearing was needed for the cylindrical cam because of the axial force F_A and the tangential force F_T:

$$F_A = F_T = \frac{T_{max}}{l_L} = 17.6 \text{ kN}$$

- The outer diameter of the bolted joint between test specimen and lever had to be about 400 mm to provide a torsionally stiff connection.

The analysis showed that the auxiliary function carriers had only a marginal influence on the dimensions of the embodiment.

Figure 7.155a shows a preliminary layout based on function structure variant *4/1*, where the speed control is achieved by means of an adjustable mechanism that is located behind the clutch in terms of the energy flow. Figure 7.155b shows

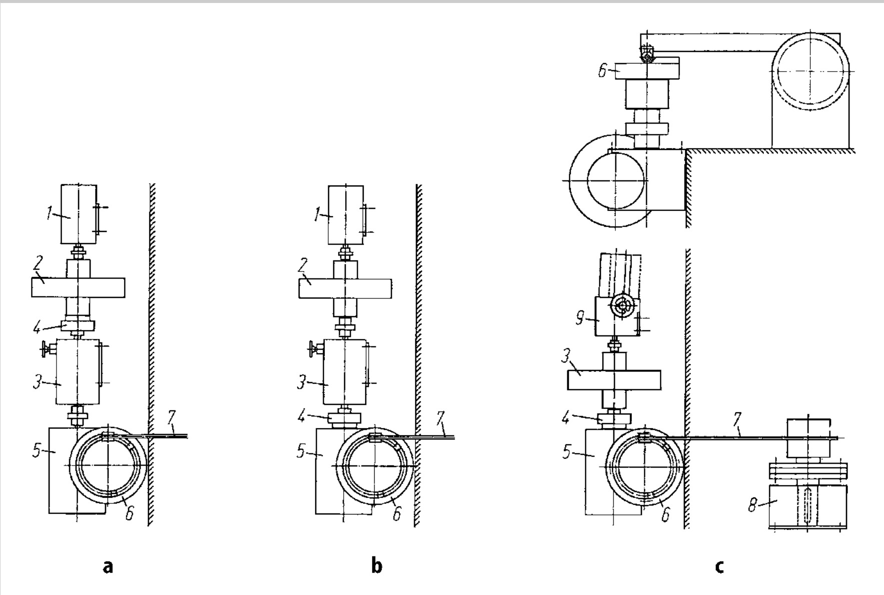

Figure 7.155. Layout of main function carriers: **a** for function structure variant *4/1*; **b** for function structure variant *4/2*; **c** for function structure variant *4/3*; *1* motor, *2* flywheel, 3 adjustable gear, *4* clutch, *5* worm gear (angular), 6 cylindrical cam, *7* transmission lever, *8* test connection, *9* adjustable geared motor

a preliminary layout based on function structure variant *4/2*, where the adjustable mechanism is located before the clutch. Variant *4/3* (see Figure 7.155c) employs an adjustable geared motor.

Step 5: Selecting Suitable Preliminary Layouts

Variant *4/3* was selected for further detailing because it took up less space due to the adjustable geared motor (function integration).

Step 6: Developing Preliminary Layouts and Form Designs for the Remaining Main Function Carriers

The preliminary layouts and form designs for the remaining main function carriers were based on the following requirements identified in step 4:

- motor drive speed for cylindrical cam

$$n_{CAM} = 12.4\ldots 32.6\ \text{min}^{-1}$$

- speed control range

$$C = 2.6$$

- driving torque of cylindrical cam

$$T_{CAM} = F_T \cdot D_{CAM}/2 \text{ and } F_T = F_A = T/l_L \text{ gives } T_{CAM} = 2650\ \text{Nm}$$

- driving power of cylindrical cam

$$P_{CAM} = T_{CAM} \cdot \omega_{CAM}, \text{ thus } P_{CAM} = 9\ \text{kW}$$

For reasons of safety, the maximum flywheel speed n_F (and therefore also that of the motor n_M) was chosen to be:

$$n_F = 1000\ \text{min}^{-1}$$

This required a transmission ratio of:

$$i = 80.7\ldots 30.7$$

For the other main function carriers, the characteristics were estimated as follows:

- Transferred torque of the coupling based on the driving torque of the cylindrical cam $T_{CAM} = 2\,650$ Nm and the actual transmission ratio i between the cylindrical cam and clutch

$$T_{CL} = T_{CAM}/i$$

- Moment of inertia of the flywheel from the actual torque T_F taken up by the flywheel, the impact time Δt, the flywheel speed n_F and the allowable drop in speed $\Delta n = 5\%$

$$J_F = \frac{T_F \cdot \Delta t}{2 \cdot \pi \cdot n_{CAM} \cdot \Delta n}$$

- The power of the electric motor P_M after calculating the required acceleration torque T_A from the moment of inertia J_F of the flywheel, the motor speed n_M, the run-up time $t_M = 10$ s and the maximum acceleration torque of the motor $T_{A_{max}}$ (from manufacturer's data)

$$T_A = \frac{J_F \cdot 2 \cdot \pi \cdot n_M}{t_M} < T_{A_{max}}$$

Table 7.9 lists the calculated values for the main characteristics. Apart from the flywheel, the main function carriers could all be selected from catalogues and bought directly from suppliers.

The following characteristics were chosen for the flywheel:

- speed $n_F = 1010\ \mathrm{min}^{-1}$
- moment of inertia $J_F = 1.9\ \mathrm{kg\,m}^2$.

Because losses such as those from friction had not been taken into account, the final value of J_F was chosen to be substantially larger than this.

To save weight, the flywheel was made from a hollow cylinder:

- Outer diameter $D_o = 480$ mm
- Inner diameter $D_i = 410$ mm
- Width $W = 100$ mm
- Mass $m = 38$ kg.

The final preliminary layout drawing was then produced on the basis of the main function carriers shown in Figure 7.155c and by adding the frame.

Table 7.9. Calculated values for the characteristics of the main function carriers of variant *4/3*

Functions	Function carriers	Calculated values
Change energy Increase E-component Adjust speed	Electric motor with mechanical adjustment- variant 4/3	Power $P_M = 1.1$ kW Speed $n_M = 380 \ldots 1000\ \mathrm{min}^{-1}$ Speed control range $C = 2.6$
Store energy	Flywheel	Moment of inertia $J_F = 1.4\ \mathrm{kg\,m}^2$ Speed $n_F = 380 \ldots 1000\ \mathrm{min}^{-1}$
Release energy	Electromagnetic clutch	Transferred torque $T_{CL} = 86$ Nm
Increase E-component	Gear	Power $P_G = 9$ kW Nominal torque $T_G = 2650$ Nm at speed $n_G = 32\ \mathrm{min}^{-1}$ Transmission ratio $i_G = 40.7$

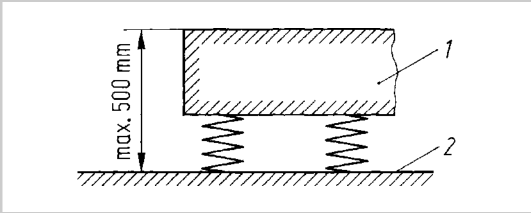

Figure 7.156. Final spatial constraints: *1*, base plate for fixing the test machine; *2*, foundation

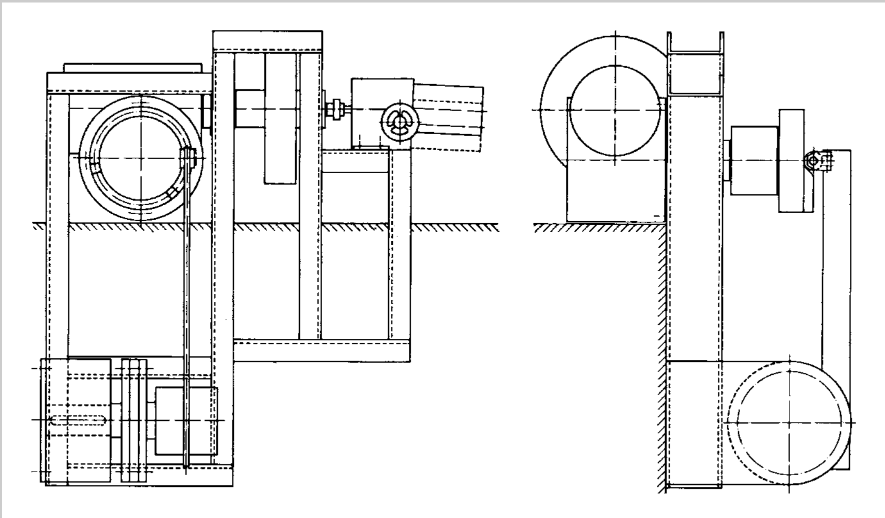

Figure 7.157. Preliminary layout drawing for the main function carriers

Because the combined height of the lever bearing and the test specimen was much smaller than the combined height of the cylindrical cam and the entire drive system, the spatial constraints for the test rig shown in Figure 7.156 were selected after a discussion with the client.

Steel channel sections were used for the frame for the following reasons:

- large second moment of area for a small cross-sectional area
- no round corners
- three flat reference surfaces available
- cheap.

Figure 7.157 shows the completed preliminary layout drawing for the main function carriers.

Step 7: Searching for Solutions for Auxiliary Functions

The production of a detailed layout drawing involved the following steps:

- Searching for and selecting auxiliary function carriers.

- Detailing the embodiment of the main function carriers based on the auxiliary function carriers.
- Detailing the embodiment of the auxiliary function carriers.

These steps were much more interrelated than those for the preliminary layout drawing. They influenced each other because they dealt with more concrete aspects which often required a repetition of previous steps on a higher information level.

The auxiliary function carriers were divided into three groups:

- Carriers that connect the main function carriers together.
- Carriers that support those main function carriers that move relative to the frame.
- Carriers that permanently connect main function carriers to the frame.

The auxiliary function carriers that connected the main function carriers together were:

- A bolted joint between the lever and test specimens; a form-fit membrane to avoid additional bending moments and to ensure easy assembly.
- A torsionally stiff connection between the worm gear pair and the cylindrical cam. This connection can be of two types (see Figure 7.158):
  - a worm gear pair with hollow shaft—cylindrical cam.
  - a worm gear pair—torsionally stiff connection—cylindrical cam.

  The following arguments favour the torsionally stiff connection:
  - separate assembly of worm gear pair and cylindrical cam possible (design for assembly).
  - no interruption of the frame caused by a high shaft position (simple embodiment).
  - easy centering of worm gear pair and cylindrical cam (design for production).
- Torsionally flexible connection between the flywheel and the electric motor.

The auxiliary function carriers used to support those main function carriers that move relative to the frame were:

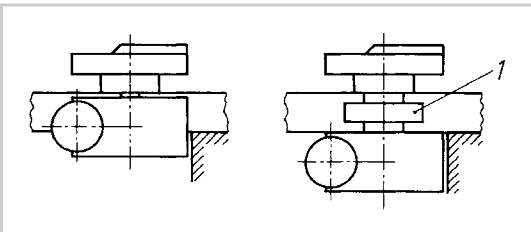

Figure 7.158. Connections between the worm gear pair and the cylindrical cam: *1*, coupling

- *Flywheel support*. The requirements were: simple production (i.e. no accurate balancing needed); direct safety techniques to withstand the dynamic forces (safe-life principle); and suspend from the frame. The use of bought-out parts (bearing housing with roller bearings) was not possible because these bearing housings are usually cast and are more suitable for standing rather than suspended applications. Because the flywheel was to be produced in-house, the magnitudes of the dynamic forces were relatively uncertain and so its support needed to be specially designed.
- *Support for the cylindrical cam and lever*. Commercially available rolling element bearings were selected.

The auxiliary function carriers used to permanently connect main function carriers to the frame were:

- Simple half-finished products (welded sheet steel), to which the main function carriers were bolted.
- A special solution for connecting the test specimen to the lever (i.e. the frame). The requirements were: easy to assemble but separable connection; movable in the axial direction; free of play; and no tight tolerances. A Ringfeder connection was chosen.

Step 8: Detailing the Main Function Carriers Taking into Account the Auxiliary Function Carriers

The main function carriers had to be adapted so as to match the solutions selected for the auxiliary function carriers. This resulted in the following:

- electric motor: bought-out part
- flywheel: see Figure 7.159
- clutch: bought-out part
- gearbox: bought-out part
- cylindrical cam: see Figure 7.160
- lever: see preliminary layout drawing in Figure 7.161
- test specimen: see preliminary layout drawing in Figure 7.161
- frame: modified to suit the geometry of the selected motor.

Step 9: Detailing the Auxiliary Function Carriers and Completing the Preliminary Layout

The flywheel support bearing is taken as an example, using the guidelines for embodiment design shown in Figure 7.3.

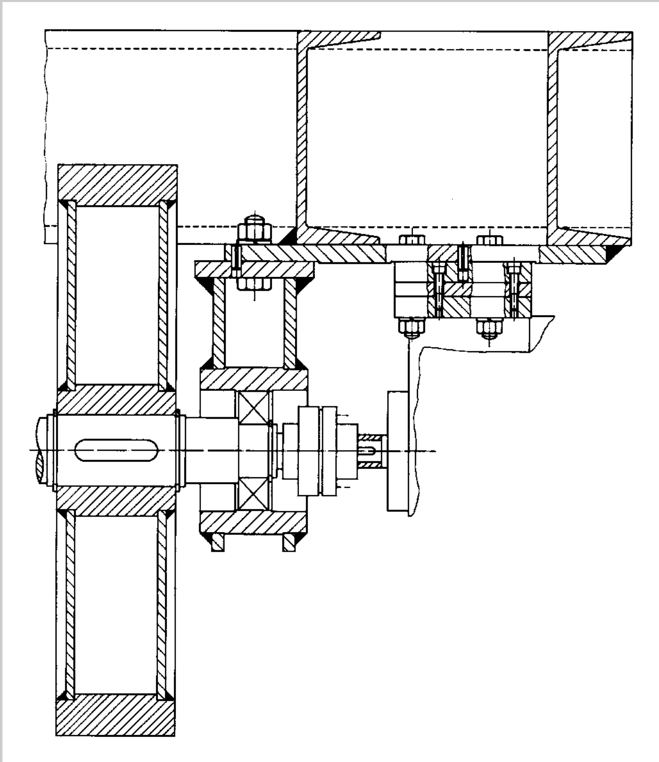

Figure 7.159. Detailed layout of the flywheel and the flywheel shaft bearing

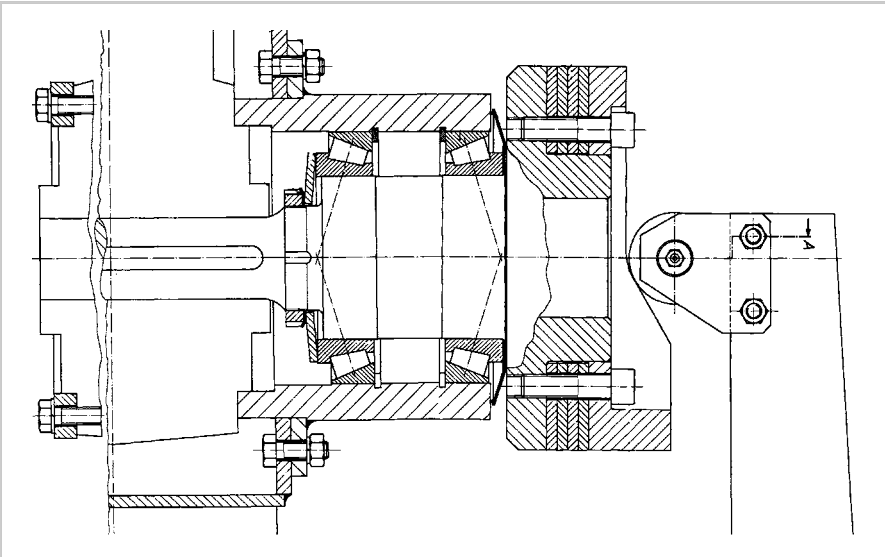

Figure 7.160. Detailed layout of the bearing arrangement for the cylindrical cam

Layout

The bearing forces were estimated as follows:

$$F_B = F_{dyn} + F_{stat}$$

with the weight being:

$$F_{stat} = m \cdot g = 400\ \text{N}$$

and the dynamic force being:

$$F_{dyn} = m \cdot e \cdot 4 \cdot \pi^2 \cdot n_F^2$$

With a mass $m = 40$ kg; speed $n_F = 1\,750\ \text{min}^{-1}$ (= max motor speed); eccentricity of flywheel $e = 0.6$ mm (based on: dimensional and shape accuracy of flywheel = 0.3 mm; play in flywheel shaft and bearings = 0.2 mm; and unbalanced mass distribution = 0.1 mm), the bearing force is:

$$F_B = 1130\ \text{N}$$

This implies that even when additional gyroscopic forces occur, the bearing (dynamic capacity 65 000 N) and all the other parts that are in the force transmission path have adequate dimensions.

Resonance

The embodiment of the bearing and frame was made very rigid so that resonance excited by the flywheel (maximum 30 Hz) was unlikely.

Production

The embodiment allowed easy production because the flywheel support bearing did not require tight tolerances for the frame.

Assembly

The support for the flywheel could be assembled easily due to:

- the application of a simple bottom-up approach
- the easy accessibility to the connecting screws
- the simple adjustment of the clutch using a spacer after accurate location of the flywheel bearing support using dowel pins (possible without the flywheel).

Maintenance

Maintenance-free bearings were used.

Figure 7.161 shows the preliminary layout drawing of the test rig resulting from the embodiment steps discussed above.

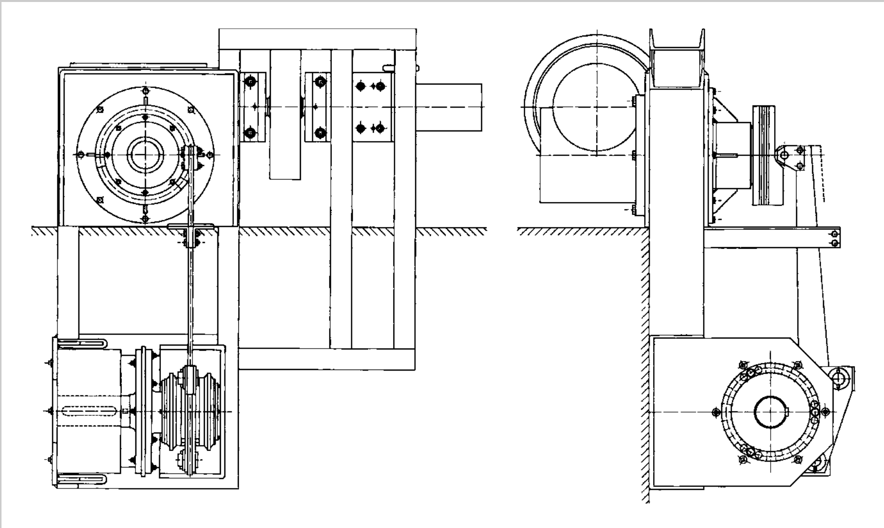

Figure 7.161. Preliminary layout drawing

Step 10: Evaluating Using Technical and Economic Criteria

Because only one final embodiment was developed, no selection was involved, only an assessment of the final embodiment based on criteria derived from the requirements list. The objective was to identify and eliminate weak spots.

The procedure involved the following steps in accordance with Section 3.3.2:

- identifying evaluation criteria
- assessing whether the parameters meet the evaluation criteria
- determining the overall rating
- searching for weak spots
- eliminating weak spots, if required.

For the evaluation we used 11 of the 13 criteria that were used to evaluate the concepts, see Figure 7.162. The use of weightings was not considered to be necessary.

The expected and calculated parameters of the test rig were evaluated against an ideal solution using a value range of 0–4, in line with VDI 2225. A more detailed evaluation did not seem worthwhile. The result is shown in Figure 7.162.

Only the technical rating was used in the calculation of the overall rating because there were no data for a formal assessment of the economic rating:

$$R = 29/44 = 0.66$$

This rating is rather low, so a search for weak spots seemed necessary. First, those parameters that had the lowest values were identified. A proposal was then made to improve those parameters that received only one or two marks:

Evaluation criteria			Parameters		Variant 4/3			Variant 4/3 impr.		
No.		Wt		Unit	Magn	Value	Weighted value	Magn	Value	Weighted value
1	Good reproducibility		Disturbing factors	–	low	4				
2				–						
3				–						
4	Tolerance of overloading		Overload reserve	%	10	3				
5	High level of safety		Danger of injury	–	average	2		see text	4	
6	Few possible operator errors		Possibilities of operator errors	–	high	1		see text	3	
7	Small number of components		No. of components	–	low	3				
8	Low complexity of components		Complexity of components	–	low	3				
9	Many standard and bought-out parts		Proportion of standards and bought-out comp.	–	high	4				
10	Simple assembly		Simplicity of assembly	–	high	3				
11	Easy change of load profile		Change of load profile	–	bad	1		see text	2	
12	Quick exchange of test connections		Estimated time needed to exchange test con.	–	average	2		see text	2	
13	Good accessibilitiy of measuring system		Accessibility of measuring system	–	good	3				
		$\Sigma W_i=1.0$				$OV_1=29$ $R_1=0.66$			$OV_2=34$ $R_2=0.77$	

Figure 7.162. Evaluation chart for embodiment based on Figures 7.161, 6.54 and 6.55

- Few possible operator errors.

  Weak spot: motor speed: (1) the speed could be set at a value higher than necessary for the maximum rate of torque increase; and (2) the run-up of the motor should only take place slowly because of the heat generated.

  Remedy: the allowed range for run-up and operation can be marked on the speed indicator of the motor. The machine can be shut down automatically if the speed becomes too high.

- Easy to change the load profile.

  Weak spot: exchange of the cylindrical cam was not possible because of the clamping pressure of the lever on the cam.

  Remedy: provide a means to lift the lever.

- High level of safety.

  Weak spot: rotating cylindrical cam was not protected.

  Remedy: provide protective cover.

- Quick exchange of test specimens (test connections).

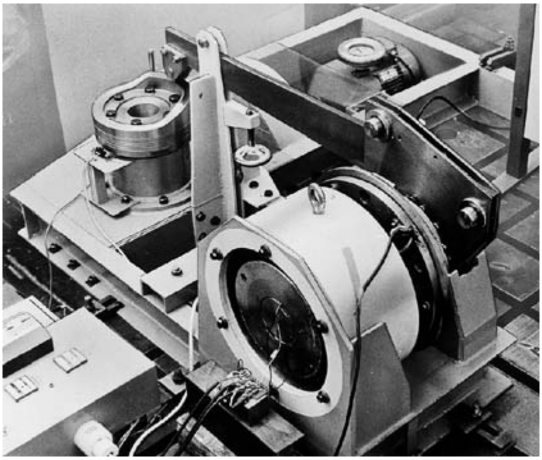

Figure 7.163. Final impulse-loading test rig, after [7.188]

Weak spot: slow because of the number of screws in the Ringfeder connection.

Remedy: no economic alternative possible.

The improved variant has been added to the evaluation chart (see Figure 7.162).

The remaining working steps used to *define the overall layout* proposed in Figure 7.1 are not discussed here. They were not very complex in the case of this test rig because it was a one-off product for a research institute and did not need a high degree of optimisation. The *detail design* of the test rig (following the working steps in Section 7.8) is also not discussed. It only involved conventional drawing and detail design steps.

Figure 7.163 shows the final impulse loading test rig. It fulfilled the main expectations and confirmed the effectiveness of a systematic approach [7.122].

7.8 Detail Design

Detail design is that part of the design process which completes the embodiment of technical products with final instructions about the shapes, forms, dimensions and surface properties of all individual components, the definitive selection of materials, and a final scrutiny of the production methods, operating procedures and costs.

Another—and perhaps the most important—aspect of the detail design phase is the elaboration of production documents, including detailed component drawings, assembly drawings, and appropriate parts lists. These activities are increasingly undertaken using CAD software. This allows the direct use of product data for production planning and the control of CNC machine tools.

Depending on the type of product and production schedule (one-off, small batch, mass production), the design department must also provide the production department with assembly instructions, transport documentation and quality

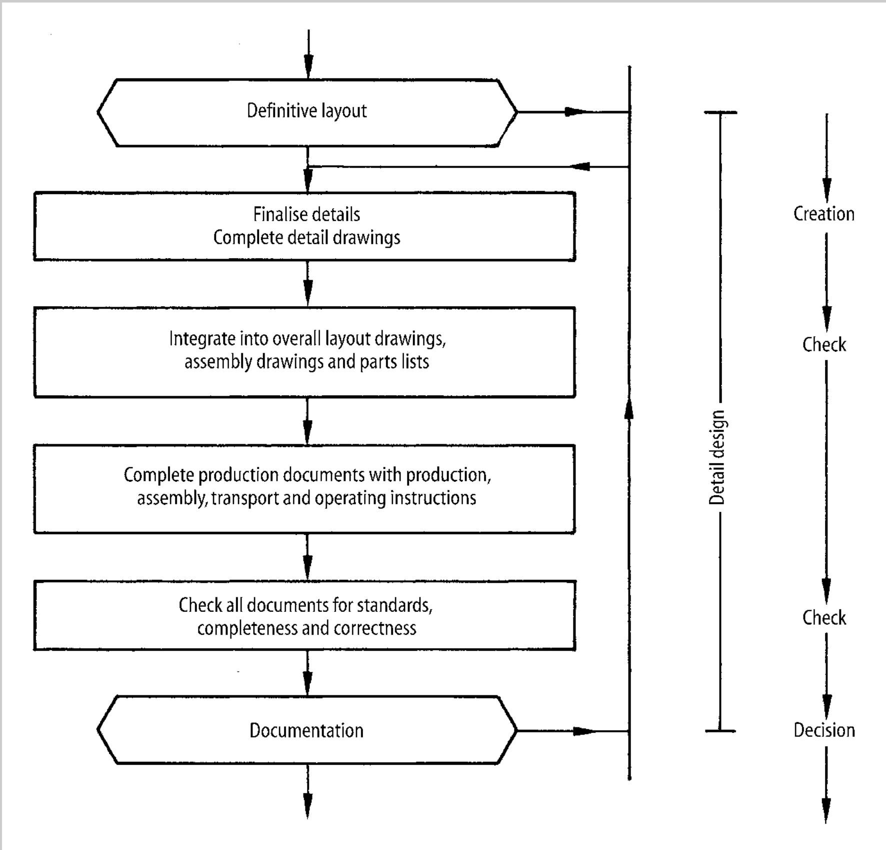

Figure 7.164. Steps of detail design

control measures (see Chapter 10), and the user with operating, maintenance and repair manuals. The documents drawn up at this stage are the basis for executing orders and for production scheduling, that is, for operations planning and control. In practice, the respective contributions of the design and production departments in this area may not be distinct.

The detail design phase involves the following steps (see Figure 7.164).

Finalise the definitive layout, comprising the detailed drawing of components, and the detailed optimisation of shapes, materials, surfaces, tolerances and fits. To that end, designers should refer to the guidelines given in Section 7.5. Optimisation aims at maximum utilisation of the most suitable materials (uniform strength), at cost-effectiveness and at ease of production, with due attention being paid to standards (including the use of standard parts and company repeat parts).

Integrate individual components into assemblies and into the overall product (fully documented with the help of drawings, parts lists and numbering systems). This is strongly influenced by production scheduling, delivery dates, and assembly and transport considerations.

Complete production documents with production, assembly, transport and operating instructions.

Check all documents, especially detail drawings and parts lists, for:

- observance of general and in-house standards
- accuracy of dimensions and tolerances
- other essential production data
- ease of acquisition, for instance, the availability of standard parts.

Whether such checks are made by the design department itself or by a separate standards department will depend largely on the organisational structure of the company concerned, and it plays a subordinate role in the actual execution of the task. The steps of the embodiment and detail design phases overlap in the same way as the steps of the conceptual and embodiment phases often do. Long lead-time parts, such as those involving forging and casting, should be dealt with first and their detail designs and production instructions are often completed before the definitive layout has been finalised. This overlapping of two design phases is particularly common in one-off production and in heavy engineering.

Detail design is very domain- and product-dependent and designers should refer to the many technical handbooks, suppliers catalogues and standards that deal with the detail design and selection of machine elements.

Corners must never be cut during the detail design phase, which has a critical effect on the technical functions, on the production processes and on the elimination of production errors. Detail design has a major influence on production costs and product quality, and hence the success of a product in the market.