Engineering D

5. Engineering Design

The development and design of engineering systems following a methodical approach based on information from the literature [5.1–3] is a useful procedure. The guidelines for design methodology have also been applied to interdisciplinary development projects of this type, using aids such as requirements lists, the functional structure and morphological boxes, to name just a few. During the design phase of the product development process it is important to comply with the basic design rules: *simple*, *clear* and *safe* [5.3]. Several examples that clearly show the realization of these three criteria are included in this chapter.

5.1 Basics

The methodical approach to the development and design of technical systems (engineering design) has established itself in virtually all design departments. Teaching specialized knowledge about methodical design is also a fixed component of the curriculum in the teaching of engineering sciences in universities and technical colleges.

There are a large number of approaches to design methodology, which are documented the technical literature. For example, *Ehrlenspiel* [5.1] focuses more on the cost approach to product development. One way of reducing and identifying costs early, according to Ehrlenspiel, is integrated product development. In his method on the other hand, *Roth* [5.2] divides the design process into many smaller steps and places strong emphasis on the incorporation of design catalogues in the solution process. *Pahl* et al. [5.3] worked very actively on the German guidelines VDI2221 [5.4] and VDI2222 [5.5] and subdivided the design process into individual activities, to which detailed methods are assigned. Further methods exist for these purposes, for example from *Gierse* [5.6], *Hubka* [5.7], *Koller* [5.8], *Bock* [5.9] and *Rugenstein* [5.10]. The essential aspect of each of these is the structuring of the task. This takes place, e.g., by drawing up flow diagrams and using methodical structuring aids, e.g., functional structures, efficacy structures or classification diagrams [5.11].

The methodical approach to the development of a technical system is clarified in this chapter using a practical example from the interdisciplinary field of biomedical engineering, based on the methodical method of *Pahl* et al. [5.3].

According to Pahl et al., the design process is divided into four stages:

- precisely defining the task (problem identification)
- the concept stage
- the design
- drawing up the final solution (detailed design)

As the example involves an interdisciplinary development project, it is particularly important to draw up only a few, but at the same time all, of the problem or work-related (sub)functions required for adequate structuring of the task and to represent these in a functional structure. It is also necessary to use a generally understood vocabulary. This enables us to ensure that people not yet involved in the process or people who do not have engineering training, e.g., medical experts or biologists can easily obtain an overview. This integration of employees from the individual specialized fields is necessary in order to be able to implement all medical and biological requirements at a high level.

5.2 Precisely Defining the Task

5.2.1 Task

The engineering system to be developed is a test setup for experiments with live human cells. The task (problem) for the designers was drawn up by the responsible medical experts. An extract from this is shown in the following.

For decades it has been known that certain cells in the human immune system are practically incapable of functioning in weightlessness. This can pose a serious problem for long-term stays in space on the International Space Station (ISS), or flights to Mars. The basic mechanism is to be investigated by means of weightlessness experiments with the help of parabolic (ballistic) flights. To this end, experimental equipment is to be designed with which tests on live cells can be performed onboard parabolic flights and in weightlessness. These experiments should also answer the question of whether humans are at all capable of living in weightlessness for any lengthy period. The findings can also be used in therapy for diseases of the immune system. It is necessary to mix the living human cells with an activator liquid and with a stopping liquid after a certain time. All the necessary safety requirements must be observed.

The designer's task consists of precisely defining this problem. This means that they must first draw up a functional engineering description. The aim is to draw up the whole function and all input and output variables for the engineering system to be developed.

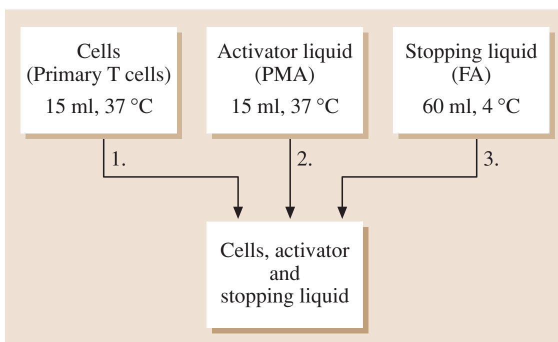


Fig. 5.1 Liquids to be mixed

5.2.2 Functional Description

The functional engineering description is drawn up by the responsible designer. It is used to clearly define the task or problem the designer has been set. At the same time it provides a basis for discussion with the other team members. In this way it is possible to identify early on whether there are any communication problems. In interdisciplinary projects it is particularly important to integrate the information of the non-engineering science team members into the technical preparations and therefore to create a basis for a methodical approach. It this project it was particularly important for the medical experts/biologists and engineers to speak the *same language*. The functional description is usually verbal. Frequently diagrams or initial sketches are also produced to depict the whole function to be fulfilled transparently. Figure 5.1 shows the outline technology for the test setup to be developed.

This rough structuring was based on notes taken during team meetings and a functional structure drawn up by one of the medical–biological team members (Fig. 5.2).

This is already very finely structured. However, it is not drawn up in the usual form used in design methodology [5.3]. Further, such a precise description of a focused possible solution excludes other approaches and solutions in advance. The functional engineering description or the overall function to be fulfilled by the test setup can be described as follows.

A test setup is to be developed that enables three different cell lines to be mixed, to a large extent ho-

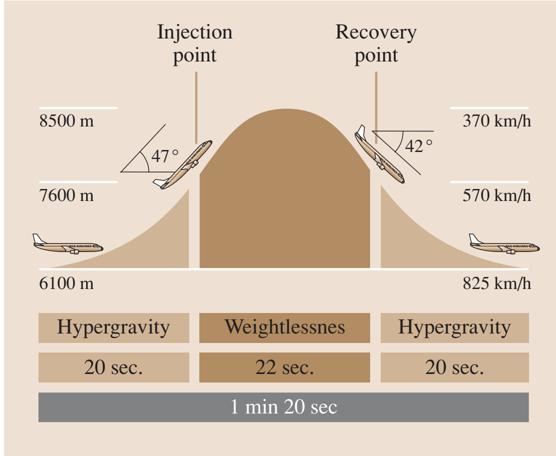


Fig. 5.3 Flight parabola for generating weightlessness (microgravitation) (after [5.61])

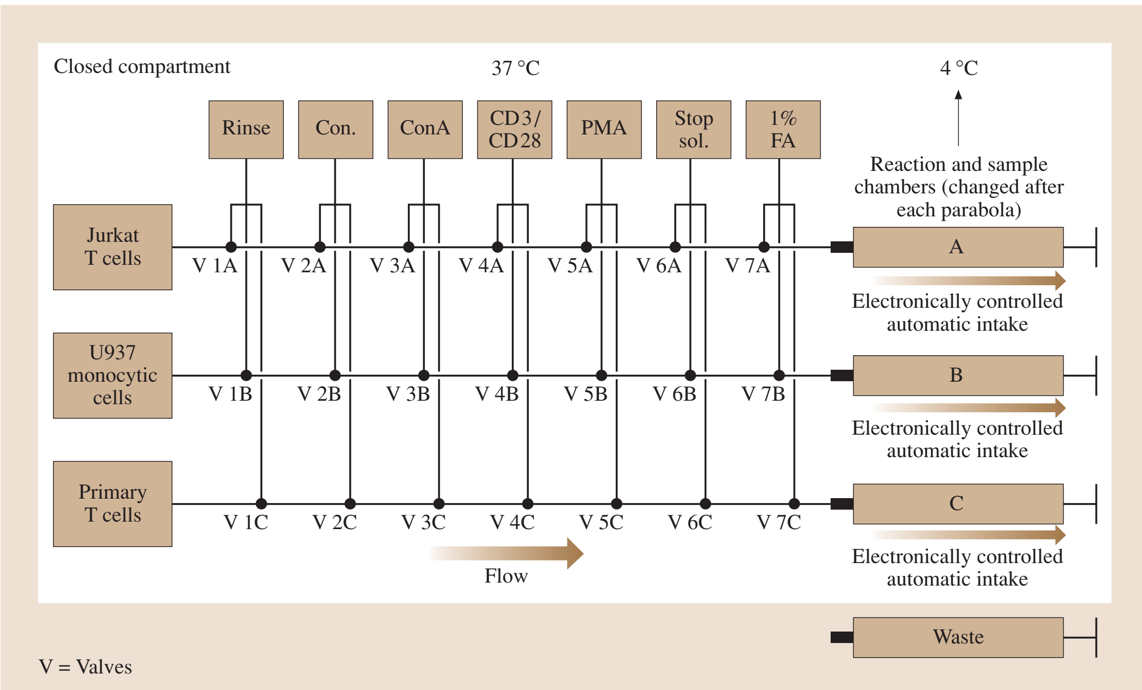


Fig. 5.2 Functional description from a medical point of view

	Product: *Parabolic Flight*		Date: 06.02.06	Sheet 03
	Requirements			Source Respon-sibility
	No.	Descriptive information	Numerical info/comments	
Overall space required/ connection dimensions/ installation conditions		Aircraft door width	– 1.07 m	
		Aircraft door height	– 1.93 m	
		Cabin length	– 20 m	
		Maximum rack height	– 1,500 mm	
		Fixing points for experimental setup	– Mean rail spacing (y-axis) a) 503 mm b) 1006 mm – Hole diameter for screw M10 = 12 mm – Hole spacing in x direction = n * 25.4 mm > 20 inches (1 inch = 25.4 mm)	
		Maximum load per unit area over 1 m fixing rail length	– 100 kg	
		Rack structure	– Baseplate or frame connected to the seat rail system of the aircraft	
			– There must not be any parts protruding from the baseplate in the direction of the flooring	

Fig. 5.4 Extract from the requirements list

mogeneously, with certain activator liquids at the start of the weightlessness phase. Just before the end of the weightlessness phase a stopping liquid is to be added to the cell vessels filled with a cell type and an activator liquid.

In order to fulfil the specified medical requirements, combinations of three different cell liquids, three different activator liquids and two stopping liquids (Fig. 5.1) must be realized.

The condition of weightlessness was achieved with the help of parabolic flights. This means that an aircraft flies in a precisely defined parabola and the condition of weightlessness (micro-gravitation) is available for approximately 22–25 s (Fig. 5.3).

A main requirement is the fulfilment of all safety requirements in the test setup. Primarily, that under no circumstances may liquids escape from the test setup during the parabolic flights. Some of the cell lines used are genetically modified tumor cells and immune cells isolated from blood donators, and toxic liquids such as formaldehyde. These could pose a risk to the flight personnel during the weightlessness phase. This means that all parts that come into contact with the media or cell, activator or stopping liquids must be designed with double walls.

A further requirement is that the temperature of the cell and activator liquids must be 37 °C and the temperature of the stopping liquids must be 4 °C (Fig. 5.1). Further points included in an initial functional engineering description are:

- enable fast and easy equipping with liquids
- realization of the direct safety stage [5.3], i.e., leakproof under the conditions in the aircraft
- clear functional sequences
- good miscibility of the liquids during the experiment in the cell culture bag
- fill under exclusion of air
- to a large extent transparent construction for observation of whether air inclusions exist
- low weight (mass)
- small space requirement
- good cost-effectiveness

This initial functional description is the basis for drawing up a requirements list.

5.2.3 Requirements List

When the task or problem is more precisely defined, other individual characteristic values and special requirements are determined. It is necessary to adequately describe all of the requirements set, both qualitatively and quantitatively. In this project this is achieved

- through discussions with the other team members (biologists, medical experts)
- through literature and patent research
- analysis and evaluation of all applicable rules, regulations, etc. (technical requirements of the aircraft operator) [5.12]

The results of the precise task definition stage are documented in the requirements list. This usually contains the objectives to be realized and the prevailing conditions in the form of requirements and wishes [5.3]. The requirements must always be fulfilled. The wishes listed are to be realized if possible. The boundary between requirements and wishes can often not be clearly defined, especially in interdisciplinary projects. For this reason, such a differentiation

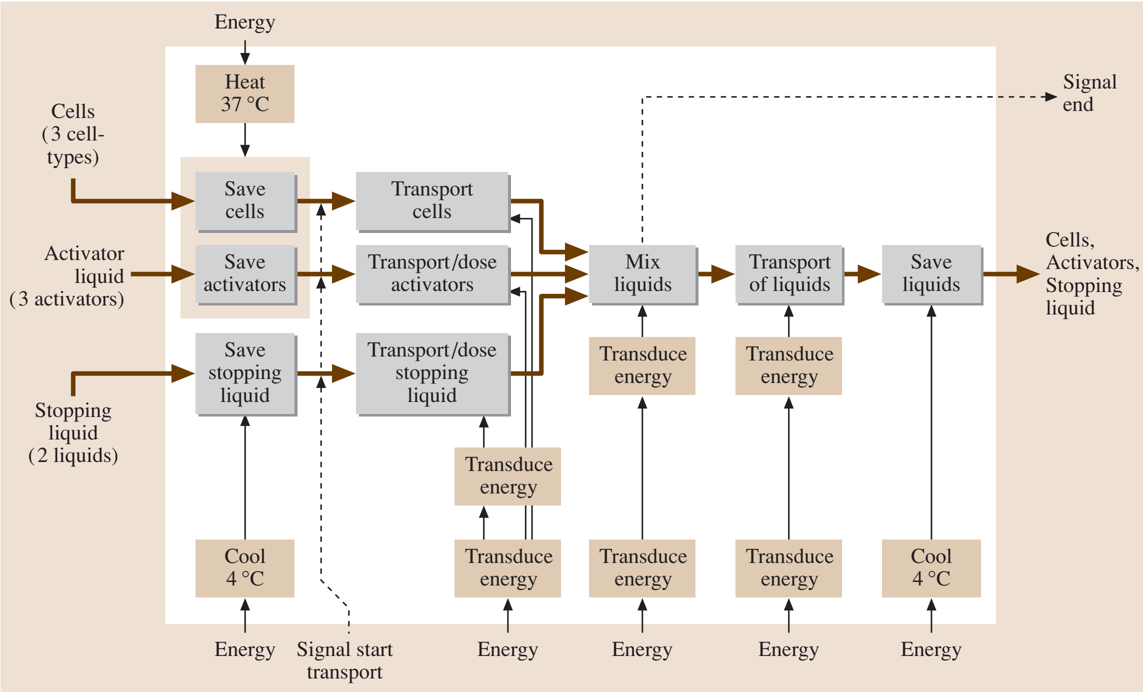


Fig. 5.5 Simplified functional structure

was dispensed with for this project. An extract from the requirements list drawn up is shown in Fig. 5.4. At the same time, the requirements list is the legal basis for all further activities, including in this project.

5.3 Conceptual Design

In the conceptual design stage the overall function is structured. The result is a functional structure (Fig. 5.5). This means that the whole system is divided into its subfunctions and their links.

This procedure enables optimum analysis of the whole system. Efficacy principles were then assigned to the subfunctions.

Efficacy principles are usually based on physical effects that enable the function to be fulfilled. These are combined with geometric and material characteristics. In this project, conventional, intuitive and discursive solution-finding methods [5.3, 13] were used to draw suitable action principles. In detail:

- conventional (e.g., literature or patent) research
- intuitive (e.g., brainstorming)
- discursive (e.g., the use of design catalogues).

When suitable efficacy principles have been determined for fulfilling the function, they are assigned to the subfunctions in a classification diagram. In this project the morphological box (Fig. 5.6) was used for this.

The efficacy principles drawn up to fulfil the individual subfunctions must then be purposefully linked to each other. When drawing up the concept for the test setup it was of primary importance that the high safety requirements be fulfilled with all the selected efficacy principles. This results in different efficacy structures. In practice it is usual to draw up a maximum of three efficacy structures. Figure 5.7 shows the path through the morphological box.

The efficacy structures generated are specified in greater detail and further developed to form basic solutions. The individual basic solutions are then assessed. An extract of the assessment (rating) undertaken in this

Function / Option	1.	2.	3.	4.
Cool	Cooling accumulators (Source: Novodirect)	Peltier cooler (Source: Rübsamen & Herr GmbH)	Cryogenics	Refrigerator principle (compressor + heat exchanger)
Heat	Sheet-type heating elements (silicon heating mats) (Source: Hewid GmbH)	Heat cartridges (Source: Hewid GmbH)	Infrared radiators (Source: Hewid GmbH)	Chemical reaction (thermal accumulators) (Source: riedborn-apotheke)
Transport/ meter	Flexible tube pump (Source: ismatec)	Piston pump (Source: Novodirect)	Diaphragm pump (Source: Novodirect)	Gear pump (Source: Novodirect)
Mix	Use of the pumps, pressure surge	Magnetic stirrer principle (Source: Novodirect)	Swivel movement of the vessels (shaker, vibrator)	

Fig. 5.6 Morphological box

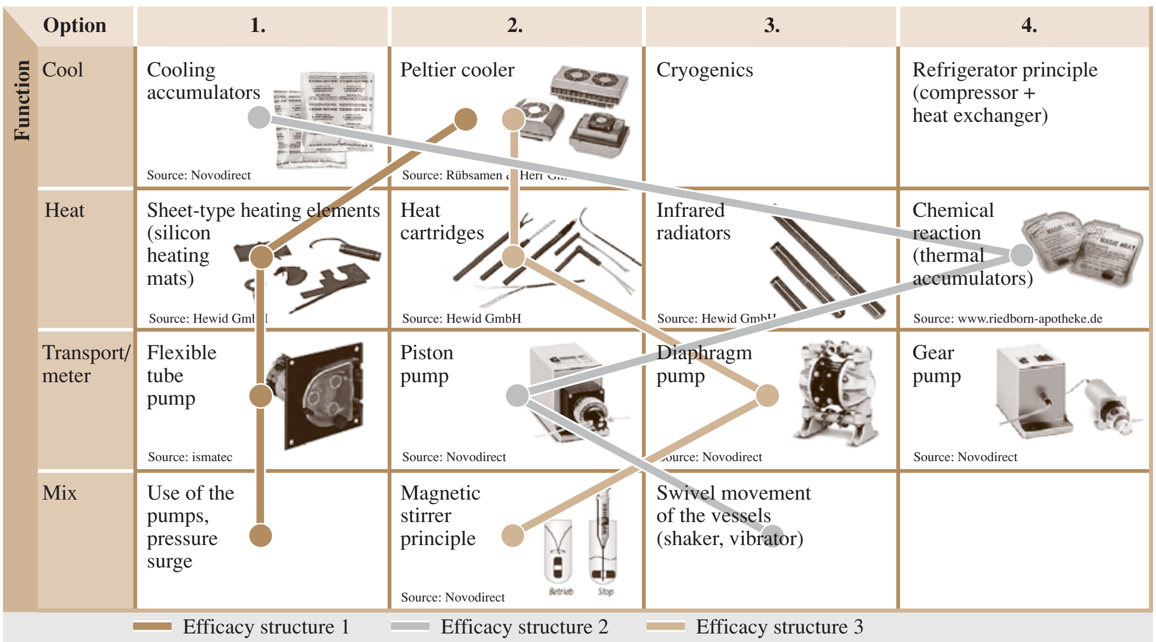


Fig. 5.7 Path through the morphological box

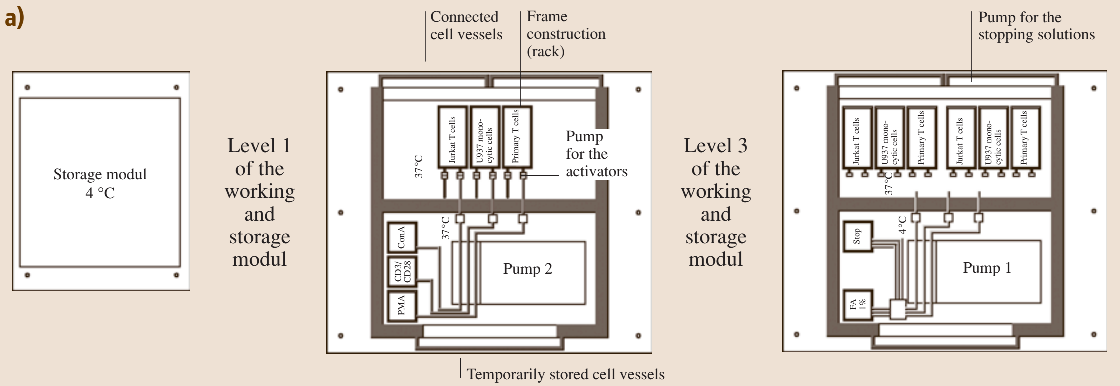
project is shown in Fig. 5.8. The assessment criteria and assessment was carried out by the whole project team.

As a result, a basic solution was released to be drawn up. In general, as in this project, this is the efficacy structure with the best rating. It forms

Assessment criteria	Weighting (W)	Opt. 1		Opt. 2		Opt. 3	
		Item (P)	W x P	Item (P)	W x P	Item (P)	W x P
37 °C uniformly distributed in the area of the cell storage and the activator liquids	0.8	4	**3.2**	1	**0.8**	3	**2.4**
4 °C uniformly distributed in the area of the stopping liquids and in the subsequent storage system	1.0	4	**4**	1	**1**	4	**4**
Low energy requirements	0.6	2	**1.2**	4	**2.4**	2	**1.2**
Low mass	0.7	3	**2.1**	3	**2.1**	2	**1.4**
Sterile pumping system with few mechanical components in area of contact with the pumped media	0.5	4	**2**	2	**1**	2	**1**
Total			30.0		25.3		27.1
Percent			0.83		0.70		0.75

Fig. 5.8 Extract from the assessment list

a)



b)

Objective	Basic rule	
	Design	
Fulfil the function	**Clear**	Helps to reliably predict effects
Economic realization	**Simple**	Small number of parts, simple shapes » fast and better production; but simple also means » clearly arrange for operation
Safety for man and the environ-ment	**Safe**	Consistent treatment of issues of durability, reliability, lack of accidents

c)

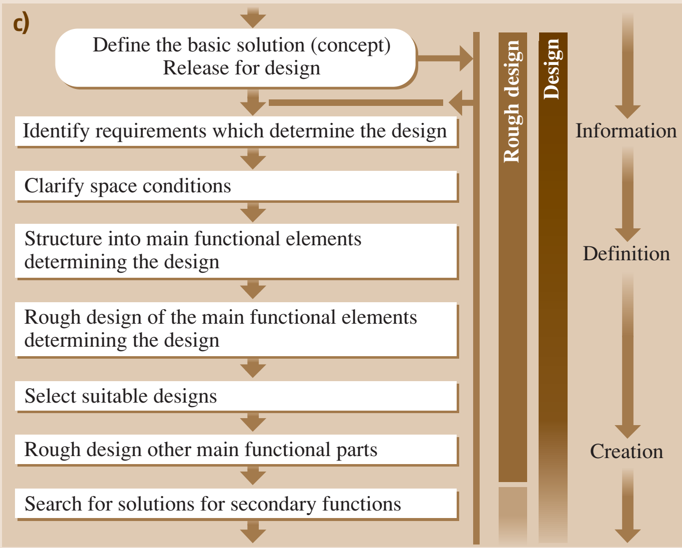


Fig. 5.9a–c Basic solution, released to be drawn up. **(c)** Extract from the main design activities (after [5.3])

the basis of the design stage. This is shown in Fig. 5.9.

The basic solution consists of two separate modules. The first module is the actual working module, in which the cells, the activator and stopping liquids and all the necessary units are installed for pumping. This module is divided into three levels/submodules positioned on top of each other. Level 1 contains the pump for the stopping liquids and the cell vessels stored for filling, which is separated from the pump by a wall. Above this is the level for the power supply and controls. The top area contains the pump for the activators and, separated from this by a wall, the cell vessels to be filled are connected. After consulting the medical experts the information was received that three individual cell vessels are filled in parallel. The second module is the cooling module in which all filled cell vessels are stored at 4 °C after the experiment.

An important basis for this design is the joint specification from the medical experts and engineers in the project team that a previously precisely defined quantity of the cell liquid is already located in special cell vessels. The activator and stopping liquids are then pumped into these. The result is a simpler and better solution than the one previously proposed by the medical experts in Fig. 5.2. This arose as a direct consequence of the methodical approach described in Sect. 5.2.2. The new solution prevents the cells themselves from being metered into the installed cell vessels by the pump, which would have generated shear forces that would have had a negative effect on the cells, exposing them to considerable stresses. In addition, it avoids repeated flushing of the pipes/lines for liquid transport. This fact thus minimizes the number of components (pumps, valves, lines) and therefore the costs incurred. In addition the costs for the liquids to be pumped are minimized (less flushing ⇒ less waste). This was an important aspect of *simply* fulfilling the basic design rule. The content is discussed in Sect. 5.4.

5.4 Design

The design stage is divided into:

- Rough design
- Detailed design
- Complete and check

The solution is more precisely defined during the design until a complete structure exists [5.3]. All the technical and economic requirements must be clearly and completely drawn up. The result is the design of the solution option, defining all the geometric, material and condition characteristics. In this stage, the following three basic design rules must be observed: *simple*, *clear* and *safe* [5.3].

Figure 5.10 shows an extract of the main design activities.

The individual activities for developing the test setup for experiments with human cells are described in the following.

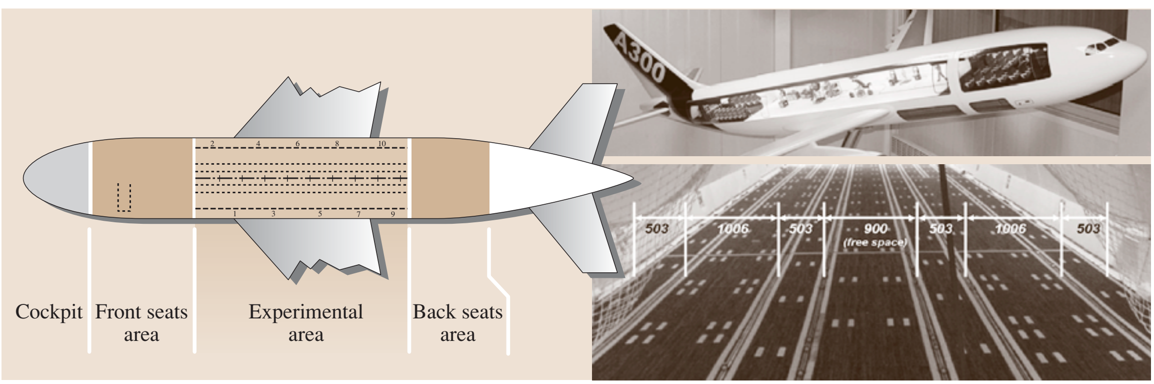


Fig. 5.10 Available (free) space and fixing options in the Airbus A300 of Novespace [5.61]

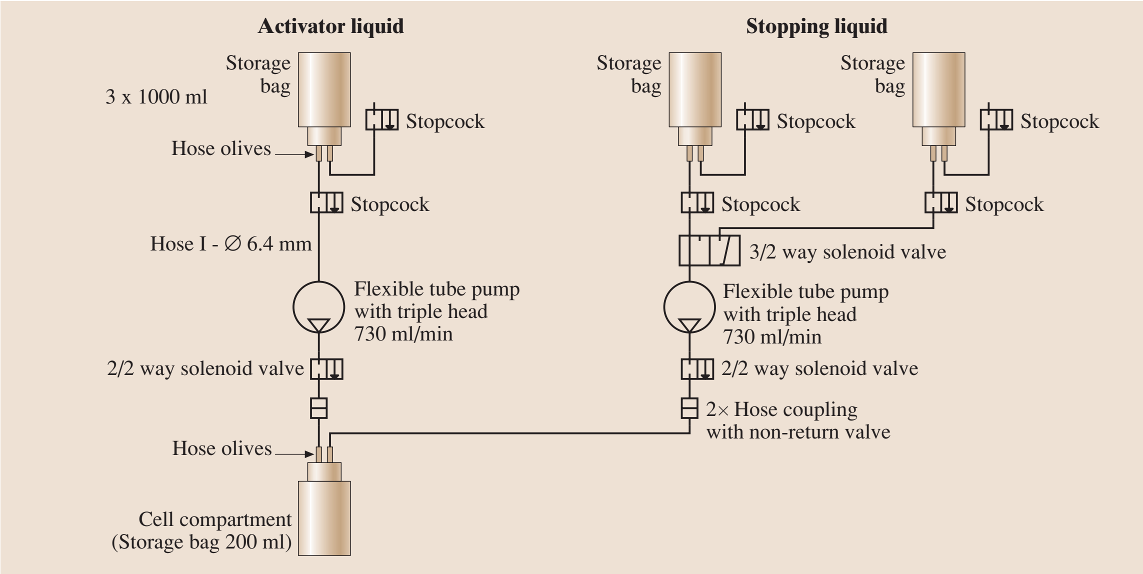


Fig. 5.11 Flow diagram for a cell vessel to be filled

5.4.1 Identify Requirements that Determine the Design and Clarify the Spatial Conditions

The decisive requirements are essentially set by the ambient conditions, e.g., available space, effective and allowable stresses and loads, and the requirements set by the work sequence. The main requirements for the test setup to be developed are specified by the information contained in the aircraft operator's user manual. This document provided information on the internal dimensions of the aircraft frame and therefore the maximum effective heights and widths, the type and location of the fixing points, door dimensions for loading, the maximum allowable loads per unit area, details of the power supply, etc. (Fig. 5.11).

Requirements determined by the layout such as the flow directions and handling sequences were specified by the biomedical description of the experiment.

5.4.2 Structuring and Rough Design of the Main Functional Elements Determining the Design and Selection of Suitable Designs

In this activity a roughly structured diagram is drawn up for the main material flow. It names the preliminary main components selected. The main material flow is the pumping of activator and stopping liquids from storage into the cell vessel. Flexible tube pumps and suitable valves and hoses were selected for this task. The pump and valve sizes were chosen on the basis of the time and delivery rate requirements

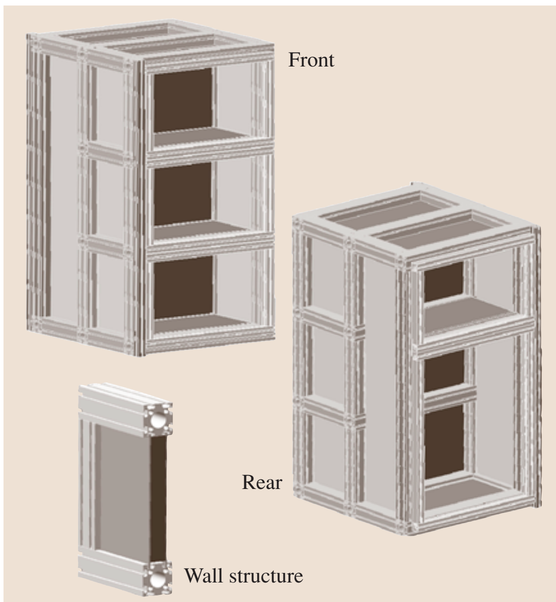


Fig. 5.12 Working module rack: front, rear, wall structure

based on the biomedical process variables. Because of these specifications, instead of the originally planned flexible tube pump with a triple head for all activators and the same pump for all stopping liquids, six separate pumps had to be selected to achieve the objective.

Another main functional element was the frame (rack) for the modules. Extruded aluminium sections and accessories, available as a modular system and frequently used for automation engineering, were used in the design. The choice of section size depended on the calculated loads. Figure 5.12 shows the initial design of the working module.

5.4.3 Detailed Design of the Main and Secondary Functional Elements

The design of the main and secondary functional elements is a process that takes place in parallel in everyday design, as both groups may have a strong influence on each other. The pump–valve module (Fig. 5.13) is one of the main functional elements. Its decisive design requirements are those resulting from the biomedical process variables (size of the metered volume) and the boundary conditions resulting from the technical requirements (low mass, small space requirement, etc.)

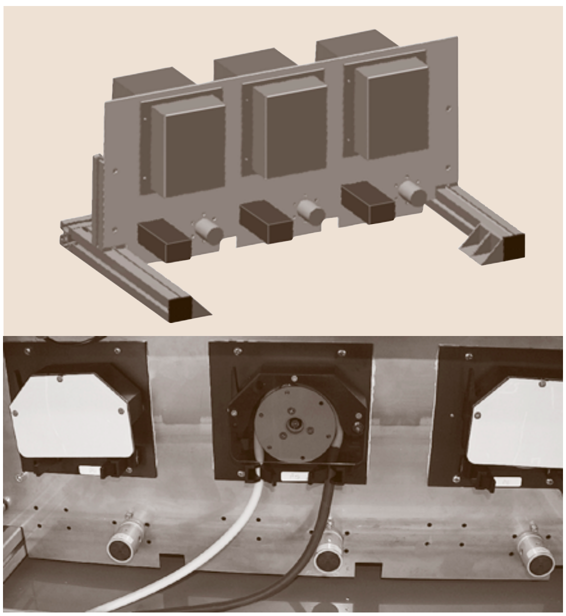


Fig. 5.13 Pump–valve module (during development and assembly)

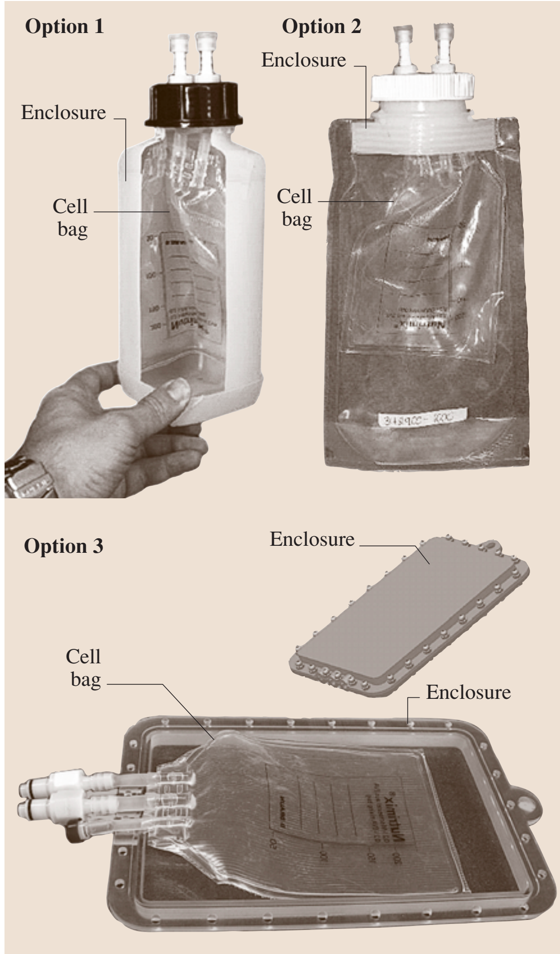


Fig. 5.14 Possible options for the secondary functional element: cell vessel (cell compartment)

A secondary functional element is the cell vessel which contains 15 ml of cell liquid at the beginning and into which the activator is injected before weightlessness starts, followed by the stopping solution after approximately 22–25 seconds. The filling must be able to take place under the exclusion of air and in sterile conditions. Further, due to the safety requirements, this vessel must be designed with a double wall and enable fast removal of the contained liquids after the experiment. For biological and economic reasons the inner part of the vessel should be a one-off (disposable) product and the outer one should be reusable. Due to these requirements, further solutions were conceived and tested (Fig. 5.14).

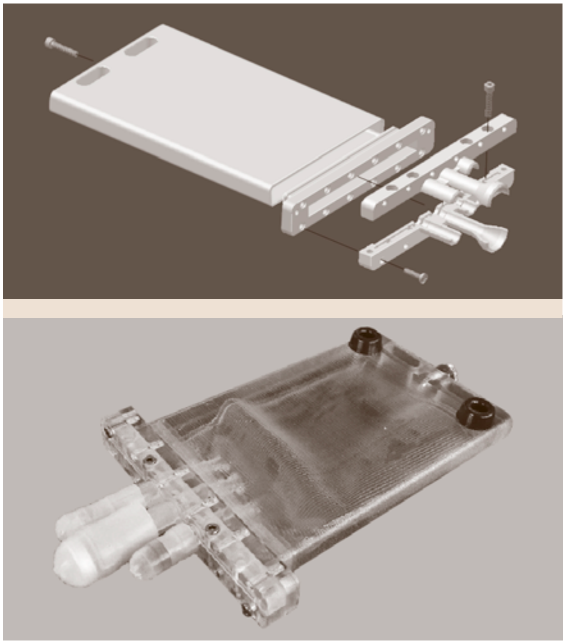


Fig. 5.15 Cell vessel structure

Option 1 consists of an inner infusion bag integrated into a conventional 1 l plastic bottle. The connections are realized via the hose olives screwed into the bottle lid. Option 2 has a similar structure with a second liquid bag with a screw lid that provides the second wall. In the third solution the outer enclosure is formed by a specially produced plastic enclosure made using a rapid prototyping method.

The first two options have a very favorable price as all the components are production items. However they contain substantial defects in their functional fulfilment (filling under the exclusion of air). The reason for this is that, when the inner infusion bag is screwed in, it irreversibly twists. As a result, clear material flow is not possible, i. e., the basic design rule *clear* was not fulfilled. The third option is the most costly. However, it enables complete functional fulfilment according to the requirements. This is the preferred option and was released for design optimization. The result of the design using a continuous functional test during the optimization phase is shown in Fig. 5.15.

5.4.4 Evaluation According to the Technical and Economic Criteria, and Specification of the Preliminary Overall Design

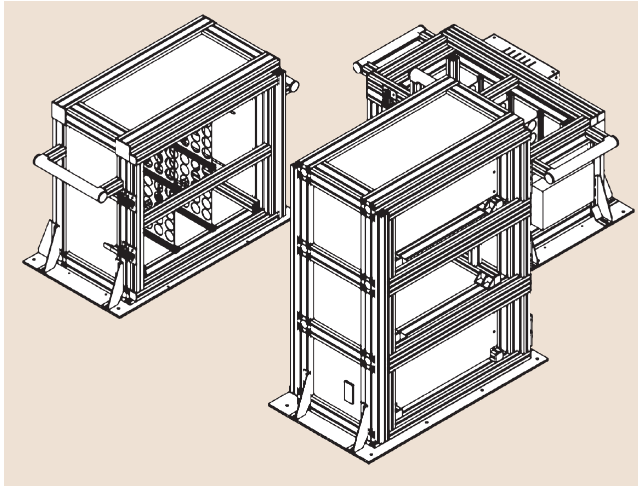


Fig. 5.16 Design for the experiment modules

During the design and associated continuously performed testing and control process it was found that individual technical requirements such as

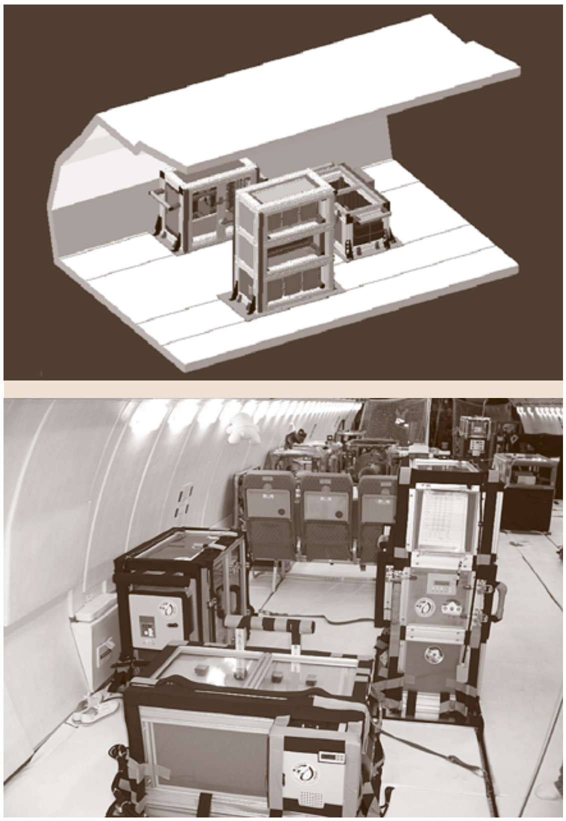


Fig. 5.17 Experiment modules

- compliance with the maximum module dimensions
- compliance with the maximum mass
- compliance with the electricity consumption

could not be realized. Deviations from the requirements set in the requirements list were found.

Furthermore, in this phase of the development work the functional fulfilment was checked. No deviations from the requirements list were found. The specified delivery rates of the pumps were fulfilled. The temperature ranges to be realized were achieved and the whole operational sequence was clear.

With respect to the economic criteria to be realized, there were also no deviations from the requirements list. All the specifications, such as material costs or production and assembly costs, were met.

A second design was drawn up based on the deviations from the requirements list. This design consisted of three separate modules (Fig. 5.16).

Module 1: The heating module for storing the cell compartments at 37 °C (incubator) before the experiment

Module 2: The actual working module, in which the cell vessels are filled

Module 3: The cooling module for storing the cell vessels after the experiment (4 °C)

This design was able to fulfil all of the technical and economic requirements and was released for further design work.

In the final phase of the design stage it is necessary to adapt the solution to existing standards and regulations. The individual components are assigned binding materials. During this phase, among other things, the drawings relevant for production are completed and the product documentation is produced. Figure 5.17 shows the result of the development.

5.4.5 Subsequent Consideration, Error Analysis, and Improvement

The main activities during the design phase according to [5.3] include the item: *checking for errors and disrupting effects*. This is a meaningful and necessary activity during design to prevent abortive development. However, systematic error analysis was only possible to a limited extent for the developed modules. Unlike other projects, in which empirical values already exist, process sequences are easy to follow or tests, or preliminary trials performed in parallel with the development process help to check for errors or faults, the analyses carried out for the experiment modules described here were to a large extent based on assumptions. During the development phase it was not possible to realize the condition of microgravitation for testing of the modules of the test setup. For this reason it was important to document and analyze the sequence and function of the modules during the parabolic flights. This was the only way to specifically enable error corrections and improvements. Several examples of modifications to the modules are listed in the following.

- Most of the hoses from the medium replaced with rigid pipes
- Integration of safety sensors to identify the presence of the vessels to be filled before injection starts
- Replacing the manually opened venting valves in the cell vessels with automatically opening valves
- Improving the fixing (stoppers) of the cell vessels in the heating and cooling module

These modifications will be realized for subsequent flights.

The development and design of engineering systems according to methodical aspects based on information from the literature [5.1–3] is a useful procedure. The guidelines of design methodology were also applied in this interdisciplinary development project together with its tools, such as the requirements list, functional structure and morphological box, to name just a few. During the design phase of the product development process it was important to comply with the basic design rules:

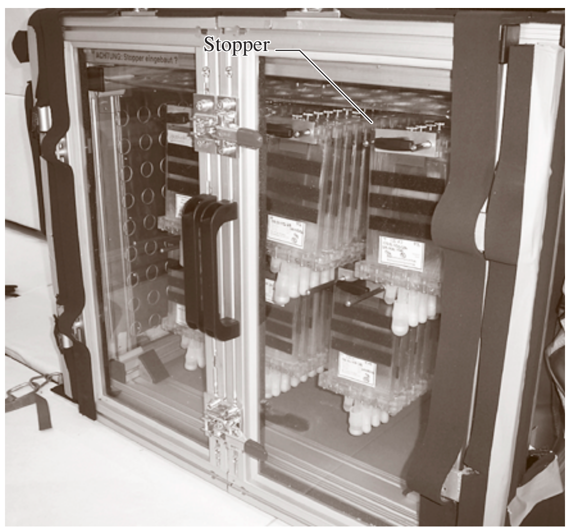


Fig. 5.18 Stopper in the heat module

Part B | 5.4

simple, *clear* and *safe* [5.3]. Several items that clearly show the realization of these three criteria are:

1. Simple:
   – Use of a module system for the rack design and
   – only 15% of the required components are specially made (turned or milled parts).
2. Clear:
   – The liquid flow path is clear and does not lead to indefinable conditions
3. Safe:
   – Redundant arrangement of parts absorbing forces and
   – fixing of moving parts (cell vessels).

Primary importance was placed on realizing the direct safety requirements during the development activity. This task was successfully solved.

However, unlike the theoretical principles, practical experience shows that, especially during the conceptual and design phases, the experience and intuition of the designer are increasingly used to find the solution and systematic development is consciously dispensed with. This is not due to the fact that taught theoretical procedures are not generally practical, but to the increasing time and cost pressure for the development. It is often not possible for the designer to define several options for all main and secondary functions or to produce designs for the overall and part solutions and still produce a solution on schedule and within the cost framework. Here there is a risk that technically and economically better solutions are overlooked. One example from the project above is the fixing mechanisms (stoppers, Fig. 5.18) for limiting the sixth degree of movement for fixing the cell vessels in the working and heating module. Several optional solutions were not determined for this secondary functional element in advance, but instead the *first best* solution was used. In the technical test evaluations after the flights the operating personnel complained that due to the high stresses during parabolic flight these stoppers were difficult to undo and refasten. This solution had worked, but not optimally and will be changed for the next series of flights.

5.5 Design and Manufacturing for the Environment

The environment can be envisioned as interacting with human society in two ways: as a *source* of natural resources, and as a *sink* for emissions and wastes. The environmental problems addressed here are all related to overuse of both sources and sinks. Overuse of sources shows up as depletion and the reduced quantity and quality of resources. Overuse of sinks shows up as unbalancing of the harmony of previously natural processes. Often the change in balance takes years to detect and can be influenced by a variety of factors, making isolation and identification of the problems difficult and sometimes controversial. Nevertheless, over time many of these problems have been identified. They include ozone depletion, global warming, acidi-

Table 5.1 List of environmental concerns and links to manufacturing processes

Environmental concerns	Linkage to manufacturing processes
1. Global climate change	Greenhouse gas (GHG) emissions from direct and indirect energy use, landfill gases, etc.
2. Human organism damage	Emission of toxins, carcinogens, etc. including use of heavy metals, acids, solvents, coal burning
3. Water availability and quality	Water usage and discharges e.g. cooling and cleaning use in particular
4. Depletion of fossil fuel resources	Electricity and direct fossil fuel usage e.g. power and heating requirements, reducing agents
5. Loss of biodiversity	Land use, water usage, acid deposition, thermal pollution
6. Stratospheric ozone depletion	Emissions of chlorofluorocarbons (CFCs), hydrochlorofluorocarbon (HCFCs), halons, nitrous oxides, e.g., cooling requirements, refrigerants, cleaning methods, use of fluorine compounds
7. Land use patterns	Land appropriated for mining, growing of biomaterials, manufacturing, waste disposal
8. Depletion of non-fossil fuel resources	Materials usage and waste
9. Acid disposition	Sulfur and NO_x emissions from smelting and fossil fuels, acid leaching and cleaning

fication, and eutrophication, among others. Corrective action often involves changes in the types and ways we use materials and energy for the production, use, and disposal of products. Table 5.1 lists commonly agreed environmental concerns and aspects of production, consumer use, and disposal that contribute to these concerns.

Table 5.1 clearly conveys the message that many of our environmental problems are directly related to materials usage, including energetic materials. In particular, note that several prominent concerns listed in Table 5.1 are directly related to our use of fossil fuels to generate energy. These include: CO_2 and NO_x emissions from the combustion of all fossil fuels, and SO_x and several heavy metals including As, Cd, Cr, and Hg, which are deposited onto land from the combustion of coal [5.14, 15]. In fact, at least four out of nine of the concerns listed above are related to fossil fuel use, including numbers 1, 2, 4, and 9. Because of this overriding importance, we will pay particular attention to tracking energy usage in the life cycle of products.

5.5.1 Life Cycle Format for Product Evaluation

A very important aspect of environmental analysis simply involves *connecting the dots*, in other words, showing the interconnectivity of human activities, and in particular, material flows. Few people contemplate where resources come from, or where they go after they are used, yet this is essential for life cycle analysis. With a life cycle accounting scheme one can then properly *burden* each product or activity with its environmental load. This information, in turn, can be used to answer the question, *is the utility gained from this product or activity worth the associated environmental load*? Although conceptually simple, this task is, in fact, quite complex. The major complexities are:

1. establishing system boundaries
2. obtaining accurate data
3. representing the data with concise descriptors that appropriately assign responsibility
4. properly valuing the results

Our approach will be to represent the product using material flow diagrams that capture the major inputs and outputs. In general, we will not attempt to relate these inputs and outputs to specific levels of environmental harm but only to identify them as *environmental loads*, known to cause harm, and which are excellent targets for technical improvement. When specific amounts of inputs used or outputs emitted are given, this type of analysis is called a life cycle inventory (LCI). The full life cycle analysis (LCA) includes LCI plus a connection between the loads produced and associated harm caused and often a ranking value among the different types of harm. Some LCA methods use these ranking values to generate a single number result. This can greatly ease decision-making, but requires agreement with all of the implied value tradeoffs, something that is often difficult to accomplish.

Before proceeding further, it is important to more clearly establish the idea of a product life cycle. This is generally conceived as a materials flow process that starts with the extraction of raw materials from the Earth and ends with the disposal of the waste products back to

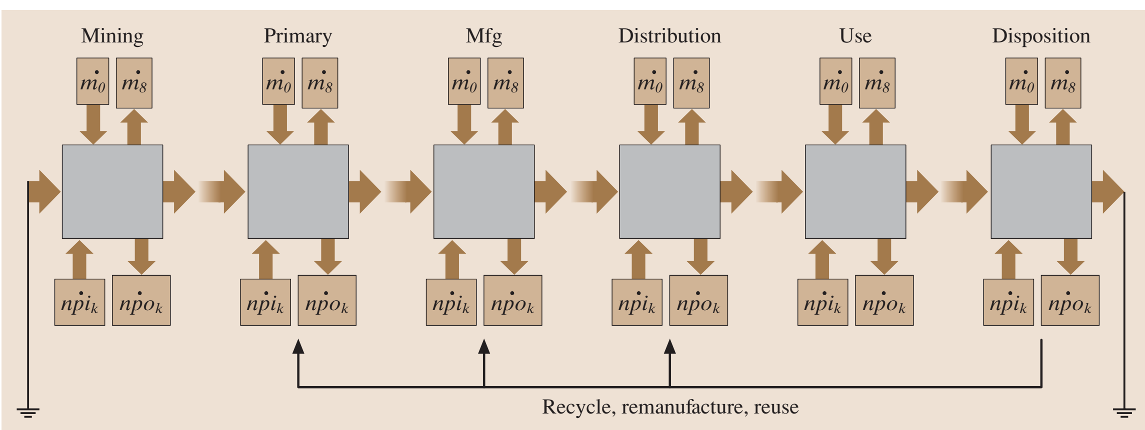


Fig. 5.19 Product life cycle material flows

Table 5.2 The environmentally responsible product assessment matrix [5.21]

Life cycle stage	Environmental stressor Materials choice	Energy use	Solid residues	Liquid residues	Gaseous residues
Premanufacture	11	12	13	14	15
Product manufacture	21	22	23	24	25
Product delivery	31	32	33	34	35
Product use	41	42	43	44	45
Refurbishment, recycling, disposal	51	52	53	54	55
(The numbers are the indices for the matrix element M_{ij})					

the Earth. The general stages of this linear *once-through* cycle are:

1. material extraction
2. primary processing and refining
3. manufacturing
4. product distribution
5. use
6. final disposition

This sequence follows the principal product material flow, but of course there are multiple cross flows (consider the materials used by products, e.g., paper in printers and gasoline in automobiles) as well as back flows, such as product reuse, component remanufacturing, and material recycling. Figure 5.19 illustrates these flows in a general way, indicating cross flows both from nature and society as well as the major recycling flows. Society can then be represented by a vast array of these networks, interconnected but ultimately all originating from and leading to the ground – the Earth. This thought experiment clearly suggests the complexity of our problem. In practice this task is simplified by clearly defining the system boundaries and the objectives of the life cycle study. Problems can arise when the system considered is too large due to the interconnectivity of materials systems, and when the system considered is too small due to truncation. Matrix inversion methods, identical to those used in economic input–output analysis [5.16], along with high-level summary statistics have been called upon to help with the first problem [5.17, 18], while experience, iteration and hybrid approaches are used to address the second [5.19, 20].

The commonest practice among LCA practitioners is based on developing process flow diagrams similar to Fig. 5.19 for the product, and tracing the major input and output paths to Earth. This requires data such as a bill of materials and lists of manufacturing processes, common use scenarios, distribution channels, and end-of-life characteristics for the product. The output is then a long list of material and energy inputs as well as emissions to the environment. These lists can easily include hundreds of materials, which then require some simplification and aggregation for interpretation. In this chapter, we will use a simplified format suggested by *Graedel* in his book on streamlined life cycle analysis (SLCA) [5.21]. This involves examining each stage of the life cycle and identifying major impacts and opportunities for improvement in five categories:

1. materials choice
2. energy use
3. solid residues
4. liquid residues
5. gaseous residues

Graedel then suggests scoring each stage of the life cycle for each of the five categories with a numerical score from 0 (the worst) to 4 (the best). These scores are given relative to best practice for the product under consideration. In general, a score of 0 is reserved for

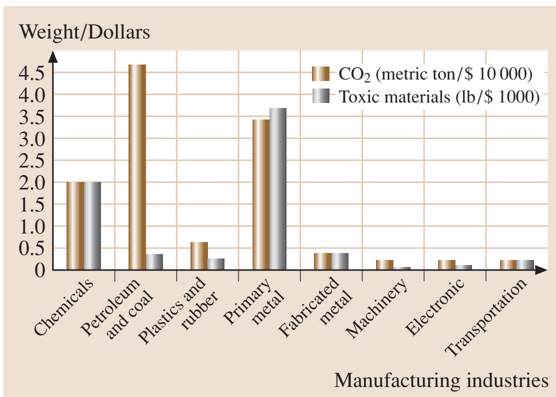


Fig. 5.20 CO_2 and toxic materials for several manufacturing industries

Part B | 5.5

a blatantly poor and/or uninformed practice that raises significant environmental concern, while a score of 4 indicates excellent environmental performance with no known serious concerns. A perfect product would thus obtain a score of 100. Graedel gives more-detailed guidance on how to score each element of the 5×5 matrix, as shown in Table 5.2, which represents the product.

5.5.2 Life Cycle Stages for a Product

In this section we will identify some of the major environmental issues that appear in each of the five stages of a product life cycle. The scoring of products for SLCA depends on the extent to which the designer and manufacturer make an effort to avoid these problems and substitute alternative materials and technology when possible.

Premanufacture: Materials Extraction and Primary Processing

Many of the environmental impacts associated with materials selection appear to occur in the very early stages of the material life cycle. This can be surmised by looking at United States national statistics for energy use, pollutants, and hazardous materials by various industrial sectors. For example, in Fig. 5.20, some of the manufacturing industries are broken down by standard industrial categories [standard industrial classification (SIC) codes] in terms of CO_2 and toxic materials per value of shipments. The primary processing of chemicals, petroleum and coal, and primary metals, have significantly larger environmental loads than other manufacturing sectors such as plastics and rubber, fabricated metals, machinery, electronics, and transportation. While not shown in Fig. 5.20, the metal mining industry would also show up prominently on this list. For example, toxic material releases for US metal mining in 1998 were equal to 145% of the toxic material releases from all of the manufacturing industries in the United States combined (including primary processing) [5.22].

These large normalized impacts can be explained in two ways – relatively large emissions and relatively low prices. Primary processing industries handle very large quantities of materials, introducing many opportunities for economies of scale. At the same time, this high materials usage leads to high waste and emissions levels. For example, mining is very material intensive, producing ore waste-to-metals ratios that range from about 3:1

Table 5.3 Typical energy requirements for some common materials [5.?]

Material	Energy cost (MJ/kg)	Made or extracted from
Aluminum	227–342	Bauxite
Copper	60–125	Sulfide ore
Glass	18–35	Sand, etc.
Iron	20–25	Iron ore
Nickel	230–70	Ore concentrate
Paper	25–50	Standing timber
Polyethylene	87–115	Crude oil
Polystyrene	62–108	Crude oil
Polyvinylchloride	85–107	Crude oil
Silicon	230–235	Silica
Steel	20–50	Iron
Titanium	900–940	Ore concentrate
Wood	3–7	Standing timber

Table 5.4 Toxicity ratings for some of the elements [5.15]

Toxicity rating	Example elements
High toxicity	Beryllium, arsenic, cadmium, mercury, lead,
Moderate toxicity	Lithium, boron, chromium, cobalt, nickel, copper, bismuth
Low toxicity	Aluminum, silicon, titanium, iron, zinc, bromine, silver, tin, tungsten, gold,

Table 5.5 Classes of supply for some of the elements [5.15]

Worldwide supply	Example elements
Infinite supply	Bromine, calcium, chlorine, krypton, magnesium, silicon
Ample supply	Aluminum (gallium), carbon, iron, potassium, sulfur, titanium
Adequate supply	Lithium, phosphorus
Potentially limited supply	Cobalt[a], chromium[b], nickel[a], lead (arsenic, bismuth), platinum[b], zirconium
Potentially highly limited supply	Silver, gold, copper, mercury, tin, zinc (cadmium)

[a] Supply is adequate, but virtually all from South Africa and Zimbabwe. This geographical distribution makes supplies potentially subject to cartel control.
[b] Maintenance of supplies will require mining seafloor nodules. Note that aterials in parentheses are co-mined with the parent material listed in front.

for iron and aluminum, to 10 000 : 1 for gold. In addition, many metals exist as, or occur in companion with, metallic sulfides. Once these materials are exposed to the surface they can oxidize into sulfates and sulfuric acid runoff, which can cause significant damage by acid mine drainage. Many of the commonest metals can lead to acid mine drainage, including copper, iron, nickel, lead, and zinc. In addition, some of the early processes can use other hazardous materials. If these materials escape, widespread environmental damage can occur. For example, the leaching of gold employs toxic cyanide compounds.

Similarly, primary materials processing can be both materials and energy intensive. For example, the production of 1 kg of aluminum requires on the order of 12 kg of input materials and 290 MJ of energy [5.23]. The energy for this production plus other processing effects, in turn, leads to about 15 kg of CO_2 equivalent for every kg of aluminum produced [5.24]. Table 5.3 gives the energy requirements for some materials. Note that aluminum is in the high range of these materials, on the order of silicon but substantially less than titanium. The substitution of recycled materials can greatly reduce this energy requirement. Conversely the requirement for ultra high purity can greatly increase this requirement. For example, the recycled energy requirement versus *virgin* material is only about 5% for aluminum and 30% for steel [5.25], while the energy requirements for wafer-grade silicon used in the semiconductor industry is about 33 times that of commercial grade [5.26]. Hence, the mere act of selecting materials can in itself define a large part of the environmental footprint for a product. *Graedel* and *Allenby* suggest several other criteria to consider when selecting materials, including toxicity and abundance [5.15]. The ratings for some elements are given below in Tables 5.4 and 5.5.

Manufacturing Processes

As a group, manufacturing processes appear to be quite benign compared to materials extraction and primary processing, as indicated in Fig. 5.20. However, manufacturing processes often set many of the requirements for primary processing outputs. For example, processes with higher scrap rates require more energy in primary processing. Alternatively, processes that can use large quantities of recycled materials will have greatly reduced primary energy needs. This concept can be illustrated more rigorously by writing an equation for the embodied energy content for a hypothetical manufacturing process that uses E_m energy per kilogram of product produced. It has become common to discuss the energy *used up*

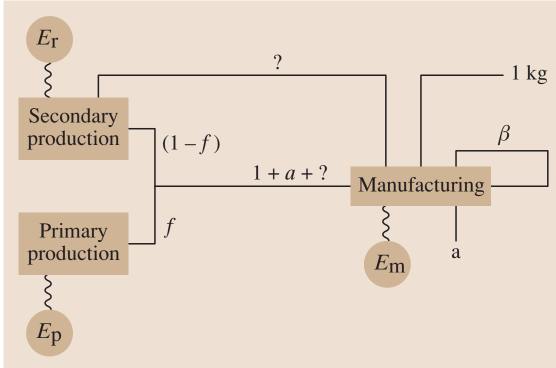


Fig. 5.21 System energy requirements for a manufacturing process

in a process, but by the first law of thermodynamics we know that the energy is not actually lost. Rather, it is made unavailable. A more accurate thermodynamic quantity, *exergy* can be used up, and is more precisely what we mean in our discussion of *energy used*. Let the waste fractions be: α to ground, γ to recycle, and β to *prompt scrap* (recycled within the factory). This process uses a fraction ϕ of primary material with embodied energy E_p and a fraction $(1-\phi)$ of recycled material with embodied energy E_r, where in general $E_r \leq E_p$. From this, the sum of the energy requirement E_s, to produce one kilogram of product is (Fig. 5.21).

$$E_s = (\phi E_p + (1-\phi)E_r)(1+\alpha+\gamma) + E_m(1+\alpha+\beta+\gamma) . \quad (5.1)$$

Hence, even though it may be that $E_m \ll E_p$, (5.1) illustrates the long reach of the manufacturing process and its influence both up and down the product life cycle. As an example, consider the differences between machining and casting a part. While it might be true that $E_{m\,casting} > E_{m\,machining}$, generally speaking $\phi_{machining} \gg \phi_{casting}$. Furthermore, the waste for machining, particular α and γ, which show up in the first part of (5.1), can be quite large. In contrast, for large casting operations, most metal waste shows up in β, which does not occur in the first term. Hence in some situations, and quite counterintuitively, casting may be a more environmentally benign process than machining. Of course, this statement is based only on embodied energy usage and ignores other possible emissions.

Generally speaking however, while primary processing adds energy of order 100 MJ/kg (E_p) to any product, manufacturing adds energy of order 10 MJ/kg (E_m) [5.27, 28]. The real role of manufacturing is that it draws in materials and energy not directly incorporated into the product and then expels them, often as wastes or emissions to the environment.

In addition to fossil fuel usage, a second environmentally important class of materials used in manufacture is cleaning fluids and coatings. Manufacturing often involves the cleaning and preparation of surfaces. Of particular concern are many of the solvents that are used to remove cutting fluids, lubricants, and other materials from the surface of the parts. In order to avoid the use of hazardous materials, many manufactures have replaced organics with water-based and mechanical cleaning methods [5.29].

Product Delivery

Product delivery involves two important types of environmental loads: transportation and packaging. The transportation of products around the world provides jobs and opportunities for many, but at the same time constitutes a major component of energy usage and related emissions. Furthermore, the geographical separation of product use from manufacturing can create significant barriers for the recycling of some materials.

Packaging waste is particularly egregious because of the large amounts of materials with only a very short intended lifetime. Furthermore, the customer gets the opportunity to experience this waste first hand.

Product Use

It is probably true that the vast majority of consumer appliances, electrical products, vehicles, lawn equipment, power tools, etc. – in short anything that has a power cord or runs on gasoline – has its largest or second largest impact during the use phase. Products with power cords draw energy from the utility station, which, in the US, have an average efficiency of about 35% and still burn 50% coal. These two facts alone often completely dominate the environmental impact of some products. Furthermore, powered devices can consume still other materials, e.g., paper and ink in printers, coffee in espresso machines, water in refrigerators with electric ice makers, etc. By and large, these automated appliances are considered desirable conveniences, but automated usage often, and unintentionally, leads to automated waste too.

Disposition

Most products in the United States end up in landfills, some are incinerated, and a few are recycled. In general, US landfill access has been significantly diminishing, particularly in the highly populated northeast. Many states have been closing landfills faster than they are opening new ones. Some states have moratoriums on new landfill development, and many ship their waste out of state. Furthermore, lined landfill sites for the collection of hazardous materials are highly restricted, leading to very high transportation and disposal costs for hazardous substances.

While incineration is not very popular in the United States, particularly in well-to-do communities, it is very much an active option for a significant portion of the municipal solid waste (MSW) generated. Incineration can be combined with an electrical generation facility to produce power. Furthermore, the emissions can be scrubbed for various emissions. Nevertheless, it is difficult to tightly control the incoming waste stream and hence a wide variety of emissions, some not anticipated, can occur. In addition, it is well known that municipal incinerators are one of the top producers of dioxins in the United States, which are extremely expensive to scrub [5.30,31]. Dioxins are a group of chemicals that have been found to be highly persistent, toxic and carcinogenic.

A number of products are widely recycled in the United States. These include automobiles, tires (as a fuel to generate energy), newspapers, aluminum cans and, to a lesser extent, mixed paper and high=density polyethylene (HDPE) and polyethylene terephthalate (PET) bottles.

5.5.3 Product Examples: Automobiles and Computers

LCA, LCI and SLCA can all help identify where major opportunities for environmental improvement occur for

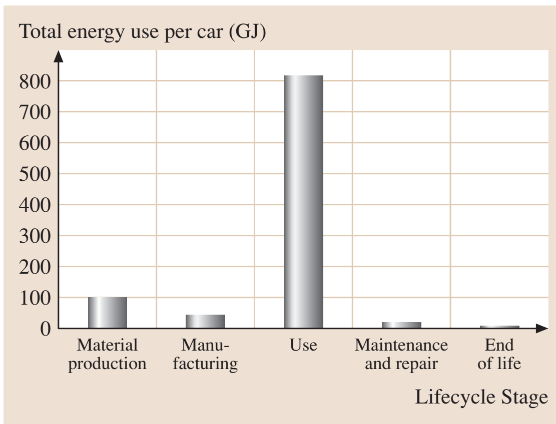


Fig. 5.22 Total energy use by life cycle stage for an automobile (after [5.33])

Table 5.6 Characteristics of generic automobiles [5.21]

Characteristics	ca. 1950s automobile	ca. 1990s automobile
Material (kg)		
Plastics	0	101
Aluminum	0	68
Copper	25	22
Lead	23	15
Zinc	25	10
Iron	220	207
Steels	1290	793
Glass	54	38
Rubber	85	61
Fluids	96	81
Other	83	38
Total weight (kg)	1901	1434
Fuel efficiency (miles/gallon)	15	27
Exhaust catalyst	No	Yes
Air conditioning	CFC-12	HFC-134a

a product. The results depend on the product characteristics and the environmental loads of concern. Often our attention goes to those loads with the highest environmental profile. For example, in the life of a paper cup the use stage is short and the disposal can be benign, hence our attention goes immediately to the paper-making process, which has a variety of issues, many associated with the pulp bleaching process for kraft paper making, and possibly to the distribution stage, if the cups are transported a long distance. Another example, the disposable diaper, focuses attention on the waste disposal problem, while the reusable cloth diaper focuses attention on the energy-intensive washing cycle. Other products can be more complex, with major issues in several life cycle stages. Here we review life cycle issues for automobiles and computers.

Automobiles

The automobile has been subject to numerous studies concerning its environmental load [5.21, 32–37]. This discussion focuses on the automobile as a product. Other issues related to the automobile, for example how it has shaped our lifestyles and land use patterns, while very important, are not included in this discussion. As one can imagine, given the tens of thousands of parts, and the complexity of consumer behavior, vehicle types, and driving conditions, this is an enormous task. Yet, in spite of all of this complexity the results have been quite consistent. By far the most important place to look for opportunities for environmental improvement is in the vehicle use stage. It is during this approximately 10 y period where the average vehicle, with a fuel efficiency of about 10 km/l

Table 5.7 Premanufacturing ratings [5.21]

Element designation		Element value & explanation: 1950s automobile		Element value & explanation: 1990s automobile	
Materials choice	1, 1	2	Few hazardous materials are used, but most materials are virgin	3	Few hazardous materials are used, and much recycled material, Pb in battery in closed recycle loop
Energy use	1, 2	2	Virgin material shipping is energy intensive	3	Virgin material shipping is energy intensive
Solid residue	1, 3	3	Iron and copper ore mining generate substantial solid residues	3	Metal mining generates solid residues
Liquid residue	1, 4	3	Resource extraction generates moderate amounts of liquid residues	3	Resource extraction generates moderate amounts of liquid residues
Gas residue	1, 5	2	Ore smelting generates significant amounts of gaseous residues.	3	Ore processing generates moderate amounts of gaseous residues

Table 5.8 Product manufacture ratings [5.21]

Element designation		Element value & explanation: 1950s automobile		Element value & explanation: 1990s automobile	
Materials choice	2, 1	0	Chlorinated solvents, cyanide	3	Good materials choices, except for lead solder waste
Energy use	2, 2	1	Energy use during manufacture is high	3	Energy use during manufacture is fairly high
Solid residue	2, 3	2	Lots of metal scrap and packaging scrap produced	3	Some metal scrap and packaging scrap produced
Liquid residue	2, 4	2	Substantial liquid residues from cleaning and painting	3	Some liquid residues from cleaning and painting
Gas residue	2, 5	1	Volatile hydrocarbons emitted from paint shop	3	Small amounts of volatile hydrocarbons emitted

Table 5.9 Product delivery ratings [5.21]

Element designation		Element value & explanation: 1950s automobile		Element value & explanation: 1990s automobile	
Materials choice	3, 1	3	Sparse, recyclable materials used during packaging and shipping	3	Sparse, recyclable materials used during packaging and shipping
Energy use	3, 2	2	Over-the-road truck shipping is energy-intensive	3	Long-distance land and sea shipping is energy-intensive
Solid residue	3, 3	3	Small amounts of packaging during shipment could be further minimized	3	Small amounts of packaging during shipment could be further minimized
Liquid residue	3, 4	4	Negligible amounts of liquids are generated by packaging and shipping	4	Negligible amounts of liquids are generated by packaging and shipping
Gas residue	3, 5	2	Substantial fluxes of greenhouse gases are produced during shipment.	3	Moderate fluxes of greenhouse gases are produced during shipment

Table 5.10 Product use ratings [5.21]

Element designation		Element value & explanation: 1950s automobile		Element value & explanation: 1990s automobile	
Materials choice	4,1	1	Petroleum is a resource in limited supply	1	Petroleum is a resource in limited supply
Energy use	4,2	0	Fossil fuel energy use is very large	2	Fossil fuel energy use is large
Solid residue	4,3	1	Significant residues of tires, defective or obsolete parts	3	Modest residues of tires, defective or obsolete parts
Liquid residue	4,4	1	Fluid systems are very leaky	3	Fluid systems are somewhat dissipative
Gas residue	4,5	0	No exhaust gas scrubbing; high emissions	2	CO_2, lead (in some locales)

Table 5.11 Refurbishment/recycling/disposal ratings [5.21]

Element designation		Element value & explanation: 1950s automobile		Element value & explanation: 1990s automobile	
Materials choice	5, 1	3	Most materials used are recyclable	3	Most materials recyclable; plastics, glass, foam not recycled; sodium azide presents difficulty
Energy use	5, 2	2	Moderate energy use required to disassemble and recycle materials	2	Moderate energy use required to disassemble and recycle materials
Solid residue	5, 3	2	A number of components are difficult to recycle	3	Some components are difficult to recycle
Liquid residue	5, 4	3	Liquid residues from recycling are minimal	3	Liquid residues from recycling are minimal
Gas residue	5, 5	1	Recycling commonly involves open burning of residues	2	Recycling involves some open burning of residues

(23.8 miles/gallon), burns about 14 metric tons of gasoline while traveling about 120 000 miles. Furthermore, due to the stoichiometry of the combustion process, this fuel consumption translates into some 40 metric tons of CO_2. When other aspects of the life cycle are included (the energy to make the fuel, etc.) and other greenhouse gases are converted into their CO_2 equivalent, the resulting equivalent CO_2 emissions over the life time of the vehicle are about 94 metric tons or 9.4 t/y. Other emissions during the use stage are also high, including NO_x, volatile organic compounds (VOCs), which contribute to ground-level ozone and smog, and other hazardous materials at lower levels. Other areas of concern are painting and cleaning during manufacturing, leaks and emissions during use and maintenance, and remaining quantities of unrecyclable materials: plastics, glass, foam, rubber, etc. The total energy use by stage, shown in Fig. 5.22, indicates that energy use during material production and manufacturing are also significant [5.33].

A general assessment of how the environmental performance of the automobile has changed over the years can be found in Graedel, who performed an SLCA to compare a 1950s automobile to one from the 1990s [5.21]. The assumed characteristics of the cars are given in Table 5.6. Their ratings for each of the five impact categories in each of the five life cycle stages are given in Tables 5.7–5.11. The final matrix values are summarized in Tables 5.12, 13, and plotted as a target plot in Fig. 5.23.

Computers

The study of the environmental footprint for computers is an interesting contrast to automobiles. While

Table 5.12 Environmentally responsible product assessment for a generic 1950s automobile [5.21]

Life cycle stage	Environmental stressor Materials choice	Energy use	Solid residues	Liquid residues	Gaseous residues	Total
Premanufacture	2	2	3	3	2	12/20
Product manufacture	0	1	2	2	1	6/20
Product delivery	3	2	3	4	2	14/20
Product use	1	0	1	1	0	3/20
Refurbishment, recycling, disposal	3	2	2	3	1	11/20
Total	9/20	7/20	11/20	13/20	6/20	46/100

Table 5.13 Environmentally responsible product assessment for a generic 1990s automobile [5.21]

Life cycle stage	Environmental stressor Materials choice	Energy use	Solid residues	Liquid residues	Gaseous residues	Total
Premanufacture	3	3	3	3	3	15/20
Product manufacture	3	2	3	3	3	14/20
Product delivery	3	3	3	4	3	16/20
Product use	1	2	2	3	2	10/20
Refurbishment, recycling, disposal	3	2	3	3	2	13/20
Total	13/20	12/20	14/20	16/20	13/20	68/100

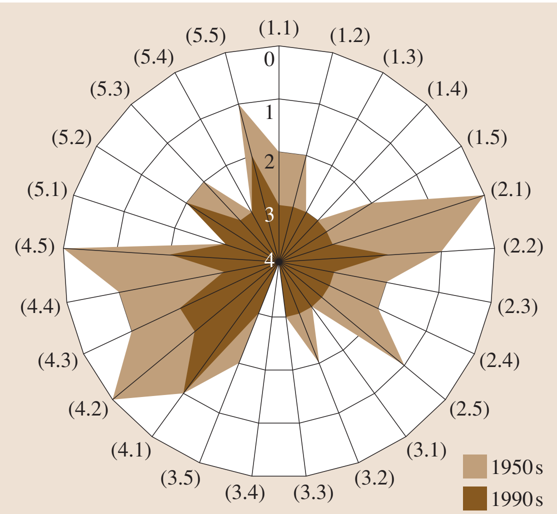


Fig. 5.23 Target plot of the environmental impact of generic automobiles for the 1950s and 1990s, see text (after [5.21])

automobiles use mostly conventional materials and many standard manufacturing processes, the microchips in computers use much more-specialized materials and rapidly changing process technology. The result is that the complete life cycle of the computer has not been filled in to the extent that the automobile has. This is clearly illustrated in the important paper *The 1.7 kilogram microchip: Energy and materials use in the production of semiconductor devices*, by *Williams*, *Ayres*, and *Heller* [5.26], which illustrated that there is far less agreement on the magnitudes of the environmental impacts associated with microchip fabrication.

Nevertheless the available data indicate that microelectronics fabrication is very materials and energy intensive, in fact orders of magnitude more so than, for example, automobile manufacturing. In particular, approximately 1.7 kg of materials (including fuel) are needed to make a 2 g microchip. This certainly undermines some claims that microelectronics represent a form of dematerialization. Some of the chief findings of Williams et al. are summarized in Table 5.14.

Table 5.14 Chief findings for microelectronics fabrication for a dynamic random-access memory (DRAM) chip [5.26]

Mass of 32 MB DRAM chip	2 g
Total chemical inputs	72 g/chip
Total fossil fuel inputs	1600 g/chip
Total water use	32 000 g/chip
Total elemental gas use	700 g/chip

Table 5.15 Bill of materials for a desktop computer and CRT monitor [5.39]

Material	Mass (g)	Use
Desktop computer		
Steel	6050	Housing
Copper	670	Wires, circuit boards
Aluminum	440	Housing, CD ROM
Plastics	650	Circuit boards
Epoxy	1040	Solder
Tin	47	Solder
Lead	27	Disk drive
Nickel	18	Circuit boards
Silver	1.4	Circuit boards
Gold	0.36	
Subtotal	8944	
Other	96	
Total	9040	
17" CRT monitor		
Glass	6817	Picture tube
Steel	2830	Housing
Copper	700	Wires, circuit boards
Ferrite	480	Deflection yoke
Aluminum	240	Heat sinks
Plastics	3530	Housing
Epoxy Resin	140	Circuit boards
Tin	20	Solder (circuit boards)
Lead	593	Glass, solder
Silver	1.24	Circuit boards
Gold	0.31	Circuit boards
Subtotal	15352	
Other	98	
Total	15450	

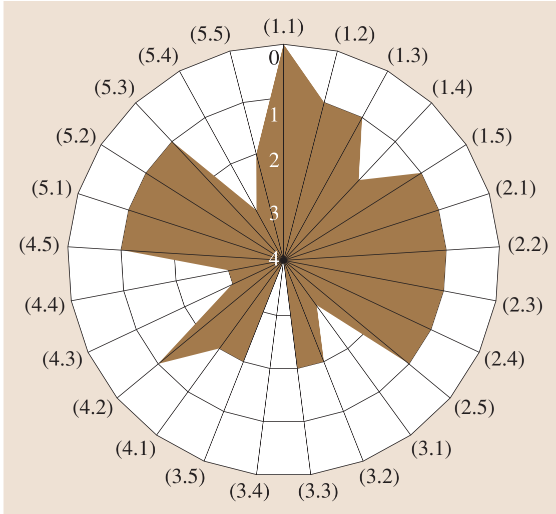


Fig. 5.24 Target plot of the environmental impacts of an early-1990s desktop computer and CRT display, see text (after [5.21])

At the same time, it is important to keep in mind that a computer is made up of much more than microchips, and the life cycle includes more than the fabrication stage. An approximate bill of materials for a desktop computer and cathode ray rube (CRT) monitor are given in Table 5.15. In this context the microchips and their constituents hardly show up. In fact many of the materials used in a computer are rather conventional. However, there are some materials of concern. Lead is present in both the central processing unit (CPU) and the monitor, cadmium (not listed) may be present in the batteries, mercury can be used in some switches and is used in laptop displays, and there is growing concern, particularly

Table 5.16 Streamlined life cycle analysis: desktop computer display and CPU. Premanufacturing

i, *j*	Environmental stressor	Score
1, 1	Material choice Few recycled materials are used. Many toxic chemicals are used, including Pb in CRT and PWB, Cd in some batteries, Hg in some switches, and brominated flame retardants in plastics.	0
1, 2	Energy use Extra-high-grade materials for microchip very energy intensive. Other high energy materials include virgin aluminum, copper, CRT glass.	1
1, 3	Solid residues Many materials are from virgin ores, creating substantial waste residues. Si wafer chain is only 9% efficient.	1
1, 4	Liquid residues Some metals from virgin ores can cause acid mine drainage.	2
1, 5	Gaseous residues Very high energy use and other materials use lead to substantial emissions of toxic, smog-producing, and greenhouse gases into the environment.	1

Table 5.17 Streamlined life cycle analysis: desktop computer display and CPU. Product manufacture

i, *j*	Environmental stressor	Score
2, 1	Material choice Manufacturing uses restricted and toxic materials. (see 1,1) plus cleaning solvents.	1
2, 2	Energy use Energy use in production is very high for ICs and PWB and moderate to high for conventional materials. If we examine energy use during the manufacture of individual parts of the computer: microchip (0), printed circuit board (1), cathode ray tube (2), LCD (0), other bulk material (3)	1
2, 3	Solid residues There are large solid residues for chemical processes, such as CVD, PVP and plating e.g. printed circuit boards yield 12 kg of waste for each kilogram of finished product. Also high performance requirements often result in low yields.	1
2, 4	Liquid residues Large quantities of waste liquid chemicals, e.g. approximately 500 kg of waste liquid chemicals for each kilogram of product including plating solutions and cleaning fluids. Very high volumes of water are also used.	1
2, 5	Gaseous residues Manufacturing energy use and processes lead to substantial emissions of toxic, smogproducing, and greenhouse gases into the environment.	1

Table 5.18 Streamlined life cycle analysis: desktop computer display and CPU. Product packaging and transport

i, *j*	Environmental stressor	Score
3, 1	Material choice Several materials, large quantities, minimal recycling activity.	3
3, 2	Energy use Long distances traveled. Large volumes of materials.	2
3, 3	Solid residues Waste volumes are large, no arrangements to take back product packaging after use.	2
3, 4	Liquid residues Little or no liquid residue is generated during packaging, transportation, or installation.	4
3, 5	Gaseous residues Gaseous emissions are released by transport vehicles.	2

Table 5.19 Streamlined life cycle analysis: desktop computer display and CPU. Product use

i, *j*	Environmental stressor	Score
4, 1	Material choice Power from electrical grid uses 50% coal.	2
4, 2	Energy use High to very high energy usage.	1
4, 3	Solid residues Little direct solid residues (excluding printing functions) but power uses coal resulting in mining residues.	3
4, 4	Liquid residues Little direct liquid residues (excluding printing function) but coal mining yields liquid residues.	3
4, 5	Gaseous residues No emissions are directly associated with the use of computers. However, gaseous emissions are associated with energy production for use of computers.	1
Does not include printing		

Table 5.20 Streamlined life cycle analysis: desktop computer display and CPU. Refurbishment/recycling/disposal ratings

i, *j*	Environmental stressor	Score
5, 1	Material choice Product contains significant quantities of lead and brominated flame retardants and may contain mercury and cadmium. Often these are not clearly identifiable or easily removable. Many materials are not recycled.	1
5, 2	Energy use The product is not designed for energy efficiency in recycling, or for high-level reuse of materials. Also, the transport of recycling is energy intensive because of weight/volume and location of suitable facilities.	1
5, 3	Solid residues Dissimilar materials are joined together is ways that are difficult to reverse and the product overall is difficult to disassemble. Little recycling. Short life cycle of computers compounds these problems.	1
5, 4	Liquid residues Product contains no operating liquids and minimal cleaning agents are necessary for reconditioning (not including printing functions).	3
5, 5	Gaseous residues Roasting of printed wiring boards (PWBs) to recycle metals leads to emissions.	2

Table 5.21 Streamlined life cycle analysis: desktop computer display and CPU. Environmentally responsible product assessment for the computer display and CPU

Life stage	Materials	Energy	Solid	Liquid	Gaseous	Total
Premanufacture	0	1	1	2	1	5/20
Product manufacture	1	1	1	1	1	5/20
Product delivery	3	2	2	4	2	13/20
Product use	2	1	3	3	1	10/20
Recycling	1	1	1	3	2	8/20
Total	7/20	6/20	8/20	13/20	7/20	41/100

in Europe, over brominated flame-retardants, which are used in the plastics.

Currently, there is no complete, up-to-date life cycle analysis available for a computer, but an earlier study looked at energy, waste, hazardous materials and water used in the life cycle of a computer workstation [5.21,38], and more-recent information particularly on the fabrication, use, and end of life stages for a personal computer is given by *Kuehr* and *Williams* [5.39]. Computers seem to raise concerns at all stages of life. The premanufacture and manufacturing stages are very material and energy intensive due primarily to the high material purity needed for the microelectronics fabrication. Distribution can be a concern due to the large amount of packing materials and the long distances some products need to travel. The use phase can be very energy intensive. For example, data given by *Kawamoto* [5.40] and *Cole* [5.41] sets the residential annual energy use for a desktop computer and monitor at about 380 MJ/y. In a commercial/industrial setting where the computer monitor may be on continuously, the estimate is 1500 MJ/y. For a three-year lifetime, this is more than half of the energy used in production. The end-of-life issues are several; there are several *materials of concern* as mentioned earlier, and the shear volume of retired computer and electronics represents a significant solid waste/recycling challenge. Currently only a very small percentage of computers are recycled [about 11%, as estimated by the Environmental Protection Agency (EPA)]. Using the materials lists given in Table 5.15 and the information cited in the references reviewed here [5.**?**, 26, 38–41] we have developed a baseline SCLA for a 1990s desktop computer and CRT display. The results are given in Tables 5.16–5.21. A target plot is given in Fig. 5.24.

Using Life Cycle Information for Product and Process Improvement

One of the primary reasons for developing life cycle environmental information is to identify opportunities for improvement. Streamlined life cycle analysis (SLCA) as developed in the two preceding sections is particularly good at this because it provides an overview with an emphasis on high-profile issues. The automobile example illustrates important environmental improvements from the 1950s to the 1990s, at the same time indicating several remaining challenges, particularly related to fossil fuel usage.

The SLCA given for the 1990s desktop computer is intended as a baseline for identifying critical areas for improvement, which are many. In comparison, the current laptop computer would score much more favorably. Important improvements would include:

1. a drastic reduction in the total weight of materials used
2. elimination of significant amount of lead found in the CRT (although small amounts of mercury are needed for the laptop display)
3. significantly reduced packing materials
4. significantly lower energy required in usage

The SLCA methodology presented here is a compact way to learn about a complex problem, however, once a significant target for environmental improvement has been identified by SLCA, a more quantitative life cycle inventory for the material(s) of concern would be warranted. This would allow a much more precise evaluation of potential improvements. For example, Fig. 5.22 gives the total energy used for a generic family automobile in the late 1990s. An LCI study would then connect each of these energy requirements to the energy technology used and the corresponding emissions. For example while the use phase burns gasoline in an internal combustion engine, the material production and manufacturing phases use a mixture of mostly coal along with natural gas, oil, and even nuclear (from the electricity grid). Hence connecting the energy requirements to the fuel cycles would lead to specific contributions of each type of pollutant of interest. For example, energy from electricity in the United States comes from 50% coal, 20% nuclear, 18% natural gas, 7% hydroelectric, 3% oil, and 2% renewables. The corresponding emissions per electricity used are: 633 kg CO_2/MWh, 2.75 kg SO_2/MWh, 1.35 kg NO_x/MWh, and 12.3 g mercury/GWh, where MWh is a megawatt-hour, and GWh is a gigawatt-hour [5.42].

A full-blown life cycle analysis (LCA) would include weightings of the different pollutants based on human value judgments. For example, the LCA software Simapro from the Netherlands employs a weighting scheme called the *Eco-indicator* that reflects the value judgments of Europeans concerning the various environmental issues that concern them. Obviously such schemes could vary widely depending upon local concerns.

Before leaving this section it is worth noting that, because SLCA yields numerical scores for products, it might be tempting to compare different types of products. This is possible but must be done with caution. In the first place the SLCA methodology developed by Graedel and Allenby was intended as a relative indicator for a particular product type. Therefore the methodology would have to be modified. A second problem is that dissimilar products can have vastly different utilities for the users. Hence the comparison may seem nonsensical to some. Nevertheless some comparisons can be useful. For example, Williams has pointed out that the fossil fuel used during the entire life cycle of the production and use for a computer is almost identical to that of a refrigerator even though the computer only lasts about one quarter of the time (2.5 y versus 10 y) and the refrigerator is on all of the time [5.43]. The obvious implication is that much more could be done to improve the energy efficiency of computers.

Table 5.22 Energy efficiency guidelines [5.15, 58, 59]

Action	Reason
Do SLCA/LCI/LCA for product	Identify energy usage
Encourage use of clean renewable energy sources	Reduce harmful by-products and preserve resources
Choose the least harmful source or energy Note for fossil fuels the cleanest is natural gas followed by oil products, and then coal	Reduce harmful by-products
Have subsystems power down when not in use	Reduce energy usage and fossil fuel consumption
Permit users to turn off systems in part or whole	Reduce energy usage and fossil fuel consumption
Avoid high energy materials	Reduce energy and preserves resources
Avoid high energy processes	Reduce energy
Specify best-in-class energy efficiency components	Reduce energy usage and fossil fuel consumption
Insulate and /or use waste heat	Reduce losses/ increases efficiency

Table 5.23 Recyclability guidelines [5.15, 58, 60]

Rating	Description or action	Reason or comment
Good	Product is reusable/remanufacturable	Extends life of product
Good	Materials in part are recyclable with a clearly defined technology and infrastructure	Most metals, some plastics in particular: PET & HDPE
Good	No toxic materials, or if present, clearly labeled and easy to remove	Avoid Pb, Hg, Cd
Good	Allow easy removal of materials, avoid adhesives and joining methods which can not be reversed	Facilitates separation and sorting
Less good	Material is technically feasible to recycle but infrastructure to support recycling is not available	Most thermoplastics, some glass
Less good	Material is organic – can be used for energy recovery but cannot be recycled	thermoplastics, rubber, wood products
Avoid	Avoid mixtures which cause contamination, and painting and coatings which are difficult to remove	e.g. polyvinylchloride (PVC) in PET, Cu in steel, painted plastics
Avoid	Material has no known or very limited technology for recycling	Heated glass, fiberglass, thermoset plastics, composite materials

5.5.4 Design for the Environment (DFE)

Design for the environment, like design for manufacturing or design for assembly, is a set of guidelines to help designers meet particular design goals. Often these guidelines are reduced to simple rules that aid understanding. However, behind these rules are observations and models that capture how the product can be expected to perform as the result of certain design decisions.

To a certain extent this whole chapter has been aimed at understanding how products and product decisions result in environmental loads. There can be, however, different environmental goals. For example, designing an automobile for lower fuel consumption may lead to using structural composite materials for weight reduction, whereas designing for recyclability would probably lead to the use of metals for the structural components. In this section we outline some of the generally agreed upon guidelines for two important environmental goals: reduced hydrocarbon fuel consumption and increased recyclability. These are summarized in Tables 5.22 and 5.23.

5.5.5 System-Level Observations

In this chapter we have presented an overview of engineering actions to lessen the impact of materials use, manufacturing, and design decisions on the environment. One of the goals of this chapter has been to identify the connections between a product life cycle and the associated environmental loads. To do this we have frequently normalized the environmentally sensitive parameters such as energy requirements or emissions by some measure of useful output such as the weight of the output, the economic activity, or, in some cases, just by the product itself. This scheme helps assign responsibility and allows us to track progress by enabling comparisons.

At the same time, however, by measuring the environmental load too narrowly there is a danger of missing the overall trend. One way of making this point is by writing the environmental impact in terms of several normalized parameters. For example, consider

$$\text{impact} = \text{population}\,\frac{\text{wealth}}{\text{person}}\,\frac{\text{impact}}{\text{wealth}}\,. \qquad (5.2)$$

This is a mathematical identity, known as the IPAT equation, which associates impact I, with three important elements: P for population, A for affluence and T for technology. Our focus has been on the last term – impact/wealth (or impact/product etc.). Many variations on the IPAT equation are possible, for example $A =$ products/person, $T =$ impact/product, etc. It is the collection of the terms on the right-hand side that give the impact. Hence, a technology improvement could be offset by increases in population and/or wealth/person. This is unfortunate, but appears not to be in the domain of the engineer. If this was all there was to the story, the IPAT equation would be a neat way to subdivide responsibility. The implication is that, if engineers can improve the technology term, then they have done their job. The actual picture unfortunately is much more complicated, as technology improvements do not only improve the environment but also play an important role in stimulating the economy. In fact, rela-

5.6 Failure Mode and Effect Analysis for Capital Goods

Failure mode and effect analysis (FMEA) [5.47, 48]) is a method to recognize and eliminate mistakes or causes of faults during the product design process and in particular in the earliest stages.

This method was developed in 1963 by the National Aeronautics and Space Agency (NASA) within the Apollo mission to design products without design failures. This is especially important when products cannot be repaired easily, e.g., satellites or spaceships. The method was adopted later by the aviation industry, the automotive industry, in medicine and nuclear technology as well as by the armaments industry [5.48, 49]. Today this method is increasingly used in all fields of the development process of consumer and capital goods [5.47, 50–52].

With regard to the rework of the initially developed and applied approach see [5.52, 53].

5.6.1 General Innovations for the Application of FMEA

The complexity of many products due to their mechatronic character but also because of the simultaneously applied engineering concepts complicates the distinction between the three traditional types of FMEA: system FMEA, the design FMEA and process FMEA (Fig. 5.25). In addition many FMEA sessions mix all three fields [5.53].

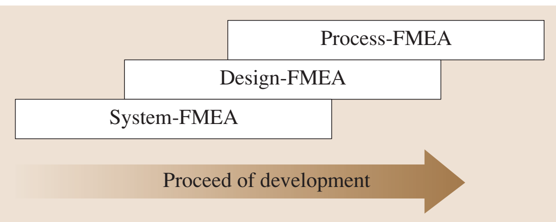


Fig. 5.25 FMEA separated in subprocesses (traditional form)

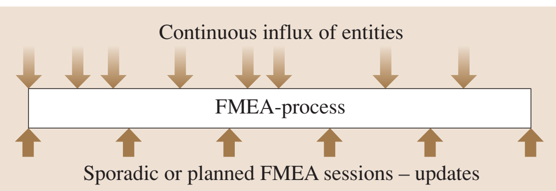


Fig. 5.26 FMEA as a continuous process

Instead of this distinction a continuous form of FMEA therefore has to be implemented, which becomes more detailed with increasing knowledge through the product development process. As the design of a product proceeds and product knowledge grows, the danger of errors increases as does the need for their recognition and elimination. This leads to the concept of a continuous FMEA process (Fig. 5.26).

Such continuity produces the best results if the group of people involved stays the same. In practice, it turns out that it is already reasonable to apply competence in manufacturing or quality control in FMEA at the concept stage. This does not contradict the demand that specialists have to be consulted for specific questions. An additional benefit is gained from all team members becoming acquainted with the product.

In general the early stages of the product development process and the stages during and after market launch are not covered by traditional FMEA. The early phases of the product development process (idea generation and market assessment) include many sources of errors that influence the success or failure (not only technically) of a new product.

The traditional form of FMEA does not take the costs of possible damage as well as the costs of avoiding this damage into account. To decide on appropriate troubleshooting actions it is important to gain an economic understanding of FMEA and its consequences.

The new form, based on the original FMEA form but now including the economic point of view, is schematized and formalized in Fig. 5.27.

5.6.2 General Rules to Carry Out FMEA

The observation of FMEA sessions in companies shows that a clear separation into the three fields of system, design and process is not performed, nor is it reasonable. This is because each failure affects the system, the design, and the process FMEA.

Since the system FMEA is carried out before the design FMEA this new influence into the system and his effects is not considered anymore. Only a completed process FMEA will discover the actual source of error, for example an unsuitable die-casting machine. Again the influence of the elimination of this failure mechanism is no longer considered in the system and design FMEAs.

Company project	**Failure mode and effect analysis – FMEA** Project- and lifecycle – FMEA									Name of functions / working principles / assemblies Ident-No.						
	Generating department:									Generated by: Date:						
Failurelocation Ident-No. Entity	Type of failure	Impact of failure	Cause of failure	Present status Means of control	A	B	E	K	RPZ	Remedial action	Improved status Realized action	A	B	E	K*	RPZ*
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Fig. 5.27 FMEA form with additional columns K and K* to consider the cost influences for decision-making

For these reasons it is not reasonable to separate the three individual FMEA methods. It is more reasonable to carry them out simultaneously in order to benefit from synergy within the group.

The Prerequisites at the Beginning of a FMEA

The following prerequisites must be met absolutely at the beginning of an FMEA process.

1. FMEA participants that are competent and confirmed in their continuity [5.54, 55]. The definition of the *risk priority number* (RPZ) numbers (see Sect. 5.6.3) is done subjectively and thus randomly. Therefore the selection of the FMEA participants has to be done carefully in order to take into account different views and issues and to obtain a realistic RPZ. This problem is similar to that of the evaluation process [5.54, 55].
2. The product idea is defined and understood by all FMEA participants.
3. The market performance process of a new product is available.
4. A clear list of demands (requirements), tested for interrelations [5.56].
5. A use analysis [5.57].
6. A functional analysis, if possible as a functional diagram.
7. Heuristic context within the product development process. The methods involved between the individual components and units as well as external (referring to the usage of a product) and internal (working principles, effects and regularities) functions (Fig. 5.28) cannot be correctly represented in conventional forms, which will result in incorrect decisions.
8. Complete documentation of the state of development.

	Examples		
Action	Operate	View	Hear
Function	Amplify	Shine	Ring
Principle	Hydraulic	Electric	Acoustic
Effect, physical principle	Static pressure	Ohm's law	Sound wave
Formula	$P_2 = P_1(A_2/A_1)$	$U = R\,I$	$E = J/(f\lambda)$

Fig. 5.28 Heuristic context within the product development process; the five stages of solution finding in the concept stage

Improvement of Error Recognition

(Formal) FMEA with conventional forms [5.47] is in principle incomplete since a suitable inspection of completeness is not given. This takes effect on the methodic context and on the other hand on the accidental error recognition. Some ways of improving error recognition rates are

1. The experience of the FMEA participants
2. Integration of other specialists
3. Knowledge of or becoming acquainted with the product to be analyzed

4. Integration of customer-oriented departments and the customers themselves
5. Collection and analysis of mistakes and experiences recorded in databases
6. Study of the history of a product (test reports, complaint reports etc.);
7. Concurrent application of heuristic support tools (e.g., *Goldfire*, Invention Machine, Boston)

Inclusion of all Secondary Fields of Development

The FMEA refers only to hardware, not to documentation, services, software logistics, test programs, manufacturing method, production plants and machines. Measurement and checking facilities, experimental setups and devices are not covered by any FMEA, although many errors could occur here. This situation only can be improved by including these new fields.

5.6.3 Procedure

The localization of risks concerning the lifetime of a product, starting from the first design concept to product use, is in principle always the same procedure, regardless of the product size. The principle and procedure is identical for a small product like a plug-in contact (Fig. 5.29) or a large technical system like a machine tool (Fig. 5.30).

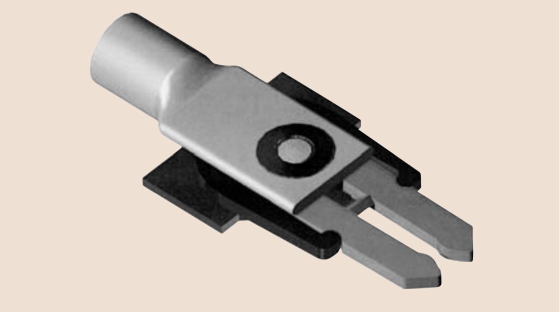


Fig. 5.29 Small product: plug-in contact (source: ABB, Baden)

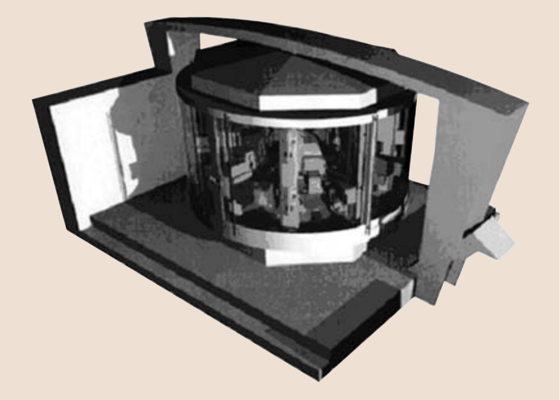


Fig. 5.30 Large product: machine tool (source: A. Breiing, MIKRON, Biel)

Description of the project.

Nomination of the FMEA moderator. The nomination is done with agreement of the responsible project manager.

Formation of an FMEA team. The formation of the team (Table 5.24) is done by the project manager with agreement of the FMEA moderator. Important is the visualization of the team members in a form. The following departments should contribute at least one participant as a continuous FMEA team member.

Structuring of functions. The basis of FMEA is functional analysis of the investigated product. This implicates the specification of functional modules or

Table 5.24 Visualization of the team members in a form

No.	Faculty/customer	Name, company
1	Project management	
2	Design, construction and calculation	
3	Manufacturing preparation	
4	Manufacturing	
5	Quality control, simultaneously presentation of FMEA	
6	Purchase department	
7	Sales department	
8	Customer support (inauguration, maintenance, repair)	

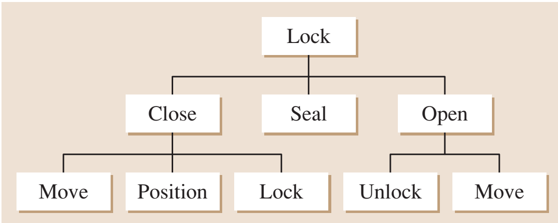


Fig. 5.31 Example of a hierarchical functional structure of an autoclave door [5.62]

submodules, for example as a hierarchical functional diagram (Fig. 5.31) or as a process-orientated diagram (Fig. 5.32).

Filling out the FMEA form (Fig. 5.27).

Column 1. This column consists of all aspects of possible sources of error, as shown in Table 5.25. Since in the early stages of product development, in particular during idea generation and during the determination of the market performance profile, sources of error can already be detected, the corresponding entities have to be entered in this column (first block). Sources of error can also be detected in the development phase (second block), during market launch (third block), and in particular during the usage phase up to product disposal (fourth block).

Column 2–4. This columns require an analysis of all possible potential failures, for example:

Possible errors in the planning stage.

- The idea of a new product cannot be realized due to physical, chemical, biological, ethical, legal or cultural constraints or restrictions.
- The product idea is already realized by competitors.
- The product idea is already protected by the competitors with patents, petty patents and/or design patents.
- There is no market potential and/or no market gap available.
- The time is not ripe.
- No foe image available or not relevant enough (for military development).
- Rare resources.
- No sustainable environment.

Possible errors in the development process.

- Internal functions from a function analysis (hierarchical and/or process functional structure)
- External functions from a use analysis
- Assembly of the product structure
- Assembly/disassembly:
  - Assembly/disassembly operation
  - Assembly/disassembly regulations
  - Utilities (e.g., oil for the removal of bearings)
  - Assembly/disassembly devices
  - Control and/or measuring devices (e.g., torque spanner)
  - Additional means (z. B. hoisting devices)
- Components from the product structure and/or parts list
- Manufacturing:
  - Manufacturing processes (e.g., lapping)

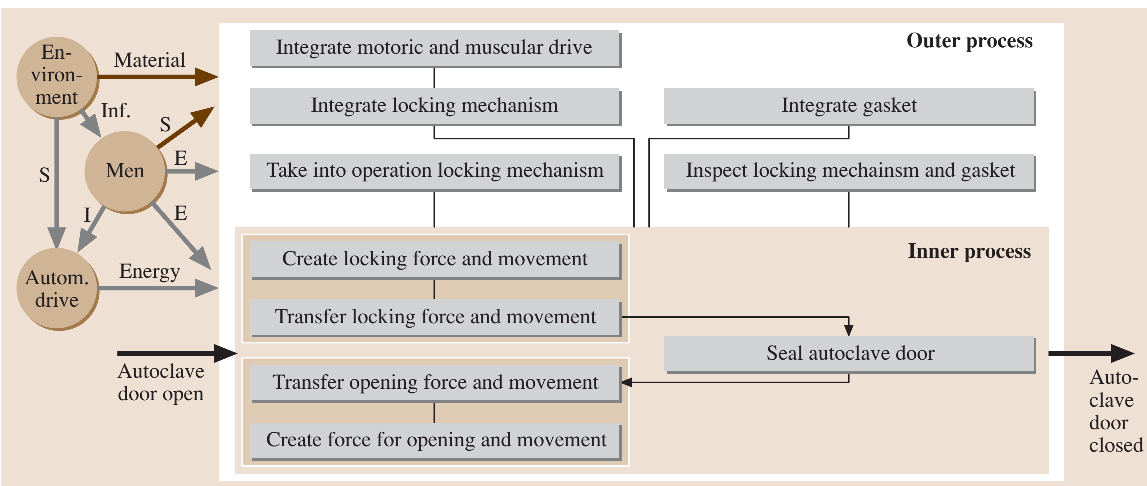


Fig. 5.32 Example of a process functional structure of an autoclave door [5.62], generated from Fig. 5.30

Table 5.25 FMEA form with entities over the complete life cycle of a product (an example)

Company **Project**	**Failure mode and effect analysis (FMEA)**			
Failure location Identification number Entity	Impact of failure	Type of failure	Failure cause	Means of control
1	2	3	4	5
Idea Market analysis Cost planning Time scheduling Strategy				
Inner functions Outer functions Module Assembly Component Manufacturing process				
Storage Transport Mounting Initiation				
Implementing Operation Controlling Maintenance Repair Recycling or liquidation				

- Manufacturing operations (for manual manufacturing, e.g., deburring)
- Manufacturing regulations
- Manufacturing means and devices (e.g., drilling patterns)
- Auxiliary manufacturing requirements (e.g., coolant)
- Control and measuring devices (e.g., calipers).

The *Outer function* takes into account the human being in his incompleteness as users during the product life must be included into the FMEA. The user is a component of the system, he influences all processes, starting from idea generation, through development and usage until the end of the product life. The user causes failures and errors at all stages. With the integration of the available use analysis (Table 5.26) that covers all stages of a product's life [5.57] possible sources of error during assembly, maintenance and repair are also considered (Table 5.25, fourth block).

In order to register these potential sources of error systematically the FMEA is expanded by the integration of the use analysis. These entities can be taken from the tabular recording of the man–machine interfaces.

Moreover each part, assembly and product needs the following documentation:

Possible errors within the technical documentation. Check the:

- manufacturing documents (drawings and lists)
- documents for assembly/disassembly (e.g., instruction sheets)
- calculation documents, such as
  - load assumptions
  - verification of strength
  - verification of deformation
  - verification of stability (e.g., buckling, bending, stability)
- Balances such as
  - balance of performance
  - balance of weight
  - position of the centers of gravity
  - balance of the moments of inertia

Table 5.26 Use analysis of a nutcracker (example)

No.	Subfunction first order	Man–product relationship: needed activities	Man–machine interface	Affiliated requirement	Required functions resp. possible carriers of function
1	Detection (of the object)	Nutcracker: Seek Ask for Find	Eye – object Sense of touch – object	Noticable design Recognizable design Shiny color	Color Contrast Grade of reflection
2	Transporting/ placing (the object)	Nutcracker: Grasp, lift, carry Put down Slacken	Hand – handle Hand – object body Eye – hand – handle	Little weight, ergonomic handle, handy surfaces, *crack protection* Stable stand	Lightweight construction Handle – leverage Corrugated surface Platform
3	Equipment (with a nut)	Open nutcracker Insert nut	Hand – object Hand – nut	Easy to equip Safely to equip	Trough Stop
4	Locating (of the nut)	Hold nut Press against stop Clamp nut	Finger – nut Hand – nut Eye – finger – nut	Easy to use Sure hold of nut Limit clamping force	Trough Clamping claw Vise
5	Produce (opening) force	Move leverage Hit against anvil Turn knob	Hand – leverage Fist – anvil Hand/finger – knob	Sure force insertion Notice finger/hand-span	Handle Leverage
6	Guide force/ amplify force	Inner function	/.	Force amount [N] Distance amount [mm] Limit force/distance	Leverage Spline Screw
7	Nut opens by: • pressure • effect of spline	Inner function	/.	Selection of effective functionalities that can be cheaply realized	Thrust piece Splines Blade Clamping screw
8	Remove (result)	Remove cracked nut Remove nut and shell	Finger – crecked nut Hand – cracked nut Eye – finger – cracked nut	Easy to remove Sure to remove	Collecting pan, sack Basin Flap Opening
9	Cleaning	Hold nutcracker Shake out crack room Clean crack room	Hand – nutcracker Finger/hand – cleaning device	Easy to handle No unreachable corners Easy to clean surface	*Room design* Shape of surface Surface roughness

- balance of temperature
- balance of coolant

- Documents such as
  - manufacturing documents
  - instruction sheets
  - instructions for maintenance and service
  - spare-part catalogue

Possible errors during market launch.

- Storage
  - Activities
  - Apparatus (e.g., bearing block)
  - Racks, halls, stacks (e.g., storage rooms with air conditioning)
- Transport
  - Activities
  - Apparatus (e.g., lifting gear)
  - Means of transportation (e.g., overhead crane)
- Mounting
  - Activities
  - Mounting regulations and instructions
  - Apparatus (e.g., lifting gear)
  - Measuring and test equipment (e.g., theodolite)
- Initial operation:
  - Activities and tests in accordance with
    - Instruction manual (Chapter *Initial setup*)
    - Checklist
    - User's handbook
    - Maintenance instruction

Possible errors in the use stage and in decommissioning.

- Initial operation:
  - Activities in accordance with
    - Instruction manual (Chapter *Initial setup*)
    - Checklist
    - Maintenance history
    - Document
- Operating:
  - Activities in accordance with
    - Instruction manual
    - User's handbook
- Maintenance:
  - Activities and test in accordance with
    - Instruction manual
    - User's handbook
    - Service documentation
    - Maintenance history (e.g., exhaust gas document for a motor vehicle)
- Service:
  - Activities and test in accordance with
    - Instruction manual
    - User's handbook
    - Service manual and Spare part catalogue
    - Logistics documents (e.g. global workshop catalogue)

Column 5. Here the status of currently used measures for the prevention of failures and test procedures is entered. These entries are used to reduce the causes of failure in column 4 and to detect possible sources of error.

Columns 6–10. These columns are used to calculate the risk priority number (RPZ).

To decide about actions for trouble-shooting it is very important to obtain an economic perspective on FMEA and its consequences. In the case of extension of the FMEA by integrating a cost calculation, the form includes an additional column K for the costs. The factor K stands for the probable costs in the case of an error occurring.

The value of column 10 has to be calculated by

$$\text{RPZ} = A \cdot B \cdot E \cdot K \tag{5.3}$$

where:

A = Probability of a failure incidence

Unlikely	1
Very low	2
Low	3
Medium	4
High	5
Very high	6

B = Consequences for the customer

Consequences not noticeable	1
Inconsiderable inconvenience for the customer	2
Small inconvenience for the customer	3
Inconvenience for the customer	4
Irritation of the customer	5
Possible loss of the customer	6

E = Probability of failure detection

Very high	1
High	2
Medium	3
Low	4
Very low	5
Unlikely	6

K = Probability costs in case of a fulfilled error

No or negligible increase of costs	1
Little additional costs	2
Medium additional costs	3
High additional costs	4
Extremely high additional costs	5
Non-budgeted costs	6

Instead of the absolute measure of 1–6 a range of values from 1–10 can also be chosen. This is only reasonable if detailed knowledge is available, for example within an FMEA at the end of the product development process.

A verbal description of the RPZ is:

Unacceptable high	1296–10 000
Medium	256–1296
Low	1–1

In practice RPZ failure values lower than 81 resp. 625 are not used to remove a failure as it is not profitable to do so.

Column 11. In this column the actions for trouble-shooting are entered.

Columns 12–17. Supposing that the recommended actions for trouble-shooting from column 11 are realized the actions are described in columns 12 and the RPZ* value is calculated again in columns 13–17. The factor K^* stands for the probable costs of the measure required to avoid or minimize a probable error. Both K and K^*

have the same range of risk factors. The measure is accepted if the RPZ* is below the level described in the above (81 resp. 625).

The value of column 17 is calculated by

$$RPZ^* = A \cdot B \cdot E \cdot K^* \quad (5.4)$$

In practice failure values RPZ* that are lower than 81 resp. 625 are not used to remove a failure as it is not profitable to do so. The verbal description of RPZ* is like that of RPZ.

If RPZ* is higher than RPZ then the measure to avoid or to minimize a probable error has to be consider critically.

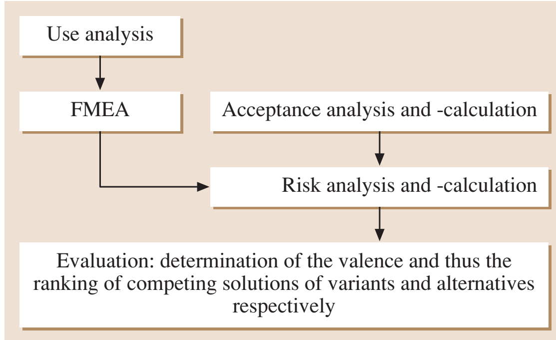


Fig. 5.33 Relationship between acceptance, risk and evaluation

5.6.4 Further Use of FMEA Results

Within the concept and sketching phases several competing solutions or alternatives are available. In order to identify the best solution a ranking procedure is carried out. If the criterion *risk* is already part of this ranking procedure it is reasonable to use the sum of the RPZ or RPZ* values of each solution.

The relationship between acceptance, risk and weighting is shown in Fig. 5.33.

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