Chapter 2
Designing in a Rule-Based Regime—Systematic Design Theory and Project Management

The first class of design regime we shall analyze in this book is that of rule-based design. This relies on a set of rules for the efficient design of new products (or services), whence the name (Le Masson and Weil 2008). Historically, several rule-based design regimes were gradually established, culminating in 1970's in systematic design, surely the most common and perhaps the most effective: it is this organizational model (often implicit and seemingly natural) which is adopted by the major R&D companies, and it is this model that provides the structure for the logic underlying project management in product development (NPD).

In this chapter we examine the design logic of "rule-based design", i.e. when well formed design resources (i.e. rule systems) are available. Hence in this chapter we shall answer the question: how do designers conceive a new object within the framework of a rule-based design regime? In the next chapter we shall address the design of the rule-based system itself. We shall see how to design a rule-based regime and at the same time discover some of their fundamental properties. In addition, examination of an historical case will provide a description of the gradual build-up of rule-based design in companies; the historical perspective will also show how theories of rule-based design have progressively developed.

Following the analysis framework of the design regimes outlined in the introductory chapter, we shall examine in turn the reasoning processes, performance and organizations, highlighting the tools associated with them.

2.1 Reasoning in Systematic Design

Systematic design forms part of a German tradition of design theory and method that arose at the start of the 19th century (König 1999; Heymann 2005; Le Masson and Weil 2010, 2013). The international work of reference is the manual written by Gerard Pahl and Wolfgang Beitz (Pahl and Beitz 1977; Pahl et al. 2007; Wallace and Blessing 2000), "Engineering design, a systematic approach", published first in

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P. Le Masson et al., *Design Theory*,
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German in 1977, translated by Ken Wallace into English in 1984 and republished several times since. This work and its successors are widespread to the point that the theory of systematic design (and its variants) is today commonly taught in engineering design courses the world over.

2.1.1 Expectations of Systematic Theory

Pahl and Betz stipulate that a good design method must satisfy several requirements:

- It must be applicable to the most varied of problems, regardless of the field of specialism—it must therefore be independent of the objects to be designed; however, it must also be compatible with the concepts and methods of the disciplines involved (engineering sciences in particular).
- It does not rely on discovering solutions by chance but contributes to the inventiveness and understanding of the whole, and facilitates the finding of "optimal" solutions; however, wherever possible it must also facilitate the application of known solutions.
- It must be easy to learn and to teach and, "taking account of advances in ergonomics and cognitive psychology", it must be capable of reducing the workload (including the mental load), saving time, avoiding human error and sustaining the interest of the designers. It must also be compatible with the instruments available (in particular the use of computers for data processing).

The systematic design they propose meets these criteria, as we shall see.

2.1.2 Fundamental Principles

According to Pahl and Betz, design follows a linear process which can be broken down into phases.

Reasoning in systematic design comprises four main phases (see Fig. 2.4), with each making use of a specific object language to the exclusion of any other language:

- **Functional design** involves clarifying the design task and of setting out the functional specifications for the future product. Only *the language of functions* is used to describe the object. During the course of this phase, several functional specifications may be developed, several possible requirements sheets may be discussed, and at the end of the phase, just one requirements sheet is retained.
- **Conceptual design** on the basis of the requirements sheet of the previous phase, involves formalizing the functional structure (interdependencies, functions and sub-functions, potential modularization) and mobilizing conceptual models, i.e.

the main techniques and technologies required to fulfill these functions. Only *the language of the main techniques* (the laws of engineering science) is used to design the object—this is no longer a matter of discussing the functions or indeed of discussing the components. Several conceptual alternatives must be developed, with one of these being selected by the end of the phase.

- **Embodiment**, **or morphological design** on the basis of the technological scheme obtained in the previous phase, consists of proceeding to the "organized assembly" of the various component parts. Only *the language of components and their inclusion in a coherent whole* is used; no alternative technologies are discussed, and neither are the exact dimensions of the components. This is an architectural design phase, where we speak in terms of components, modules, parts, assembly procedures, etc. Again, several embodiments are developed during this phase, with one of them being selected.
- **Detailed design** which, on the basis of the previous embodiment, involves dimensioning all the free parameters (sizing of parts, procedure configuration, material identification, suppliers, etc.). This is the language of dimensionalization and product reference.

It is possible to design in one of the phases using inputs from the previous phases, independently of subsequent phases (Fig. 2.1).

From a formal point of view, systematic theory takes account of the P(X) (functional specifications), checks whether they are unattainable with known solutions (K(X) does not imply P) during selection from the specifications sheet (if they are, then the design becomes a form of optimization); the process is then a series of "decisions" d_i taken from D(X) gradually defining a family of objects verifying the initial (PX). The list of d_i is not completely known at the start but the process does facilitate their development, on the one hand by structuring a priori the types of d_i (functional, conceptual embodiment, detailed), and on the other hand by enabling each stage to re-use, post hoc, the known di at each of the levels of language.

The reasoning structure in different languages for the object can be interpreted as a division of {X, K(X), P(X), D(X)} into four sub-spaces $\{X_{func}, K(X_{func}), D(X_{func}), P(X_{func})\}$, $\{X_{conc}, K(X_{conc}), D(X_{conc}), P(X_{conc})\}$, $\{X_{emb}, K(X_{emb}), D(X_{emb}), P(X_{emb})\}$ et $\{X_{det}, K(X_{det}), D(X_{det}), P(X_{det})\}$; in each of the sub-spaces the available knowledge may, or may not, allow the proposed concept to be achieved (again, if it can, we find ourselves back in a decision-optimization situation), and if it cannot, the decisions to be taken about the object will result from a learning process associated with the level of language used and restricted just to this level of language. In other words, the segmentation into language types guides the search for new d_i: even if at each level we have $D(Xx_{level\ j}) \not\subset K(X_{level\ j})$, the expansions necessary to have $K'(X_{level\ j})$ such that $D\left(Xx_{level\ j}\right) \subset K'\left(X_{level\ j}\right)$ are confined to this level, thus limiting the "distance" between $K(X_{level\ j})$ and $K'(X_{level\ j})$.

Several essential elements are introduced by systematic design. Without going into too much detail here, we can say immediately that (1) systematic design combines the logics of convergence and divergence; (2) it tends, paradoxically, to "slow down" the process of design by avoiding complete, pre-existing solutions but

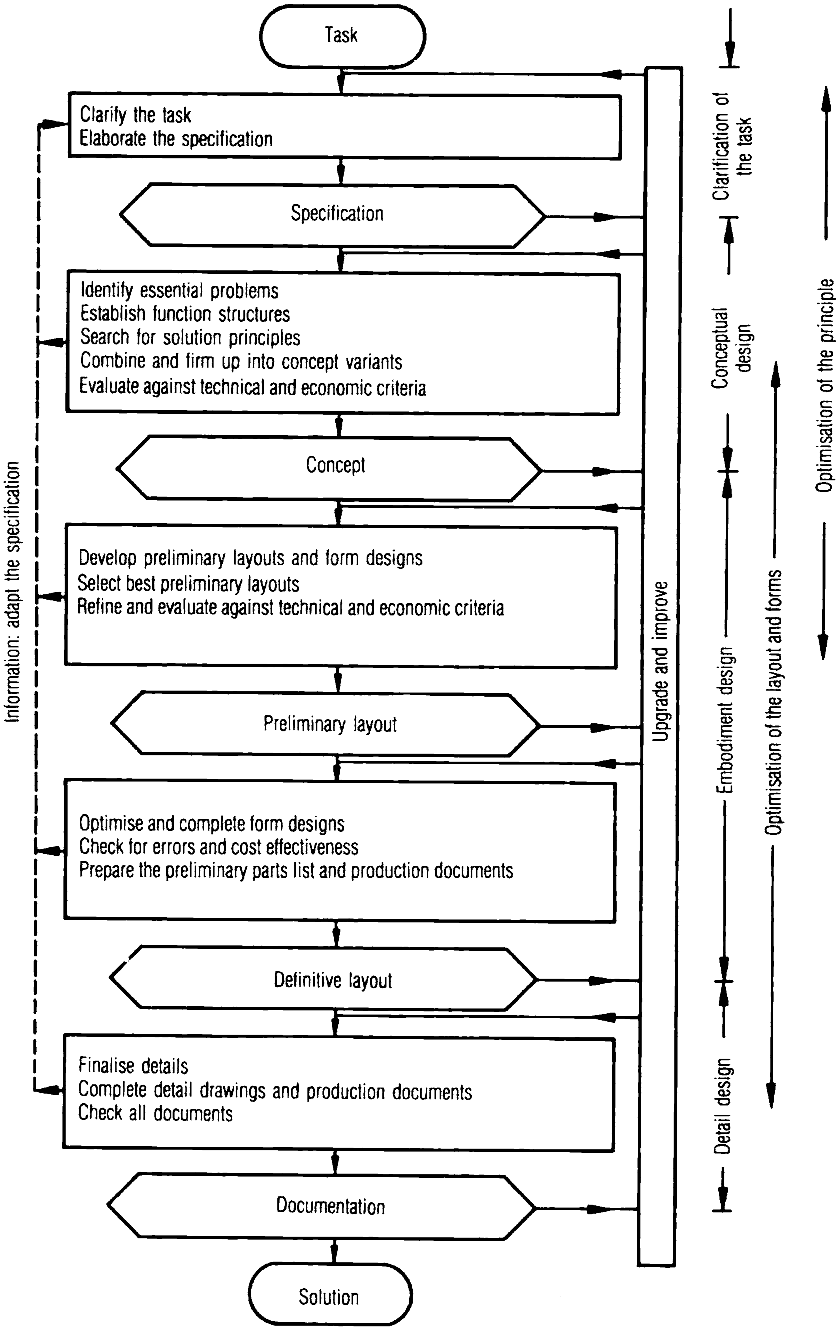


Fig. 2.1 The four main languages of systematic design in the sense of Pahl and Betz

in fact it is there to preserve forms of "technical creativity" and avoid "fixations"; (3) systematic design relies in particular on the key stage of the conceptual phase where abstract technical languages can be used to design the object—a "conceptual wedge" (like a log splitter!) for separating functions and components, thus ensuring a richer and more complex relationship between these two terms.

2.1.3 *Illustrative Examples of Language*

We give an example of the different languages for an object in the case of a refrigerator (the reader can practise by trying to do the exercise himself before reading on) (see Figs. 2.2 and 2.3).

- Functional language: this is the language of the object's conditions of value (e.g. sales criteria) and existence (e.g. commercial standards). Hence we find: "volume (in liters) at a temperature (a few degrees or tenths of a degree, more or less)", standards (for safety and power consumption, fluids and recyclability, etc.), reliability and robustness (in specific usage scenarios: opening & closing the door; air-tightness in a standardized humid atmosphere, etc.), shelves, ease of upkeep, noise, automatic defrosting, temperature indicator, etc (Fig. 2.2).
- language of embodiment: this is the language of components, often presupposing that the object itself be analyzed (disassembly). For the refrigerator we find the "cabinet" (enclosure, door, etc.) and then, on the other side, a grille (technically called a "condenser"), a black bowl-shaped object which on

Fig. 2.2 Some elements for the functional language of the refrigerator

Fig. 2.3 Some elements of the embodiment of the refrigerator

dissection turns out to be a compressor, pipes (including the expansion capillary), insulating foam inside the walls of the enclosure, and tubes inside the insulating foam (technically called an "evaporator"). A more detailed analysis shows that the pipes all connect the compressor, condenser, expansion capillary and evaporator (Fig. 2.3).

- The conceptual language is perhaps the least evident for the refrigerator non-specialist, but is essential for understanding the design of the object. In this case there is no direct correspondence between function and component (a component can be assigned a function or a function a component); it is the conceptual language, which explains the complex relation between functions and components. The main conceptual model of the refrigerator is a two-phase thermodynamic cycle which "makes cold" (the language of function) via the change of phase of a liquid to a gas, this phase change being organized in a complete cycle starting with evaporation (the "cold production" phase), going on to compression, condensation and expansion before returning to evaporation. Such a model may, for example, be represented by a (T, S) diagram (temperature and entropy) with greater or less precision in the model, each phase in the cycle then corresponding to a physical entity (the language of embodiment) (see Fig. 2.4).

Note for the moment that all we have done is describe the object (already known, already designed) in each of the languages. The systematic design reasoning applied to the design of a new refrigerator takes a different form. Let us assume now that we have to design a new range of refrigerators for the elderly. The process follows the logic below:

1. we start by skimming through all possible functions before selecting those deemed relevant for the new product (conservation of medicines, pre-prepared meals, etc.)
2. we then consider all possible conceptual designs for the product. At this stage, designers must in theory look at all possible technologies: cold via the two-phase cycle, but also cold via expansion of a gas or the thermoelectric (Peltier) effect, etc.
3. Once one of these principles has been adopted, we then look at the embodiment, and so on.

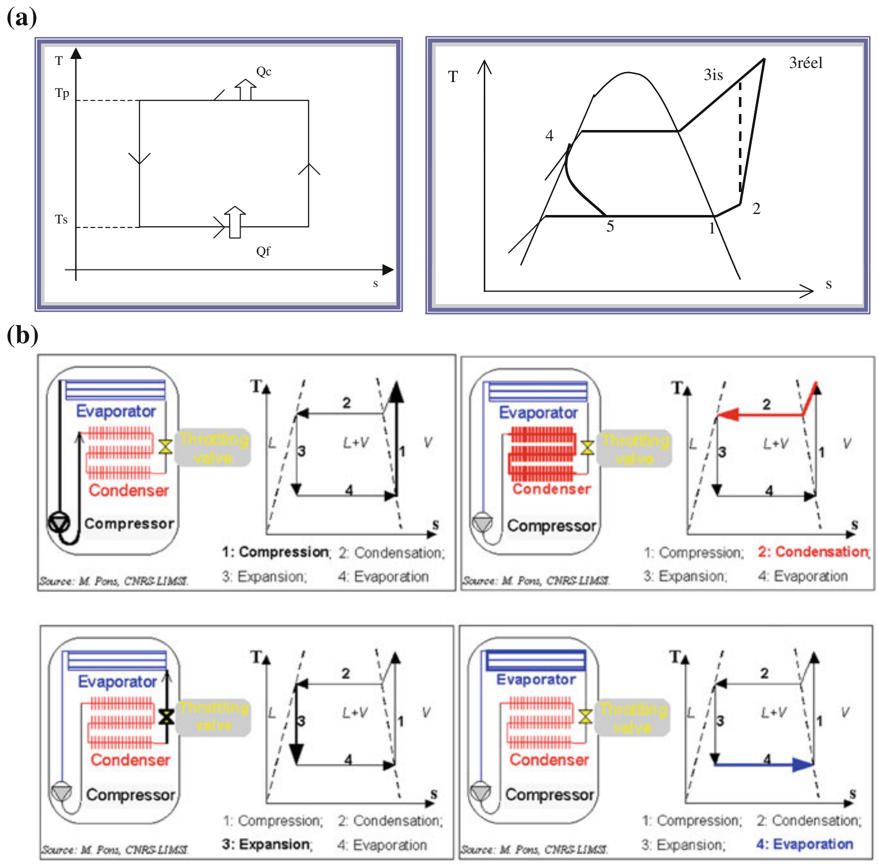


Fig. 2.4 Some elements of the conceptual language of the refrigerator. Note that the model can have several levels of precision. The first representation (Fig. 2.4**a**, **top left** on the diagram) provides a crude idea of the magnitudes of the energy exchanges (Qf = quantity of heat extracted; Qc = quantity of heat produced); the second (Fig. 2.4**a top right**) locates the cycle with respect to the phase diagram of the fluid used and in particular checking that the cycle is "good" (i.e. avoiding liquid "blips" in the compressor by ensuring that all the fluid is completely gaseous at the inlet to the compressor); on the bottom (Fig. 2.4**b**): the diagram makes each phase of the cycle correspond to a component of the embodiment: **top left**: compression requires a compressor, then on the right condensation uses a condenser, then on the **bottom left** the expansion device uses a throttling valve and on the **bottom right** evaporation takes place in an evaporator

2.1.4 Tools and Associated Techniques

The way in which reasoning is structured according to the systematic design model has given rise to the development of numerous tools associated with each of the phases. We mention three types of tool: functional analysis, knowledge management catalogues, and Computer Aided Design (CAD) .

2.1.4.1 Functional Analysis

Functional language is one of the critical languages of systematic design. Thanks to functional analysis an object can be discussed without evoking any constructional techniques, i.e. talking about the object even though it may not yet exist, and with the aim of preserving degrees of freedom for those engineers who will have to design it. The functional language also carries a concomitant logic of validation essential for design. It must be possible to validate a function, i.e. it must be associated with a protocol allowing such a validation.

We shall define a function as an object's condition of existence or value, from the perspective of a stakeholder, or the object's environment. This language must be as abstract as possible in describing the conditions of existence or value to avoid a priori technical solutions ("inform", "communicate", "beguile"), but it must also be as specific and as concrete as possible when it comes to describing the environment or the observer ("inform handicapped persons with motor disabilities who cannot reach the counter…"), to be pertinent in terms of validation.

Note that the same object may perform several functions and that the same function may mobilize several objects.

The fundamental assumption of functional analysis is that there exists a minimal group of functions qualifying the object and which are independent of how it is made.

Example: "Functional description of a system for controlling traffic at a road crossing". It must be possible to describe the functions without knowing beforehand whether to use traffic lights or a roundabout. The reader can do this exercise for himself. For example:

- F1: the system must inform drivers of the existence of the crossing.
- F2: the system must allow each driver to know what vehicles are at the crossing.
- F3: it must allow each driver to take the correct decisions when approaching the crossing.
- F4: it must clearly describe the rules of the road and any contraventions that may result in a (police) ticket.
- F5: as far as possible, the system should avoid any risk of collision.

In practice, we refer to the functional analysis workshop for more detailed elements.

This type of analysis can be refined using additional tools. Hence a functional analysis may give rise to a value analysis leading to a ranking of the functions according to their customer value (see the recent ISO standards on "value management"). Hauser and Clausing (1988) proposed building functional analysis into a "house of quality", providing a relationship between functions (functional requirements, FR, in columns) and "Customer attributes", weighted with respect to the competitor's bid (see Fig. 2.5).

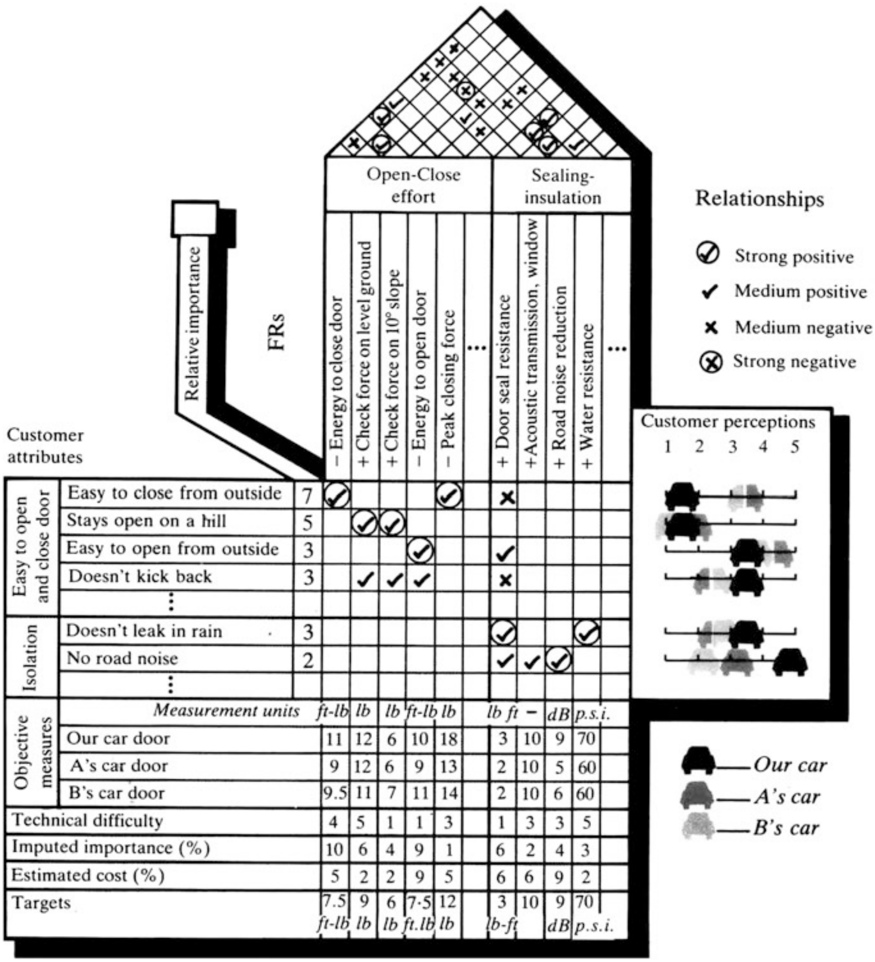


Fig. 2.5 The "house of quality" according to Hauser and Clausing

2.1.4.2 Catalogs and Knowledge Management in Systematic Design

Corresponding to systematic design reasoning is an equally systematic knowledge management: for it to be readily activated, knowledge is organized in accordance with the languages of design (knowledge of functions, conceptual design, embodiment, etc.) and conversely, gradually acquired knowledge is accumulated in each of these languages.

Thus work in systematic design can draw on a prepared knowledge base. Hence catalogs of conceptual models can be found for "energy storage" or "change of energy mode" (see Fig. 2.6). The language of embodiment will also be structured, based in particular on the list of "recommendations" set out (see the recommendations below on ease of assembly or disassembly for recycling purposes) (see Fig. 2.7).

The way in which reasoning is structured provides a knowledge management which overcomes the two classical obstacles to knowledge management as a matter of course: difficulty of use and cost of storage. This is because of the strict relationship between design stage and type of knowledge (functional, conceptual, embodiment and detailed level) which on the one hand allows the knowledge user to understand immediately what type of knowledge he should make use of, and conversely that the knowledge produced is stored appropriately to enable its effective re-use.

Note also that knowledge is not presented as is usual in the engineering science courses of an engineering university, where knowledge is grouped under major disciplines such as thermodynamics and electricity, etc. Systematic design will organize knowledge according to an entirely different logic, by listing, for example, all the energy conversion modes (in each engineering science discipline it will seek the phenomena within those sciences that are capable of energy conversion) (Figs. 2.6 and 2.7).

2.1.4.3 CAD, Digital Mock-up, Simulation and Validation Tools

These days systematic design is able to draw on the tools provided by Computer Aided Design (CAD), being highly consistent with the languages of embodiment and detailed design. Today's CAD and digital mock-up tools have gradually:

- enabled complex shapes to be mastered (freeform surfaces in aeronautics)
- enabled the resizing and local optimization of certain parameters to be facilitated
- enabled integrated technical data to be managed (product-process-resource management over the product's entire life cycle from concept to scrap)
- aided validation (simulation tools and tests on numerical mock-ups; validation process of "workstation ergonomics" type)
- enabled the product at the upstream phase to be visualized (digital demonstrators, virtual reality)

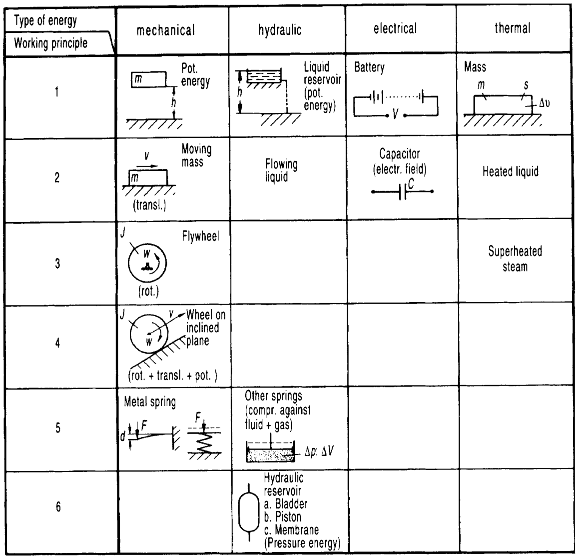
For more in-depth information on these aspects, refer to (Daloz et al. 2010). For an historical approach to CAD see also (Fridenson 2015).

2.1.5 Contemporary Trends in Rule-Based Design

We mention three of today's trends in rule-based design.

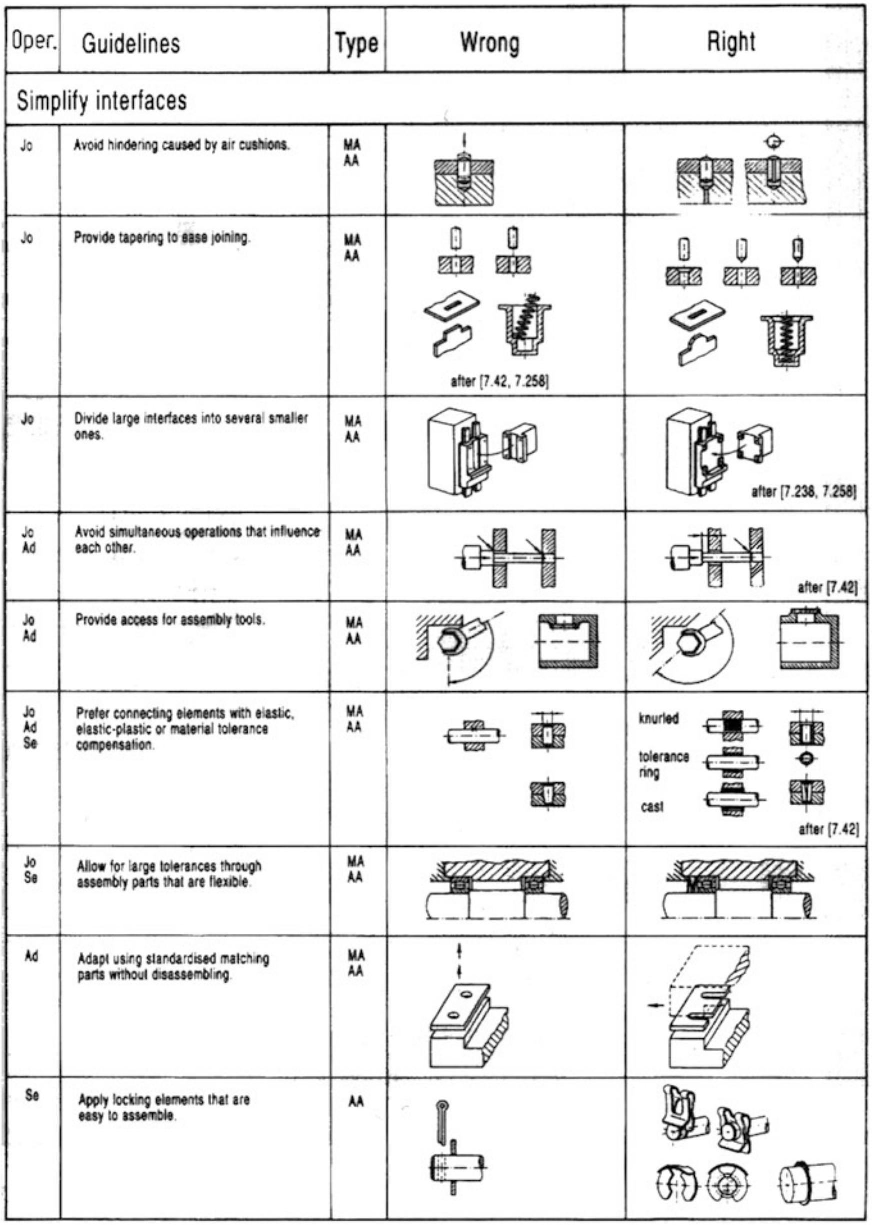
2.1.5.1 TRIZ, or the Temptation of Universal Conceptual Models

The TRIZ method provides a more systematic treatment of the conceptual design phase, enabling the transition from a specific to a general problem: by studying the bases of patents, work carried out by G. Altshuller and his teams showed that all the



Function	Input	Output	Physical effects						
E_{mech} → E_{mech}	Force, pressure, torque	Length, angle	Hooke (Tension/ compression/ bending)	Shear, torsion	Upthrust Poisson's effect	Boyle-Mariotte	Coulomb I and II	...	...
		Speed	Energy Law	Conservation of momentum	Conservation of angular momentum	...		...	...
		Accelera-tion	Newton's Law	...	...	...	...	...	...
	Length, angle	Force, pressure, torque	Hooke	Shear, torsion	Gravity	Upthrust	Boyle-Mariotte	Capillary	
			Coulomb I and II	...	...	...	...	...	...
	Speed		Coriolis force	Conservation of momentum	Magnus-effect	Energy law	Centrifugal force	Eddy current	
	Accelera-tion		Newton's Law	...	...	...	...	...	...
E_{mech} → E_{hyd}	Force, length, speed, pressure	Speed, pressure	Bernoulli	Viscosity (Newton)	Toricelli	Gravita-tional pressure	Boyle-Mariotte	Conservation of momentum	...
E_{hyd} → E_{mech}	Speed	Force, length	Profile lift	Turbulence	Magnus-effect	Flow resistance	Back pressure	Reaction principle	...
E_{mech} → E_{therm}	Force, speed	Temperature, quantity of heat	Friction (Coulomb)	1st law	Thomson-Joule	Hysteresis (damping)	Plastic deforma-tion	...	...
E_{therm} → E_{mech}	Temperature, heat	Force, pressure, length	Thermal expansion	Steam pressure	Gas Law	Osmotic pressure	...	...	...
E_{electr} → E_{mech}	Voltage current, magn field	Force, speed, pressure	Biot-Savart-effect	Electro-kinetic effect	Coulomb I	Capacitance effect	Johnsen-Rhabeck-effect	Piezoeffect	...
E_{mech} → E_{electr}	Force, length, speed, pressure	Voltage, current	Induction	Electro-kinetics	Electro-dynamic effect	Piezoeffect	Frictional electricity	Capacitance effect	...
E_{electr} → E_{therm}	Voltage, current	Temperature, heat	Joule heating	Peltier-effect	Electric arc	Eddy current	...	...	...
E_{therm} → E_{electr}	Temperature, heat	Voltage, current	Electr. conduction	Thermo-effect	Thermionic emission	Pyroelectri-city	Noise-effect	Semiconductor, Super-conductor	...
E_{mech} → E_{mech}	Force, length, pressure, speed	Force, length, pressure speed	Lever	Wedge	Poisson's effect	Friction	Crank	Hydraulic effect	...
E_{hyd} → E_{hyd}	Pressure, speed	Pressure, speed	Continuity	Bernoulli	...	...	...	...	...
E_{therm} → E_{therm}	Temperature, heat	Temperature, heat	Heat conduction	Convection	Radiation	Condensa-tion	Evaporation	Freezing	...
E_{electr} → E_{electr}	Voltage, current	Voltage, current	Transformer	Valve	Transistor	Transducer	Thermogalvan-ometer	Ohm's law ...	...
...	...	...	...	...	...	...	...	...	...

Fig. 2.6 Various principles for "energy storage" (*top*) and energy conversion (*bottom*) *Source* (Pahl et al. 2007)



Oper.	Guidelines	Type	Wrong	Right
Simplify interfaces				
Jo	Avoid hindering caused by air cushions.	MA AA		
Jo	Provide tapering to ease joining.	MA AA	after [7.42, 7.258]	
Jo	Divide large interfaces into several smaller ones.	MA AA		after [7.238, 7.258]
Jo Ad	Avoid simultaneous operations that influence each other.	MA AA		after [7.42]
Jo Ad	Provide access for assembly tools.	MA AA		
Jo Ad Se	Prefer connecting elements with elastic, elastic-plastic or material tolerance compensation.	MA AA		knurled tolerance ring cast after [7.42]
Jo Se	Allow for large tolerances through assembly parts that are flexible.	MA AA		
Ad	Adapt using standardised matching parts without disassembling.	MA AA		
Se	Apply locking elements that are easy to assemble.	AA		

Fig. 2.7 Recommendations for ease of assembly *Source* (Pahl et al. 2007)

problems resulting in patents involved resolving a contradiction between two primary techniques among a finite list of 39 principles. Hence there are just 39 × 39 possible contradictions. They also showed that these contradictions were always resolved by using one of the 40 inventive principles they listed (Altshuller 1984).

Hence the TRIZ method offers a rich catalog of conceptual models and a method for activating them.

Note that the TRIZ method is often invoked in tackling questions of innovation in the broadest sense. We should emphasize here that the method has two special properties: it presupposes a good knowledge of the object (K(X) already important) so that any critical contradiction(s) can be characterized; this leads to a decision about what technical principle to choose among a finite list – it does not model the learning process, apart from the 39 × 39 contradictions and the 40 inventive principles. These two special features make it particularly consistent with a systematic design reasoning which relies precisely on an extensive knowledge base and on a constant effort to limit the production of new knowledge. On the other hand, these two conditions make it less effective for innovative design situations such as those we shall examine in Chaps. 4 and 5 (for a more in-depth discussion of the method, see (Rasovska et al. 2009; Reich et al. 2010)).

2.1.5.2 Extension of Systematic Design to Other Designers and Other Objects

Today's numerical modeling and PLM (Product Life Cycle management) tools are able to extend the design to other participants previously marginalized by the traditional processes of engineering design. Hence systematic design processes can be deployed for product distribution, maintenance or after-sales: these participants, often treated as simple "producers" charged with carrying out routine tasks, may however contribute to the design not only by outlining their own functional requirements (as they may already have done in the systematic design model), but also by bringing in their own specific design variables (logistical scheme, original promotional campaign, after-sales contract), etc. The new tools leave these parameters "free" over the course of the process (or manage the gradual stress they are put under) and enable skilled designers in their turn to take part in the process.

Systematic design and its associated tools have gradually conquered numerous fields. These days it is not just "machines" (cars, aircraft, machine-tools, telephones, microprocessors, etc.) that are designed on these principles, but also software, medicines, buildings, urban areas, insurance contracts or banking services.

2.1.5.3 "Parameter Analysis" Approaches

Some authors have shown that, in certain cases, systematic design can slow down the design of an individual object (Ehrlenspiel 1995) by committing the designer too early and too comprehensively to dimensions which are, of course, necessary for the final object but not always necessary in the exploratory phases. Hence the author of a specifications sheet may list obvious standard functions which are easy to realize along with those that are hard to attain requiring more intensive explorations, without distinguishing between them; moreover, the exploratory leads suggested by systematic design might fall within complex superabundant combinations, sometimes a little sterile (see the combinatorics opened by the morphological matrices of Zwicky (1969)).

This is why, all the while preserving the logic of rule-based design (use of a knowledge base restricting exploration and minimizing any challenges to knowledge), more exploratory processes have been proposed. Such is the case for the "parameter analysis" method (Kroll et al. 2001, 2013), in which exploration focuses on several critical parameters before then reverting to a systematic design logic. This reasoning is based on the fact that parameters not instantiated at one level (conceptual alternatives can be explored without having all the functions, for example) are not necessary for exploration (even though they may ultimately be necessary for the final object) and that taking them into account would render the exploration less effective (contrary to the normal assumption of systematic design which avoids too broad an exploration through the constraints of the specifications sheet).

For a detailed study of the Parameter Analysis method see (Kroll 2013). It can be shown that the logic of Parameter Analysis is an extension of the Branch and Bound logic applicable to design situations (Kroll et al. 2013, 2014).

Note that the three developments mentioned satisfy the fundamental assumptions of systematic design reviewed below in conclusion:

- a linear process that can be broken down into phases
- each phase makes use of a language specific to the object and to the exclusion of others
- there are four object languages: functional, conceptual, embodiment, and detailed
- it is possible to design in one phase independently of subsequent phases

2.2 Performance in Systematic Design

2.2.1 Fundamental Principle: Maximizing the Re-use of Knowledge

The performance of a project under systematic design is based on a fundamental principle: maximize knowledge re-use to design X_x such that $P(X_x)$ is true.

This general principle appears as two guiding criteria over the course of the process:

- Limitation of explorations. Several aspects of Systematic Design contribute to this:
  - Recurrent test of unknown nature: as soon as it has been shown that the task corresponds to a known set of specifications, or that the specifications

corresponds to known technical principles, systematic design tends to an optimization-decision regime.
 - If the necessity for exploration has been demonstrated, restrict it to one of the levels of language without pushing the exploration beyond that level (making a complete prototype just to assess certain technical principles is pointless).
 - Make an early selection of the alternatives: exploring all the branches of the tree diagram created by all the examined specifications sheets and then all the technical principles for all the specifications and so on is pointless.

- A knowledge aggregation logic:
  - The knowledge produced is incorporated within K(X) and hence can be re-used for subsequent projects.
  - Design reasoning implicitly avoids any challenge to the knowledge base. Explorations of the type "a refrigerator with the same functions but a technical principle different from those with which the company is familiar" run the risk of being quickly brought to a halt.

These principles are therefore able to reconcile exploration and the generation of alternatives with the re-use and maximization of knowledge; they can also ensure forms of divergence while maintaining overall convergence at each phase of the process, thanks, in particular, to a gradual process of validation.

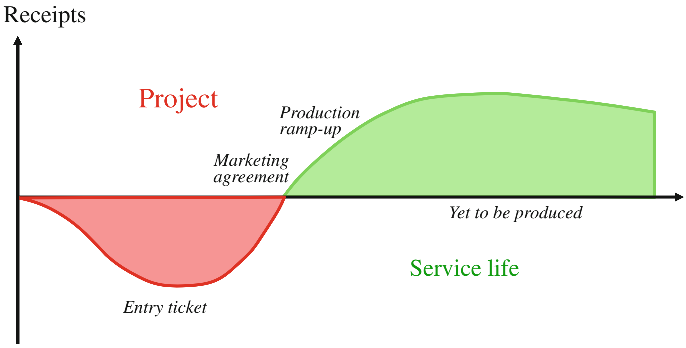
2.2.2 *Practical Assessment*

This general principle lies at the heart of measuring the performance of a systematic design project. In practice, the performance of a systematic design project is defined by a target and a drift with respect to the target.

2.2.2.1 Project Target—the Idea of NPV

A cost-quality-time (CQT) objective is clearly identified at the start. C represents the cost of development, Q the product or service target (functions, production cost, etc.), and T the development timescales (generally the time initially set between the start date and the intended date for launching the product; in the automobile sector in particular, this date corresponds with the marketing agreement).

This initial CQT objective is validated at the start of the project, and corresponds to an economic equation which characterizes its value. Value is assessed in the same way as the profitability of an investment is assessed, i.e. on the updated earnings or "net present value", NPV. The profit curve is characterized by an initial "entry ticket" (essentially costs) and a production service-life phase (essentially revenue, with deduction made for direct manufacturing costs). The transition into the positive



$$NPV = -ET_0 + \sum_{time\ n=1}^{time\ n=N} \frac{(CV.Volumes)_n - (MC.Volumes)_n}{(1+i)^n}$$

Fig. 2.8 The economic logic of a systematic design project and formula for calculating the NPV. ET = entry ticket, CV = customer value (anticipated sales price), MC = Manufacturing costs. In this formula, time n = 1 begins with the marketing agreement and the ET starts at time zero, n = 0

zone occurs with the marketing agreement defining the "timescale" T; the quality criterion Q corresponds to the expected turnover in the market and the anticipated production costs, while the cost criterion C is the "entry ticket" corresponding to the initial production investment (tools, etc.) and design costs (see Fig. 2.8).

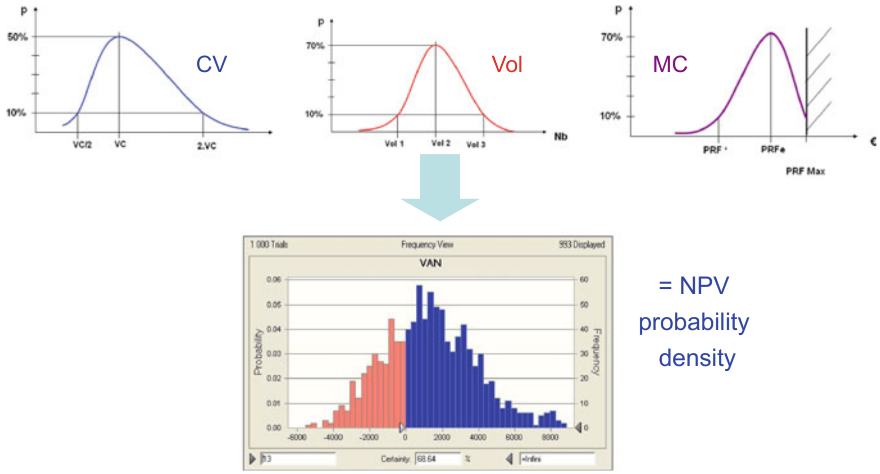


Fig. 2.9 Stochastic simulation for estimating the probability density of the NPV for an innovative project (*Source* (Hooge 2010)). Instead of taking a point value for the customer value (i.e. the forecast sales price), volumes and manufacturing costs, a random variable is taken for each of these terms. The density of the variable is given by experts (the *upper curves*) who can, for example, estimate the lowest price below which there is a 1 in 10 chance of a sale, the median price, and the highest price above which there is a 1 in 10 chance of a sale. Simulation gives the NPV's probability distribution

Note that this economic equation can be expressed in probabilistic terms (turnover, costs and time can be considered as random variables); the expectation of the NPV can then be calculated (see an estimate of the expectation of an NPV using stochastic simulation) (Hooge 2010) (Fig. 2.9).

If the NPV or the expectation of the NPV exceeds the company's conventional thresholds, the project is launched with the aim of ultimately reaching the target CQT.

2.2.2.2 Drift Assessment

Assessing a project consists of assessing a deviation from some initial target. In practice, this assumes that:

- The target is qualified in terms of CQT
- The resources allocated to the project have been identified (initially budgeted for, and reassessed over the course of the project)
- A follow-up is made and a final assessment in terms of CQT: what specifications have been attained? Within what timescales? With what costs?

In the canonical performance model the project "outputs" appear as a minimized drift with respect to a fixed target (realized—expected) (possibly weighted by the updated profit); the "inputs" are the design resources agreed upon. The "efficiency" of a project is therefore measured in terms of the ratio of drift to resources.

This measure invites a few remarks:

1. performance is indeed measured by a *deviation* from an objective: a systematic design project is a priori intended to "best" fit the target, and its objective is not to explore new targets. Note that doing something "faster" or of "higher quality" is not always expected of the company: rather, the product or service should be released "when expected" and at the predefined level of quality. What is being assessed is compliance with the target, not the target itself.
2. It is understood that the success (or failure) of a project depends on the one hand on how well (or badly) the project is guided through the course of the process but also on the definition of the initial target and its deviation from the skills and competence the allotted budget allows. In other words, the initial difference between P(Xx) and K(X) largely determines the future performance of the project. It is this definition of the "difference" between project target and available resources which lies at the heart of the project "contract" that the project leader concludes with the company. The critical points of this negotiation are the definition of reasonable but cost-effective objectives, and allocation of the necessary resources.
3. Measurement of performance must take account of unexpected events, technical and market-related uncertainties. The standard principles do this in two ways:

- vagaries of the market are generally included when calculating the expectation of the updated profit; the CQT target adopted can then be robust against external vagaries (even if the scenario of externally generated hazards is highly unfavorable, the CQT target allows the company to limit its losses). However, that generally leads to a “hardening” of the target (shorter timescales, more demanding specifications, lower costs to enable unfavorable scenarios to be dealt with). Once the CQT target is agreed, the project leader is assessed without always taking account of any externally generated pitfalls that might affect the project. In other words, the project leader is not expected to include these hazards during the course of the project (under systematic design it is assumed that the specifications will not change over the course of the project). Or further, a project leader who has reached his CQT target cannot be held responsible for commercial failure (which would be due to an error in the initial target).

- On the other hand, any technical hiccup is the responsibility of the project leader and his team. Performance is very tightly bound with the ability to gradually reduce the initial uncertainty in order to reach the set target using the allotted resources.

In terms of risk management it can be said that the project leader manages risk related to “market pull”: the market uncertainty is under control (by initial market studies and the margins taken on the initially set CQT target), and all that remains is the technical uncertainty, being reduced gradually by the rule-based design project. However, certain projects (coming out of research) may be governed by “technology push”, i.e. the technical uncertainties are reduced and there only remains the “market” uncertainty, which market research or commercial predictions gradually aim to reduce.

To conclude: we have a logic in which *uncertainties have been decoupled*, and any reduction in uncertainty is built on *known elements* (there is no technical exploration without market assumptions and no commercial exploration without the available technology).

2.2.2.3 Risk Management in Rule-Based Design—Decision Theory Under Uncertain Conditions and Real Options

Project Selection Tools in an Uncertain Situation

The decision model can be enhanced to take account of externally generated hazards. In decision theory under uncertainty we reason according to the models introduced by Savage, Wald and especially Raïffa (Savage 1972; Wald 1950; Raïffa 1968) (Models for calculating real options are derived from these models (Trigeorgis 1996, 2005)) (see Fig. 2.10).

The figure below outlines the tool’s underlying principle, which can be effectively analyzed within the {X, D(X), K(X), P(X)} framework. K(X) is constituted thus: the decider knows a set of alternatives D_i, a set of states of random E_j independent of D_i and whose (subjective) probability $P(E_j)$ is known (the weather, for example: the probability that it will be rainy or fine, on which sales of a certain product may depend), given a certain value V_{ij} associated with the pair (D_i, E_j) (we assume that there exists a utility function U which allows an optimal decision to be constructed—although it may

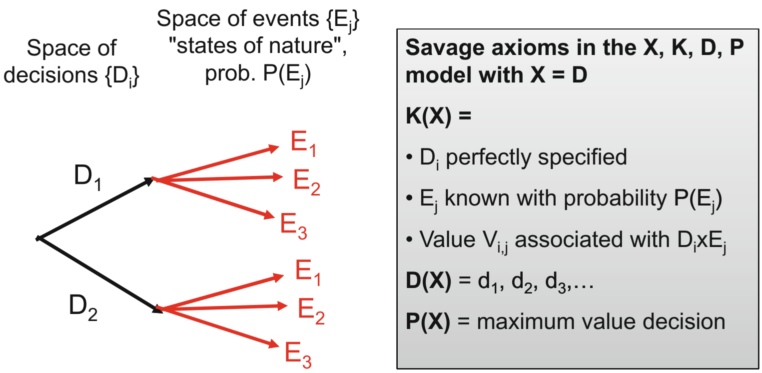


Fig. 2.10 General framework of the theory of decision under uncertainty (Savage axiom)

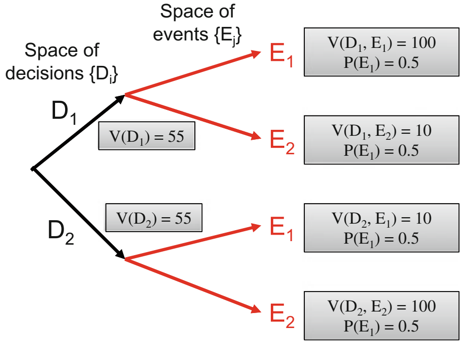
be necessary to prove the existence of an optimal solution, we will not discuss this idea here; the interested reader may refer to (Wald 1950)); this decider then maximizes the value of the decision D (the performance function P(X)) taking that decision D_i which maximizes the expectation of utility S_i^* (Fig. 2.10):

$$S_i^* \sum_j U(V_{i,j}) \cdot P(E_j)$$

This type of technique enables a project to be selected from among a set of alternatives taking account of the uncertainty of all possible states of the world. This is a standard tool for choosing product development projects.

The figure below gives an example (a very classical case of decision-making under uncertainty) (see Fig. 2.11). There are two decisions: either to go for a walk with a raincoat (D_1) or to go for a walk with a hat (D_2). The states of nature are: there will be rain during the walk (E_1) or there will be sun during the walk (E_2). The probabilities (which are actually the beliefs of the decision-maker) are $P(E_1) = P(E_2) = 50\%$. The values are: $V(D_1, E_1) = 100$ (pleasure of the walk in the rain with a raincoat); $V(D_1, E_2) = 10$ (pleasure of the walk in the rain with a hat); and conversely $V(D_2, E_1) = 10$ and $V(D_2, E_2) = 100$. The value of the decision D_i is: $V(D_i) = \sum_j P(E_j) \cdot V(D_i, E_j)$. Here we get: $V(D_1) = V(D_2) = 55$ (See Fig. 2.11).

Fig. 2.11 Simple example of a decision-hazard tree



Project Assessment Tools for Reducing Uncertainty (Market Research or Analysis)

The previous model may also be used to calculate the value of certain additional explorations prior to choosing whether or not to develop a product, if such explorations allow uncertainty to be reduced. This is so, for example, with research projects aiming to reduce commercial uncertainty.

It is assumed that the decider can proceed to a test, this being for him a new decision D_{n+1}. This test will enable him to learn, and this learning process will alter the subjective probabilities. Following the test, he will still be able to proceed to the prior decisions D_i, but evaluated this time using the new subjective probabilities, i.e. taking account of the reduction in uncertainty due to the learning process (and also taking account of the cost of the test, which will be deducted from the value V_{ij}). The learning process is modeled by assuming that the test gives us an "index" as to the state of the nature but does not completely reveal the "true" state. The experimenter knows that if the state is E_j then the test will give a result U_i with probability $P(U_i/E_i)$.

In the case of the weather seen above, it may rain with probability $P(E_1) = 50\%$ or be fine with probability $P(E_2) = 50\%$. The test involves consulting the weather forecast, which is known not to be completely reliable, and hence it is known that when it rains, the forecast predicted 80% i.e. $P(U_1/E_1) = 80\%$ and $P(U_2/E_1) = 20\%$; conversely, when it is fine the forecast predicted 4 times out of 5, i.e. $P(U_2/E_2) = 80\%$ and $P(U_1/E_2) = 20\%$.

Using Bayes' formula and the total probability formula it is then possible to calculate $P(U_1)$ and $P(U_2)$:

$$P(U_j) = \sum_i P\left(U_j/E_i\right) \cdot P(E_i)$$

Then we calculate $P\left(E_i/U_j\right)\left(P\left(E_i/U_j\right) = P\left(U_j/E_i\right) \cdot P(E_i)/P(U_j)\right)$ (see the practical calculation in the figure below) (see Fig. 2.12).

The products s of the initial Di are recalculated with the new probabilities for each result U_i of the test.

It is important to emphasize that the test does not alter the states of the nature: whether it rains or shines does not depend on the weather forecast. The test only changes the belief as to these states: the decider believed in 50% for state E_1 before the test; after the test, he believed 80% if it was U_1 and if U_2, he believed 20%.

This process enables the value of the test to be calculated, and is the difference in value between decision D_{n+1} and the best of the decisions without the test. In the example below, the value of D_3 is subtracted from the value of D_1 (or D_2, since the two decisions are equivalent in this example), i.e. 82–55 = 27 (Fig. 2.12).

The value obtained corresponds to the value of tests whose intention is to reduce uncertainty. This approach to uncertainty reduction is one of the first modes to which industrial research and marketing studies aim to add value; this was clarified, in particular, by Peirce in 1879 (Peirce 1879); complete models had to wait for

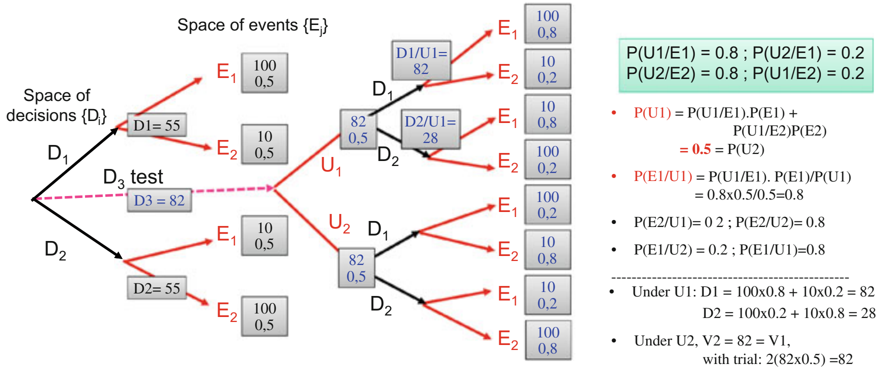


Fig. 2.12 Calculating the value of a test using the decision theory model with learning

developments within the theoretical framework of statistical decision theory (in the 1950s). Work on evaluating research projects via real options emerged directly from the above formal framework.

2.3 Organization of the Systematic Design Project

2.3.1 General Principles: Project and Project Leader

The model of reasoning in systematic design makes the latter compatible with a project management mode: there is a clear objective, resources are identified (internal or external), possible milestones, forms of division of work with respect to this objective, a partial delegation of responsibility and possible oversight by the corporate hierarchy or a project backer (CQT target).

We immediately note that in the canonical organizational model, the systematic design project is characterized by a form of cohesion with a clear "common purpose" (CQT objective endorsed by the company strategy); we shall see that systematic design encourages relatively simple forms of coordination based on prescribed and controlled tasks.

We emphasize the paradoxical side of this organization: as we have seen in the introductory chapter, design is quite generally distinct from traditional optimization and decision situations, and is liable to revise the associated knowledge and interests, rendering obsolete the skills of the company and calling its strategy into question—but systematic design can fit into a simplified, not to say bureaucratic, organizational form where the reasons to act are clearly established at the outset and stable over the course of the process, hence avoiding constant changes in company skills and strategy.

2.3.2 Division of Labor in Systematic Design: Stage-Gate Process and "V" Cycle

The linear structure of systematic design reasoning first of all allows a temporal sequencing with phases of exploration and decision milestones. According to the terminology introduced by Cooper (1990) we speak of an organization in "stage" and in "gate".

In a finer sense, the structure of reasoning in systematic design allows a complex and a priori exploratory task to be broken down into elementary tasks. This breakdown can be described by the famous "V" cycle (see Fig. 2.13): the overall task of the project is broken down in terms of ranked specifications; we begin by specifying the services offered, these services being themselves split into systems and sub-systems finally giving rise to the elements of machines. To these machine elements correspond the elementary tasks of detailed design. Once this has been done, we then move on to an integration process of validation and synthesis: whatever can be validated is validated at component level, then at sub-assembly level and then at the systems architecture level to finally validate the services provided. The interlocking validations correspond to an economic principle: don't include a defective component if the faults can be detected beforehand; simplify the quest for causes when a sub-assembly or system is faulty. The "V" cycle also aims to guarantee that the project converges, avoiding any late discoveries of defects in quality or the failure to meet technical objectives. The coherence between the breakdown of the specifications and the available validation protocols is a determining factor in the performance of a project under rule-based design (Fig. 2.13).

This task breakdown enables a division of design labor thus: prescribing some elementary tasks to competent experts; coordination between tasks (definition of interdependencies and precedence constraints); allocation of responsibilities and resources, etc.

Again we must make it clear that it is because systematic design involves reasoning, that stage-gate type processes are possible along with the division of work into prescribed elementary tasks.

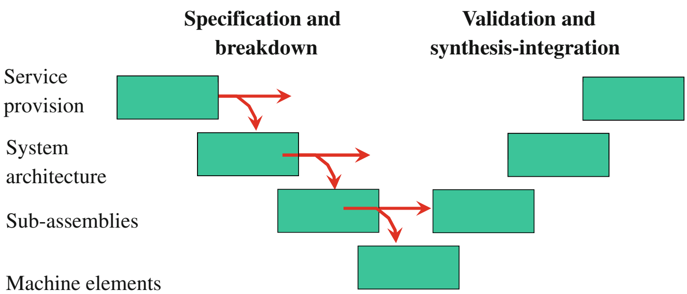


Fig. 2.13 General scheme of the "V" cycle

2.3.3 Project Leader's Management Tools: Planning, PERT Charts and Budget Reporting

2.3.3.1 Planning

An action can be planned provided it is divided into elementary tasks of known duration and dependency links. If the elementary tasks of the detailed design can be given a duration, we can construct a planning schedule for a systematic design project.

However, note that the elementary tasks are essentially limited to the detailed design phase and then validation. In practice, this means that the project generally includes a short, sparsely detailed "front-loaded" preliminary phase or pre-project with reasoning applied up to the detailed design. Strictly speaking, the planning, i.e. the part where tasks are organized such that they are "concurrent", relies solely on the validation and detailed design part.

2.3.3.2 PERT and Critical Path

PERT, which stands for "Program Evaluation and Review Technique", is a technique developed in the 1950s for overseeing large-scale American military projects (for an historical perspective on PERT and project management of these large military programs, see Lenfle and Loch 2010).

A PERT chart is constructed using a graph of tasks defined by their duration and inter-task succession constraints (see Fig. 2.14). The so-called "earliest dates" are then calculated, beginning from the project start date, propagating forwards and writing down for each task the "earliest date" (ED) and the "earliest end date" (see graph 2 on Fig. 2.14). The so-called "latest dates" (LD) are calculated starting from the project end date and propagating backwards through the preceding tasks. The LD is written down for the completion and launch of each task (see graph 3 on Fig. 2.14). The margin for each task is calculated, this being the difference between the "earliest" and the "latest" date. The path leading from the initial to the final task is critical if the margins for all the tasks on this path are zero (see graph 4 on Fig. 2.14).

Hence the PERT chart is able to organize the correspondence between tasks, handling a large number of tasks, but also continuously rescheduling and incorporating specific temporal constraints (mandatory start date, dates defined with respect to a benchmark, etc.). Note, however, that the PERT process takes no account of resources. This means managing production with no constraints on production resources (the capabilities of machines and personnel, etc.) (Fig. 2.14).

2.3.3.3 Management Tools: Budget Reporting

In particular, the PERT technique allows budget reporting tools to be developed. What is forecast is compared with what actually exists at some date t.

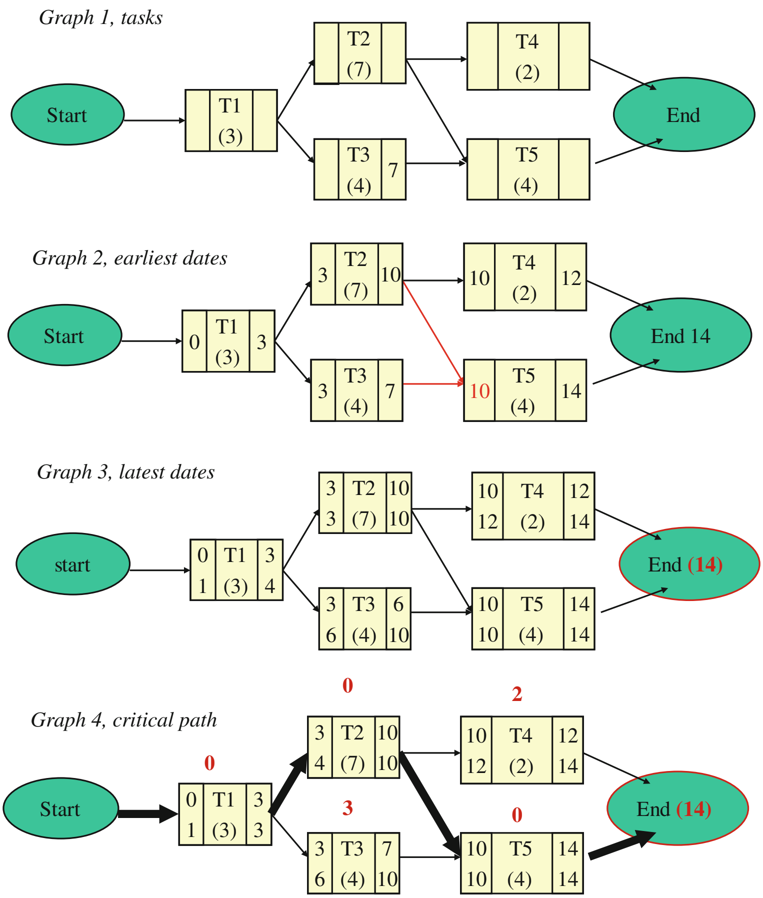


Fig. 2.14 Example of constructing a critical path on a PERT chart

Using the PERT chart we can construct a curve of forecast commitments including the forecast expenditure for each task (BCWS curve, Budgeted Cost of Work Scheduled). In addition, actual expenditure is monitored regularly (ACWP curve, Actual Cost of Work Performed). Finally the progress curve can be drawn, i.e. the BCWP curve, Budgeted Cost of Work Performed).

Timescales can be monitored using the cost difference between BCWP and BCWS (see graphs on Fig. 2.15)

Costs can be monitored by the difference between ACWP and BCWP (Fig. 2.15).

2.4 Conclusion

In systematic design, design follows a linear reasoning process as per the languages predetermined for the object. Design is project-based, the project having to hit a Quality-Cost-Time target with the resources already in place and maximizing the

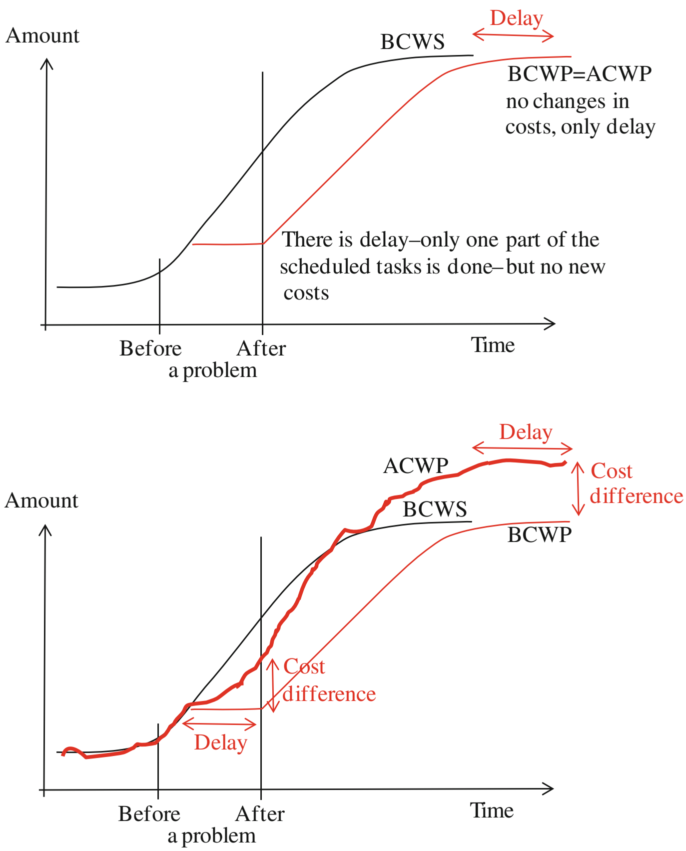


Fig. 2.15 Budgetary oversight tools

use of all available knowledge. We again emphasize that it is because the reasoning process is conducted in this way that the logic of performance and organization (especially organization in planned projects) can be deployed.

It is interesting to observe that, in the event of the failure (or success) of a project, there are always two possible causes: either the project team and project leader have been unable to make use of the systematic design tools (forgetting a function in the functional analysis, poor planning, forgetting a resource, etc.), or the conditions for applying systematic design failed to come together. In the rest of this book it is therefore necessary to set out these conditions. In particular, we contemplate how a knowledge base, i.e. expertise and skills, etc., can be built that is sufficiently well matched to the project that very little learning will be required.

With systematic design we have studied one of the most sophisticated and effective rule-based design regimes. However, what are the conditions laid on the rule base that allow this regime to function?

2.4.1 Main Ideas of the Chapter

- The stages and languages of systematic design
- The fundamental assumptions of systematic design
- The notion of function and functional analysis
- PERT charts and the critical path
- Project performance: CQT

2.4.2 Additional Reading

This chapter can be extended in several directions:

- on New Product Development Management, the reader can study the seminal reference works of (Clark and Fujimoto 1991; Wheelwright and Clark 1992), Front Loading (Fujimoto 1997; Thomke and Fujimoto 2000) and variants on Flexible Product Development (MacCormack et al. 2001) and Fuzzy Front End (Cooper 1997; Khurana and Rosenthal 1998; Reid and De Brentani 2004).
- On Integrated Product Development see (Olsson 1976; Andreasen 1987; Magrab 2010)
- On Project Management (Midler 1995; Lenfle and Midler 2009; Ben Mahmoud-Jouini et al. 2004)
- On the notion of function: the contradictions of functional analyses (Vermaas 2013); the house of quality (Hauser and Clausing 1988); see the notion of function in other disciplines—notably the famous "Form follows function" of the architect Louis Sullivan.
- On PERT and planning: (Moisdon and Nakhla 2010); for the logical processes of more advanced planning, see the work on interactive planning by (Hatchuel et al. 1997).
- On decision under uncertain conditions and project selection: see (Moisdon and Nakhla 2010) and classical courses on economic calculation. For more in-depth information, the reader can refer to (Hooge 2010) for the assessment of innovative projects.
- On systematic design and its variants: in engineering design (Pugh 1991; Cross 2000; Ulrich and Eppinger 2008); under more technical forms (Karniel and Reich 2011); in Stage Gate management (Cooper et al. 2001; Cooper and Kleinschmidt 1987, 1993) and its critique (Varnes 2005)
- In particular, see also the relationship between Systematic design and the Theory of Technical Systems (Hubka and Eder 1988; Eder and Hosnedl 2010)
- On recent development of evolutionary approaches on engineering design see (Vajna 2005; Vajna 2011)

2.5 Workshop 2.1: Functional Analysis

Exercise, first part: make a functional analysis of a bus station.

This exercise will highlight several critical elements in the practice of functional analysis. The main lessons are:

1. Functional statements should be neither too precise nor too general. If too general they may allow misguided interpretation; if too detailed they put the designers into a straightjacket of ready-made solutions or combining them leads to insurmountable contradictions. The functional statement is like a contractual clause binding the "requestor" to the "bidder" (the engineering department charged with carrying out the functions), and hence presupposes a validation procedure to check that the function has been properly fulfilled.

Example: "the bus station should allow users to wait in comfort" is too vague a statement to constitute a function; once the bus station has been designed, how would one check that it will be "sufficiently" comfortable?

2. A functional analysis might start by identifying the various constituent parts (clients at all levels—clients of clients of clients, etc.; users, the whole supply chain, maintenance, ecosystem, prescribers, institutions, etc.) and different environments (atmospheric conditions, day or night, type of country, place, situations encountered by the product within its life-cycle, etc.).

In the bus station example: don't forget the roadway, maintenance, residents, town services, etc.

3. Functional analysis depends on the business model associated with the object. On this point, note that business models do not correspond to a dimension "to be designed" in systematic design, and are in fact considered as data, especially in stakeholder models expressing what they expect from the object.

Example: in the case of Parisian bus stations, these are made available to the operator by the Decaux company which, in return, has the right to put up advertizing material in the station. This business model requires taking a new participant into account, namely the station's financing company (in this case Decaux): they will define the functions that are critical for them. Hence the station must possess suitable surfaces for posters which must be visible (also at night), clean, and easily accessible for changing the advertisements, etc.

4. Take care: functional analysis is *not* a user concept. On the one hand functional analysis incorporates dimensions other than those of usage (standards and norms including social norms not corresponding to a single particular user (see the functions associated with respect for the environment and sustainable development), the logic of risk demanding an awareness of very rare events for which there is no proven purpose). On the other hand, certain uses will not be included

in the functional analysis; for instance deviant uses that are not statistically significant will not be taken into account. In the general case, functional analysis does not have recourse to an analysis of usage, often relying as it does on too limited a number of uses and individuals to reach a statistically significant threshold. Rather, functional analysis depends on the modeling of standard users and stakeholders, characterized by a small number of attributes. There exists a conceptual model specific to functional analysis, a model which plays a critical role in formulating the functions (and associated tests).

Example: the observation that a writer has written his entire novel sitting under a bus shelter will be difficult to include within a functional analysis. On the other hand, the observation can be generalized and incorporated within the standard user model; for instance, a new function can be added such as "the user wishes to pursue some activities while waiting for the bus" (e.g. a bus station with internet access).

5. We can generally assume that there are three sets of specifications (i.e. three highly contrasting sources of functional specifications):
    a. The customer's specifications sheet, i.e. the list of specifications drawn up by the customer.
    b. The set of professional and industrial specifications, i.e. the list of specifications which are either not explicitly requested by the customer but essential nevertheless, or do not involve the customer directly but rather other stakeholders.
    c. The company's own requirements specification, i.e. the list of specifications associated with the company's strategy (their image of quality, robustness, high-tech, innovation, etc.).

*Exercise, second part: carry out a functional analysis of a **night** bus station.*

This question must be put back into context: when the Paris night bus service (Noctilien) was established, the transport authority, RATP, created new bus routes and new conditions for operating them. In particular, they had to design special night bus stations, requiring adaptation to the bus station's specifications.

This second part generally leads to an upgrade of certain parameters in the requirements specification ("better lit", "more comfortable", "better arrival announcements in real time", etc.).

One or two limits of the functional analysis tool can be highlighted:

1. Functional analysis ignores any exploratory efforts that might be required by new environments or stakeholders. Hence any analysis of the "night" bus station requires learning about what night is. We would discover: (a) that stations have already been operating "at night" (in winter night falls at 17.00 in Paris); (b) that there are several types of night in Paris: night with "day-like" activity (up to around

22.00 and then from 06.30 to 08.00), night with a drop in activity (from 22.00 to 01.00, the traditional closing time that bars and the transport system have in common; then from 05.00 to 06.30), and (c) the night when nothing happens, when the entire town is "closed" (from 01.00 to 05.00 in the morning). We can see that it is only this last version of night which poses problems, very new problems, in fact: for example, there is no simple emergency response in the event of illness or attack, such first response being provided typically by residents or passers-by in day time. New functions then appear: raising the alarm, giving first aid, having water available, etc.

2. Functional analysis also ignores the difficulties of these explorations: in certain situations it is impossible to know the stakeholders' expectations of the object, quite simply because the situation does not yet exist. Before the Noctilien service, it was difficult to anticipate the functional specifications related to the station's expectations. In cases of this type functional analysis might demand a far more complex prototyping and test protocol, assuming a design effort akin to innovative design (see Chaps. 4 and 5). With this kind of reasoning we can envisage, for example, "mobile stations" which can be imagined as fully equipped buses (heating, emergency response facilities, water, etc.) that might be deployed at a few critical points in the town to act as night bus stations in the depths of night.

2.6 Case Study 2.1: The Logic Underlying the Domestication of Design: The Origin and Success of Systematic Design

In this study of historical cases we shall present a few significant episodes in the history of the domestication of design and that of the invention of the "engineering department" by large companies. Within the scope of the canonical performance model (see the introductory chapter) we shall analyze the succession of rule-based design regimes and in each case set out the industrial context, the issues and underlying logic of performance, what had been designed and by which designers (for a more extended version see Le Masson and Weil 2008).

2.6.1 Wild Design: The Inventor-Entrepreneurs of the First Industrial Revolution in England

The first industrial revolution born in England took place in the absence of any engineering departments. However, it came about through the emergence of new industrial sectors (mechanical spinning machines, steam engines, machine tools, railways, steamships, etc.) and through the design and production of an extraordinary variety of new objects. These were made by highly inventive independent engineers with considerable business acumen making up a very active milieu. The exchange of information between them, including that with scientists and businessmen, were intense, particularly through the many learned societies such as the Lunar Society of Birmingham (Agogué 2012; Schofield 1957, 1963) or the Smeatonian Society of Civil Engineers. They were present at a burgeoning of ideas and experiments. The development of the railway was typical of the dynamic of the time. Essentially this was down to half a dozen or so "great" engineers such as Stephenson, Brunel, Locke, etc.

Take, for example, the case of locomotive design by the Stephenson father and son duo, often presented as the "fathers" of the English railway. This they illustrated with the opening of the first commercial line between Stockton and Darlington in 1825, going on to participate ceaselessly in the growth and rapid development of this new means of transport. However, they were not alone, and there was fierce competition to win bids for new lines. In this context they developed two companies: the first, dedicated to civil engineering, handled the design and construction of the lines, while the second was devoted to the design and manufacture of locomotives. Everything had to be designed: the characteristics of the line and civil engineering structures, as well as stations, the organizational principles of the various services, fee structures, etc. Locomotives were designed by quite a small number of engineers. The newly completed line served as a test-bed and prototype for refining the next generation. In this way the main difficulties they encountered were gradually resolved. Major enhancements were brought into improve the thermal or mechanical performance, without recourse to established scientific results or generating exhaustive scientific investigations. Drawings were extremely perfunctory and were little more than a diagram of some essential part or other and a list of components. Design relied on the manufacturing workshops where highly skilled workers, immensely capable of building the parts from the very basic sketches they were provided with, made the design workable by adjusting and modifying to obtain one of the most complex and sophisticated objects ever made.

We shall call this first design regime the “wild” design of the inventor-entrepreneur. How to characterize it? The resources were limited to a few engineers, their initial knowledge was poor, and the learning process, primarily through the trial and error of successive generations, served as a design space and hence learning for those that followed. In terms of expansion, there was still only a poor organisation for repeating or reproducing a particular design, and it was always just one product (and its associated process) that was designed: the designers attempted to discover the extent of its performance and gradually stabilize the object’s identity. The customer at that time was not always well-informed and did not always know how to get what he wanted. Performance consisted of constructing a potential for a specific value/skill which would be brought to bear in winning bids and maintain progress in an ever-changing field (see the table and summarizing graph at the end of the case study).

2.6.2 Parametric Rule-Based Design: “Recipe-Based” Design or Pathways for Industrial “Catch-Up”

At a time when industrial development in England was in full swing, France and Germany were wondering about how to catch up industrially. One thing was certain: the process of building up a population of technical specialists and inventor-entrepreneur engineers similar to that which existed in England would take too long and seemed difficult to push forward. In France, scientists concentrated on conceptual developments with the aim of establishing a science of machines (mechanics, kinematics, strength of materials, heat, hydraulics, etc.) and scientific teaching at an advanced level (The Ecole Polytechnique, etc.).

In Germany, an original approach distanced itself from the tradition of applying the results of scientific investigation. Ferdinand Redtenbacher became the moving force behind this approach. He was initially professor of mathematics and geometry at the Ecole Polytechnique in Zurich, and then taught mechanics and mechanical engineering at Karlsruhe. He was also closely in touch with industrial machine manufacturers. In the preface to his 1852 book he stated his critique thus: “We don’t invent machines using the principles of mechanics, for that would also require, besides an inventive talent, an exact knowledge of the mechanical process the machine was intended to fulfill. Using the principles of mechanics we cannot provide a sketch of the machine for that would also require a sense of composition, layout and shape. No machine can be built using the principles of mechanics for that would require practical knowledge of the materials with which we work and familiarity with tools and handling machines. No industrial project can be led using the principles of mechanics for that would require a particular personality and a knowledge of business affairs." (Redtenbacher 1852). His ambition was not to train designers capable of making use of all these sorts of knowledge and designing machines in their entirety. Rather, he imagined a two-stage design process. In his book he sets out a set of "recipes for design" which allowed the specialists under his tutelage to design all sorts of machines adapted to the varied situations they might encounter. It was sufficient for them to follow the stages and calculations defined by the "recipe" to be sure of obtaining a satisfactory result.

This method was much better than a mere catalog since each time it enabled a design suited to the situation to be obtained without having to design all possible machines beforehand. The procedure proposed by Redtenbacher displaced the effort of design: this was no longer a unique product to be designed but a recipe capable of generating an entire family of products. Moreover, the value of the recipe lay in its ability also to guarantee the performance of the products it generated. In conceiving his recipes for design, Redtenbacher came up against a dual problem, namely the development of a conceptual model linking performance with the design parameters of the device (K(X)), and that of a generator model (a previously defined series $d_i \in D$, where the d_i are parametric) ordering the design stages in a linear sequence (the idea of the generator model will be introduced and discussed in Chap. 3). The recipes given in his books covered a vast range of machines from water wheels (very widespread in Germany but often with mediocre performance) to the most modern machines such as locomotives. It was by following these famous recipes that the nascent Alstom company started to manufacture locomotives. Thus were forged the skills that would become essential for keeping up with the accelerated pace of change in the world of railway innovation.

We give an example of how the method works in a simple case, namely the design of water wheels.[1] In the first part of his book (Chaps. 1–3) Redtenbacher surveys the state of the art for water wheels and existing theories to gradually formulate a set of "equations of effects" covering the performance and dimensions of a water wheel.

Redtenbacher draws on the work of Poncelet (op. cit.), Navier, Morin and Smeaton, whose tests were already ancient (1759), and also provides results from his own tests. As Redtenbacher wrote: "one might think that water wheels were already widely understood… and that any practical or scientific treatment would be of no value today". Most of the work took account only

[1]Redtenbacher, 1858, op. cit.

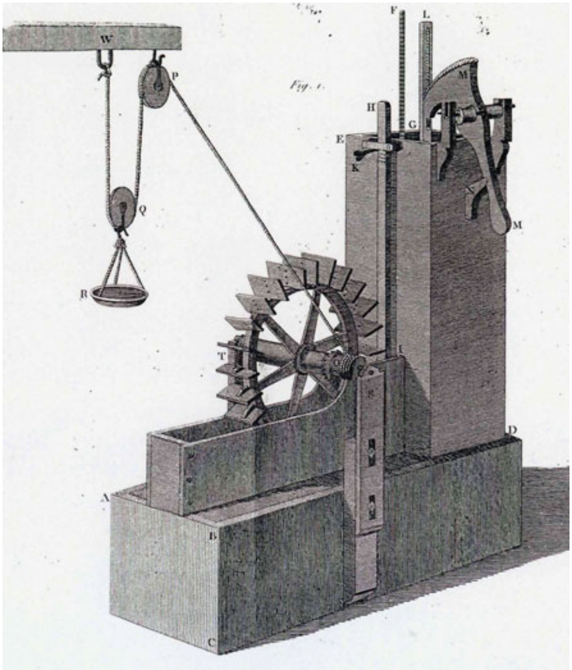


Fig. 2.16 Smeaton's experimental method (1759)

of the head, the volume of water, the speed of the water course, and the inlet speed. For example, using an experimental method, Smeaton's investigation sought the height of the water on entry to the wheel for optimizing the transmission of motion (see Fig. 2.16).

However, these studies failed to deal with the particular arrangements of the wheel or with the environment in which it was located. Also lacking were the equations relating to the size of the wheel, its diameter and width, choice of vanes or buckets, number of buckets, their shape, the depth to which the wheel had to be immersed in the water, the constructional quality of the mounting and control of leaks, etc. All these limits meant that the designers were unable to use the scientific results hitherto obtained. Hence (and still in the first part) Redtenbacher concluded his state of the art using complete models of existing machines grouped together under major types.

Once these major descriptive models had been drawn up, Redtenbacher moved on to the second, and most original, part of his book: the method of ratios. Chap. 5 sets out the rules to be followed to assess "the specific forms and dimensions on which the wheel preferentially depends under the conditions for a perfect realization of the structure". The method starts off by following the major steps of a fictitious dialog between the designer-entrepreneur and his client. According to Redtenbacher, the first question concerns the budget that the client is prepared to spend on his machine since, depending on the response, the designer will tend towards either a metal or wooden wheel, wheels whose efficiencies and sizing equations are very different. Once the material has been chosen, two questions have to be asked: the head of the water course and the usable flowrate (or, which amounts to the same thing, the power expected on the shaft). The designer then has to use a chart (see diagram below) which, depending on the head and flowrate, enables him to choose the best type of wheel (e.g. a mountain stream of large head and low flowrate would use an overshot wheel, while a watercourse in the plains, of low head and high flowrate, would tend to favor a Poncelet type wheel). He then goes on to define the main dimensions (radius, fill rate, circumferential speed, bucket volume, depth of the wheel, number of buckets, number of arms, the clearance of the wheel in the race). At this stage the method allows the designer to choose a class of wheel, assessing the expected performance without yet stating all the dimensions (Fig. 2.17).

At that time this was for Redtenbacher the most critical part of the reasoning process, since (he observed) most wheels were ill suited to their context.

The second part of the design process consists of specifying, step by step, all the parts of the machine by following the methods of calculation or even the drawings (proposed in the engineering design) which correspond with the patterns (as seen in sewing patterns): the drawing is non-dimensional and also

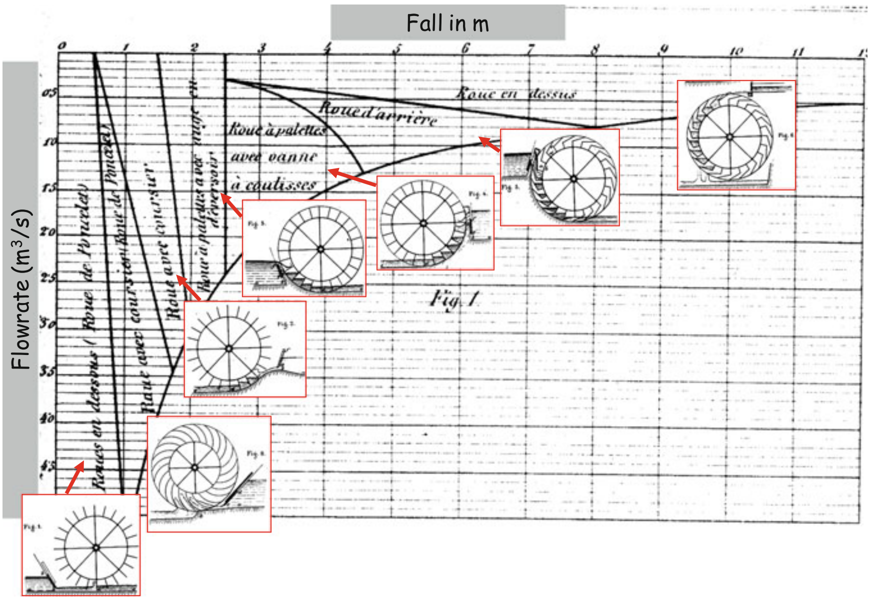


Fig. 2.17 Chart for choosing the type of water wheel depending on the conditions of use

provides the ratios between the parts as a function of some known fixed unit. It then sets out the modes of linkage and the level of precision with which the assembly must be put together. Finally, the last part deals with what we can call "tuning": Redtenbacher restates the theoretical efficiency formulae and the technique for measuring the actual efficiency. He invites the designer to compare the efficiency measured on the installation and indicates the means for improving the actual efficiency on an almost completed wheel.

In this second part of the calculations, Redtenbacher notes that industrial wheels are rather well designed, emphasizing the fact that his method allows performance to be checked, to "get rid of imperfections" and to "relate all uncertainties to solid rules".

We have gone from "wild" design to "rule-based" design, where the recipe allows parameterization. We now examine the various dimensions of this new regime (see Fig. 2.18 and Table 2.1):

Design rules figure at the very top of the resources, i.e. a generative model based on several conceptual models. Introduction of the recipe also leads to the need to distinguish between two types of designer: one makes the recipe and one uses the recipe; and there are two associated types of reasoning, different for each designer. Creating the rules demands a major exploratory effort, production of knowledge (experimental methods, tests, etc.), modeling and rare skills. The use of rules is compatible with limited and far more widespread skills.

The expansion made possible by these rules is no longer limited to a specific product, and leads to a diversified family of products. However, such variety is predetermined by the generative model contained within the recipe.

Finally, the logic underlying performance is that of industrial catch-up where the number of completed designs (conjunctions) has to be maximized while limiting, as

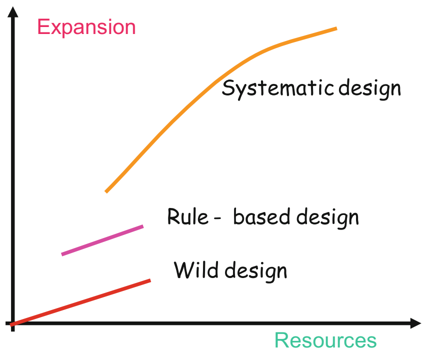


Fig. 2.18 Performance of the different recipe-based design regimes

Table 2.1 comparison of rule-based design regimes

	Resources	Expansion	Performance
Wild design	A few engineers Initial knowledge poor Learning by trial and error P_i = learning space for P_{i+1}	Gradually work out the dimensions and stabilize the identity of the objects	Construct a potential skill/singular value
Rule-based design	Recipe (Generator model based on a conceptual model) Distinction between designing the recipe and designing the product	Product family but product determined by the generator model	Catch-up Maximize connectivity without producing additional knowledge
Systematic design	Design department 4 languages Division of labor and specialized skills	Product family (dominant design) = Variety + cone of innovation on known performance Set out in ranges and families	Expansion extended by controlling learning processes (δK) Still connective (robustness: minimize risk) Industrial system

far as possible, the additional effort in the production of knowledge. The recipe offers the ability to effectively exploit the product line, guaranteeing the variety and economies of knowledge. On the other hand, this regime is highly sensitive to any technical evolution that may require the recipe to be redesigned.

2.6.3 Systematic Rule-Based Design: The Invention of the Engineering Department

Under the joint thrust of some changes characteristic of the second industrial revolution, research and experimentation in other forms of rule-based design were not going to be held back. With the increase in production volumes, preoccupation with industrial efficiency became a priority. Customers (often in a B2B situation) became more competent and more demanding. Finally, the product dynamic made it essential to reconcile the new knowledge spaces: heat or electricity might be added to mechanics, for example.

2.6.3.1 The Baldwin Locomotive Works, or the Power of Expansion and Organization in Generator Models

One of the first and best models of this evolution was provided by the Baldwin Locomotive Works (BLW) of Philadelphia which, due to the methodology of its design organization, was to become the undisputed leader in this sector during the second half of the 19th century (for information on this company see Brown 1995). At its creation en 1831, the Baldwin company was similar to that of Stephenson. Very quickly, however, it found itself face to face with unprecedented problems: the vertiginous growth of the America railway market was punctuated by abrupt halts corresponding to the recurrent financial crises while the railway companies were engaged in a race for performance. Furthermore, these railway companies operated in varied contexts which led their "engineer" to make their orders very specific. How could this demand for variety, potential for evolution and the constraints of an industrial complex of then unknown size be reconciled (the factory employed about 10,000 staff in 1900)? Around 1900, BLW produced over 1200 locomotives per year, including nearly 120 different models, delivering their locomotives two months after being ordered (design included). How was such a feat possible?

Three elements played a significant part. First was the structuring into product families based on studiously analyzed reference architectures, covering all the requirements and supporting the constant improvement in performance. The directors of the company regularly took part themselves in this redesign effort, incorporating recent technical advances, including if possible any differentiating innovations but organizing variety as well (this meant having certain degrees of freedom) and authorizing enhancements to the primary dimensions of performance so that the locomotives designed on this basis would remain competitive. These families embodied the design strategy of the firm. Secondly, the commercial relationship with their customers was also handled directly by the directors. This relationship relied on a scalable description of the main elements of the locomotive. Hence the customer had complete freedom in defining the characteristics of his locomotive but in a language consistent with the product families mentioned above. Thirdly (and finally), on the basis of this requirements specification the designer had instructions to employ previously used standard parts for which pre-existing drawings would make the best use of the capabilities of the machine tools. Where the designer could not meet the requirements specifications with existing components, he was not permitted to design a special part, but had to design a new standard component which could be used in future projects and approved by the manufacturing department.

Resources: as in the case of the recipe, there were two types of designer: those who designed the generative model (how it would be possible to design a locomotive with the most standard components) and those who defined the bases on which the major conceptual models were used. In particular their effort was focused on the definition of several mutually articulated languages. These second designers formed increasingly numerous and specialized collectives, with the division of labor made possible by the effort in defining a dominant design. Rather, they designed the parts under a restrictive, but evolving, system of rules (dictated in particular by manufacturing and industrial capabilities).

Expansion: associated with the variety guaranteed by the product families were "cones of innovation" which enabled the primary dimensions of product performance to be improved from design to design.

A high level of design performance resulted from this strong ability to expand, obtained by limiting and controlling the effort in producing new knowledge. Risks were managed using an important property of the generator model, namely its connective power, by means of which the designer could predict whether or not he would succeed in designing a product meeting the initial specifications. Finally, the attention given to the industrial system drew out the best in it.

2.6.3.2 Germany and Systematic Design

Similar changes were occurring in Germany, where they were accompanied by important theoretical debate on the formalisation and development of a doctrine, namely systematic design. New industrial companies appeared such as AEG which, thanks to the organisation of their design department, were more successful than their older rivals (Siemens, for example) in designing a great variety of electrical machines for the mass market; these combined the use of standard components with steady progress in improving the performance of these machines.

Above all, however, there was a renewal in the debate around the teaching of design. Such debate emphasized the limitations of recipes and questioned how the production of knowledge could be integrated within the design process (König 1999).

The major advance was in the gradual and difficult distinction of four main languages used to describe the objects to be designed: functional language (expressing the needs of the customer in a language the designers could use), conceptual language (where the primary languages of the engineer are to be found: mechanics, strength of materials, kinematics, thermodynamics, hydraulics, electricity, etc.), morphological language (the assembly of machines) and the language of detailed design (in which the constraints of the manufacturing process might intervene in defining the smallest detail in the shapes of elementary parts).

Authors, teachers and consultants in regular contact with manufacturers suggested organizing design as a staged process articulating these different languages in sequence. Powerful engineering departments were not slow to organize themselves on this basis. Such was their performance that the two previous forms of design organization gradually disappeared or merged into this new model.

There thus appeared a new model of the industrial firm based on systematic design (see Fig. 2.18 and Table 2.1, Last line), and this was clearly the point at which the modern large enterprise was born (Segrestin and Hatchuel 2012). Drawing on the design office model, Taylor created the process and planning department for organizing the production system. R&D laboratories sprang up around the design offices (see also the case study on the history of the industrial research laboratory in Chap. 3). The rationalization of product development was accompanied by a rationalization of communication, commercialization, distribution and the emergence of powerful marketing departments (the start of the 20th century), and a rationalization of purchasing systems. The first design studios also appeared, sometimes as part of the company. These various entities were of greater or lesser importance in the big companies. However, behind the diversity of the organizations we should note the predominance of a systematic design model based on a stable dominant design, i.e. a design model in which products shared the same reference points in terms of performance, function, architecture, technology and skills. This is what we shall study in Chap. 4.

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