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## Effectiveness of the systematic engineering design methodology

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## **EFFECTIVENESS OF THE SYSTEMATIC ENGINEERING DESIGN METHODOLOGY**

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### **Abstract**

This paper reviews a set of published industrial applications and research studies in order to assess the effectiveness of the systematic engineering design methodology. Effectiveness, which can be considered as the degree to which the final design solution fulfils the design requirements, is one of the critical features of a design methodology.

It cannot be concluded upon the reviewed publications that the methodology is not effective but it cannot be concluded either that the methodology is superior to an intuitive approach. The published industrial applications that have been identified have served mainly to confirm that the systematic engineering design methodology can lead to successful results. The identified research studies present more mixed results and show that several factors such as the engineering designer's experience and motivation dramatically influence the outcome, at least as much as methodology. Both proponents and opponents of the systematic engineering design methodology seem to agree that the systematic methodology used flexibly is more effective, but guidance on how to use the methodology in this way is required.

**Keywords:** Design methodology, Design practice, Effectiveness

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# 1 INTRODUCTION

For the last decades, systematic engineering design methodologies, whose archetype is represented by the book *Engineering Design* from Pahl and Beitz (2007), have been prominent in engineering design education and research. The characteristics shared by these methodologies are summarized hereafter. They have a generic or idealised process model, with associated methods. They intend to be branch-independent; the engineering designer is recommended to start at an abstract (functional) level and to get more concrete as the technical system (TS) is developed. They are strongly oriented towards the search for an optimal design, obtained through decomposition and combination of the problems and solutions, and through systematic variations. These methodologies present of course some disparities among each others but they do not differ significantly, therefore the term systematic (engineering design) methodology will be used in singular henceforward.

A recurring question in research has been: is this the ‘right’ or ‘best’ way to do design? Quite early, systematic engineering design methodologies have been criticised (e.g. Jung, 1973; Jorden, 1983), and alternative views on engineering design, that contradict parts of the systematic approach, exist, such as the claim for a more opportunistic approach (see Bender, 2004).

It can be stated right away that it will never be possible to firmly validate or invalidate any systematic methodology. There are too many parameters to control: Pahl and Beitz (1996, pp. 2-6) classify engineering design tasks with no less than 28 characteristics regrouped in 7 types (origin of the task, organization, novelty, batch size, branch, complexity, goals). The engineering designer as a person, alone or in team, also induces many variations (technical knowledge, competencies, motivation, group dynamics...). Moreover, proponents of the systematic methodology can rightfully add that the systematic methodology is to be used as a support, not as an algorithm or a recipe.

On the other hand, it is possible to study a limited number of critical elements that form the core of the systematic methodology. If under the scrutiny of those elements important problems appear, the systematic methodology should be questioned. This approach is a feature of qualitative research, e.g. (Lincoln and Guba, 1985), but is also a trait of scientific inquiry in general: if several of the core properties of a theory or model are questioned, the theory might be abandoned all together, even if not formally disproved (Lakatos et al., 1978).

Some of these core elements have been investigated in the literature: the systematic methodology, despite its rigorous arrangement, presents serious *inconsistencies* (Franke, 1985; Motte, 2008)—the claim that a functional diagram is solution-independent, the separation between working principles and embodiment, etc. The systematic methodology has also some severe shortcoming dealing with *compatibility* with its context, mainly product development (Motte et al., 2011)—most product development process models position conceptual design in product planning, emphasize re-use of existing technologies even for novel products, focus much on risk management, etc. On the other hand, regarding *learnability*, the systematic methodology is sometimes recognised as being easy to teach (due among others to the logic behind the process and its clarity), an important aspect if one wants the systematic methodology to be taken up and used by students.

In this work, the investigated element is the systematic methodology’s *effectiveness*, defined as: the degree to which the systematic methodology allows the design goals to be achieved (in most cases: how well the final design fulfils the requirements). It has been determined to be such a core element of the systematic methodology. Indeed, regardless of flaws or negative aspects, a systematic methodology can lead to good results. It can for example give good direction and support so that the engineering designer ends up with the right design.

The investigation of the effectiveness of the systematic approach has been mainly made through a review of empirical studies. The review has been done by screening mainly the *International Conferences on Engineering Design (ICED) proceedings* (starting 1981) and *Design conferences proceedings* (starting 2002), as well as the *Konstruktion* journal (starting 1981) as many studies have been made in Germany. Only studies concerning the use of the whole systematic methodology or at least of a complete design phase of the systematic methodology, such conceptual design or embodiment design, are reported. Studies on other or smaller parts of the process—for example, clarification of the task— or methods have been discarded, even if these were linked to effectiveness. For those more specific aspects, see e.g. (Pahl and Beelich, 1981; Pahl et al., 1999; Dinar et al., 2015). Two main ways of determining the effectiveness of the systematic methodology have been found in the literature. The first one has been to show the effectiveness of the systematic engineering design

methodology by means of case studies. These case studies can be illustrative examples, or industrial applications. In this review, only documented industrial cases have been reviewed. This way, the review is more stringent. The second approach has been to empirically or theoretically compare the design quality (how well the design fulfils the requirement) of engineering designers following the systematic approach vs. following it flexibly or not at all.

## 2 INDUSTRIAL APPLICATIONS

More than thirty documented industrial applications using the systematic approach have been identified in the literature. These are presented Table 1.

Table 1. Published industrial applications using systematic engineering design methodology

Reference	Application	Specific used methodology (if known)
(Collin, 1971)	Single-roller calendar	(Rodenacker, 1966)
(Schmidt, 1973; Hähn, 1973) in (Pahl et al., 2007)	Impulse-loading test rig for shaft-hub connections (one-off device)	Working material to (Pahl and Beitz, 1977)
(Roth et al., 1975)	Seat belt mechanism	Design catalogues, working material to (Roth, 1982)
(Mauderer, 1976) in (Pahl and Beelich, 1981)	High-voltage circuit breaker-drive system	
(Weber, 1978)	Extruder with a slurry pump	
(Birkhofer, 1979)	Snap fastener attaching machines	Mainly design catalogues (Roth et al., 1975)
(Franke, 1979)	Large centrifugal pumps	Pragmatic use of all methodologies
(Gerber, 1979)	Electrical attenuator and electrical connectors	VDI 2222 (1977), design catalogues
(Jarchow and Haensel, 1979)	Production machine for glued multi-layered insulated glass	VDI 2222 (VDI, 1973/1977)
(Krumhauer, 1979)	Triggering device for pipe rupture protection	VDI 2222 (VDI, 1973)
(Simonek, 1979)	Recirculating document handler for a copying machine	VDI 2222 (VDI, 1973)
(Valdés-Neri et al., 1983)	Glass burn-off machine	(Tjalve, 1978; Koller, 1976; Hubka, 1973)
(Ehrlenspiel and Balken, 1984)	New TSs within the constant-velocity joints domain	Mainly own working material
(Birkhofer et al., 1985)*	1. Novel medical treatment chair 2. Folding mechanism of a textile treatment machine 3. New locking and blocking system for drawers cabinets 4a. Pocket triangle made of sheet metal to reinforce pockets in garment (working clothes) 4b. Specific transfer fixture 5. Co-rotating forced-flow mixer	Own methodology: summaries of diverse systematic engineering design methodologies, mainly (Pahl and Beitz, 1977; Roth, 1982) and value analysis
(Derhake, 1985)	Loose material sluice	(Roth, 1982; Pahl and Beitz, 1977; Koller, 1976; draft to VDI 2221, 1986)
(Hales, 1987/1991)	Participation to, and report of, the development of a coal gasifier test rig for British Gas, a large-scale three-year project	(Pahl and Beitz, 1984)
(Feldle, 1990)	Pump series	Own methodology
(Welp, 1990)	Paper processing machine	
(Beitz et al., 1992)	Discuss several design project examples. Report design quality for the design of a production facility for plastic bags.	(Pahl and Beitz, 1986; VDI, 1986)
(Feldhusen, 1992)	Power converter for railway vehicles	(Pahl & Beitz, 1986), design catalogues (Roth, 1982), Value Analysis
(Tonn, 1992)	Submersible centrifugal pump	(VDI 2222, 1977; Pahl and Beitz, 1986; Roth, 1982)
(Tooten, 1995)	Wrap spring type reverse-locking clutch	(Pahl and Beitz, 1993; Roth, 1982)
(Eder and Hosnedl, 2010; Eder, 2014)†	Wind tunnel balance model support (one-off device, 70s), several subsystems for a sailing barge (mid-90s), portable trapeze frame (one-off device, 1996/1997)	Based on Hubka's procedural model, see e.g. (Hubka and Eder, 1996)

\* These industrial applications in medium-sized enterprises have been preceded by training in systematic methodology. Three of those cases are reproduced in *Konstruktion*.

† The full list of the applications is to be found in the last publication. The industrial applications have been performed by Eder and others.

Beside the development of single TSs, some publications report results from companies using the systematic methodology. Wiendahl (1981) reports the successful results of five years of use of the systematic approach in a company that had implemented VDI guideline 2222 (1973/1977) at the level of the whole research and development function. So does Diederich (1992) for a medium-sized company developing mainly capital equipment. Moreover, Pahl and Beelich (1981) present a survey of fourteen companies dealing with the introduction and acceptance of the systematic approach in industry), although it is not always possible to differentiate cases where the systematic methodology was completely or only partially used (p. 781).

These examples are illustrations that the systematic approach can yield good results. Collin (1971, p. 98), and Ehrlenspiel and Balken (1984, p. 419), emphasize that a non-systematic approach would not

have given such good results. Pahl et al. (2007, p. 436) report that the final impulse loading test rig “fulfilled the main expectations and confirmed the effectiveness of a systematic approach”. Hales also reported positive outcomes from using the systematic approach (Hales, 1987/1991).

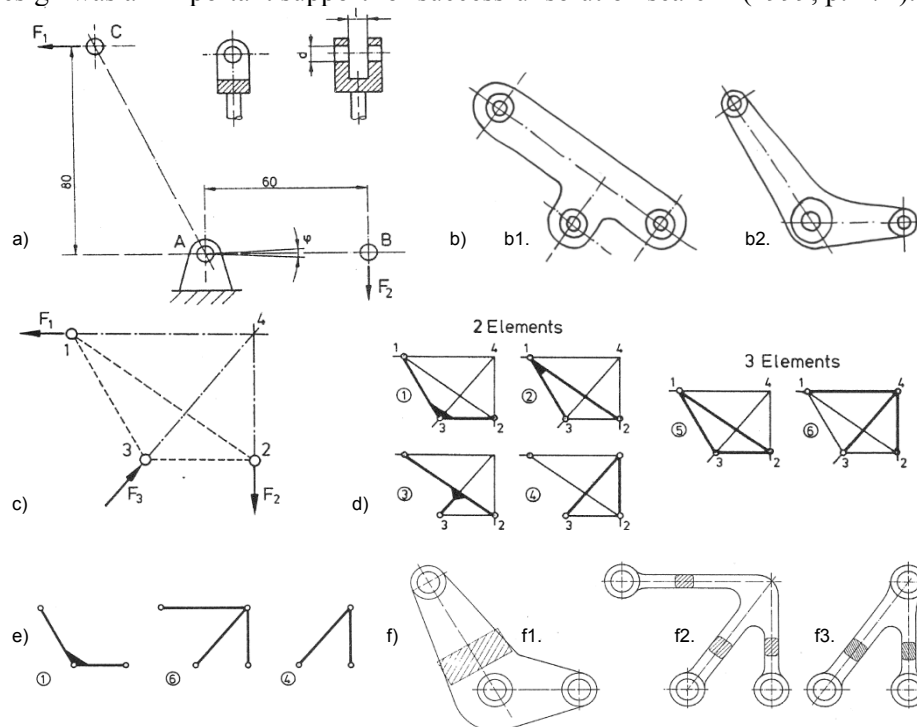
A few of these publications reported some experienced limitations of the systematic methodology or at least some hands-on recommendations on how to use the methodology. In the later publications from Eder (publications reported in Eder, 2014), the flexible use of Hubka’s procedural model (see e.g. Hubka and Eder, 1996) is emphasized. In their 1981 survey, Pahl and Beelich report that a formal process model was generally not followed, but an opportunistic one (p. 780), but “the firms that had introduced consistently the systematic engineering design approach or its fundamental elements, that used it in practice, and that could gather experiences about it, made unanimously the following statements: the number of protective patent applications has increased - the total development time is shorter, despite a very extensive conceptual phase - the adequacy of good solutions has been improved - the increasing complexity of tasks is easier to control – it creates an incitement in other domains to also proceed in a systematic way” (p. 780, own translation). At the same time, the companies warn about a too strong focus on methodology and its consequences: “examples were provided of academically trained graduates with or without a PhD degree who lacked sufficient effectiveness in their work for reaching usable results” (p. 780, own translation). Krumhauer (1979) mentions that the best solution was found intuitively and not with the used methodology. Finally Franke (1979) in his introduction warns that some parts of the methodology have been developed with some specific products in mind (for example functional structure for fine mechanics) and fits less other TSs (e.g. industrial pumps whose physical principles are well-known and where focus is on reliability).

### **3 EMPIRICAL AND THEORETICAL COMPARISONS OF DIFFERENT APPROACHES**

However, these studies do not account for the effectiveness of non-systematic approaches. Schregenberger (1985) emphasizes that a methodology is really useful when it gives *better* outcomes than a ‘normally’ successful engineering designer: “A methodology is a weak heuristic (as a ‘solution finding method’), if its applications do not result, on average, in better and more efficient solutions to design problems than purely intuitive or arbitrary approaches” (pp. 894-895, own translation). Several studies based on the observations of designers were subsequently performed. In those studies, the results were more mixed. In this section, results in favour of the systematic methodology are presented first, followed by inconclusive results, and ending with negative results.

Pahl (1990) reports the results of an exercise that was submitted to the participants of 21 seminars on embodiment design, representing around 540 designers. The exercise was to design a simple lever in a cast metal, represented in Figure 1(a). 90% of the participants spontaneously draw the solution (b1) and 10% the solution (b2). After explaining the bases of the systematic approach, the following results were observed: the abstraction and clarification of the problem solution (c), the generation and selection of solution principles solution (d and e) led to solutions that represented 43% (f2) resp. 31% (f3) of the material cost of the original solution (f1). Birkhofer (1991, pp. 225-226) presents an example of the development of a TS (a 3D-coordinate table) both with and without using the systematic approach. The design quality when the systematic approach was applied was better, among other things, because of the reduction of the number of elements, which reduced the production and assembly. However, the study is keen to show that success could not be assigned only to the methodical approach but also that other factors needed to be taken into account. In two examples of variant design, the contribution of the systematic approach to success was much less significant than for new design projects (p. 231). In (Fricke and Pahl, 1991) the study of fifteen engineering designers is reported. The design style characteristics that led to good design quality included adequate problem decomposition, the search for several variants and their appropriate assessment (p. 337). The successful designers also clarified the task and presented the requirements in a solution-neutral manner (Fricke, 1999, p. 428). All those elements are already present in the systematic engineering design methodology. However, in (Fricke, 1993), it is also mentioned that those who strictly followed the VDI 2221 (1987) were less successful than those who were more flexible (retrieved from Bender, 2004, pp. 94-95). In a study of teamwork in engineering design, Badke-Schaub and Frankenberger assert that “a systematic search with the use of design methods such as morphological matrix or

classification schemes occurred very seldom, but in the observed cases this theoretical education on systematic design was an important support for successful solution search” (1999, p. 474).



*Figure 1. a) embodiment design problem; b) solutions proposed by the participants; c) representation abstraction of the problem; d) extract of possible solution principles; e) chosen solution principles; f) original solution (f1, compare b2) vs. final solutions (f2, f3) (Pahl, 1990, Figures 2-6, pp. 20, 22)*

Ehrlenspiel and Dylla (1991) also reported the result of the observation of six engineering designers using different strategies to tackle an engineering design problem. But they could not see a distinction in terms of effectiveness between the participants who more or less followed the systematic approach and those who did not. Pahl (1992) reports the observation of four engineering designers. This is a part of a larger study where 21 engineering designers were observed. Three designers were educated in systematic methodology, one had also practical experience; the fourth designer was experienced and used conventional, intuitive design. The two experienced designers got one of the best design results, the two others got among the worst results. The experienced and educated designer got the best results but the other experienced designer solved the problem in half the time. It was concluded that use of systematic methodology was all in all positive but that it cannot be dissociated from good technical knowledge and practical experience. Motte and colleagues (2005) tried to establish a correlation between the quality of the process (how well the process was followed) and the quality of the results for the embodiment design phase by reviewing the report of projects assignments performed by 30 master students. The result was inconclusive. A parallel verbal protocol analysis study with a similar assignment was performed with some of the participating students. It showed that some students barely used any systematic approach, while other where on the contrary very systematic, and that both approaches did not impact of the quality of the results.

Eisentraut (1999) reports an empirical study with fifteen engineering design students. She thoroughly discusses two cases: Student A, result-oriented, started with a very short phase of task clarification, then sketched a complete, but abstract, representation of the product, and analyzed parts of the problem only if necessary but not the problem in its entirety. He finished with a good product quality (p. 435). Student C spent a lot of time on clarifying the task, made a lot of quantitative analyses, documented the whole process “intensively”, and used the solution-combination heuristic, that is, student C followed a more systematic approach. Nevertheless, he ended up with a solution judged average, “because it did not fulfill some central requirements” (p. 436). Moreover, student A took half the time of student C.

Rückert et al. (1997) reports a study where sixteen groups with seventy-nine students (up to six per group) had to solve an industrial design project during a semester, after having been taught the

systematic methodology from Pahl and Beitz (1993). Some groups did follow the methodology stringently, while others used a more flexible approach and some did not follow any methodology at all. No correlation between the approaches and the resulting design quality could be found (Rückert et al., 1997, p. 30), but when two groups had the same project to solve, the flexible group did get a better design quality. An exception was that one group, who had decided to follow the more flexible approach, could not cope with the engineering design task. They had very little field experience with engineering design. They had to follow the systematic methodology before they could solve the problem (p. 30). By the time this first study was published, not all results had been analyzed (p. 30). In a subsequent publication (Rückert et al., 1998), it was established that the groups following a flexible methodological approach had the best results, followed by those who did not have any methodology at all. One reason proposed to explain why the groups who followed the methodology stringently ended up last was that the students needed to concentrate both on the methods and the results, and had less time for the latter.

Bender (2004) compared the design quality of students with and without methodological education. There were five groups of students: the students without any prior education in systematic engineering design (A1<sup>1</sup>,  $n = 47$ ), students who just attended the course (VG A2,  $n = 9$ ) and students who had had experience in design after the course (VG A3,  $n = 5$ ); for the last two groups there were control groups: students who had the same level of experience but did not have an education in systematic engineering design methodology (KG A2,  $n = 13$  and KG A3,  $n = 9$ ). There was no difference in design quality between the control groups and methodological groups in the conceptual design phase; only VG A3 performed slightly better than KG A3 in the embodiment design phase, with  $p = .04$  in a median test (Bender, 2004, p. 173). When the design quality of the same students was analyzed in light of their *actual* engineering design process, the results were different. Four design styles were determined (Bender and Blessing, 2004, pp. 119-120):

- hierarchically phase-oriented style: breadth-first, top-down style following VDI guideline 2221 (1993),
- hierarchically object-oriented style: the TS-to-be is decomposed into subsystems and each system is designed following the systematic approach,
- opportunistic and associative style: the process is guided by the evolution of the design problem,
- trial and error style.

Very few students actually followed the VDI 2221 ( $n = 8$ ) and those who did had the poorest design quality.

*Theoretical comparisons.* The studies presented by Pahl (1990) and Birkhofer (1991) at the beginning of this section can also be considered theoretical comparisons of systematic approach vs. the conventional approach. Another study is that of Roth (1995). Roth compared the stringent systematic engineering design methodology to more flexible approaches, where the function synthesis and/or the search for physical effects were neglected or not systematically investigated. With the example of the corkscrew, he showed that only the systematic approach could lead to the finding of all solution principles presented at the bottom of Figure 2 (numbered 3.2.1.1 to 3.2.2.2). When the function synthesis is present but the physical effects are considered together with embodiment, only solution principles 3.2.1.1 to 3.2.1.5 could be found. “The others would have been the result of an accidental discovery” (Roth, 1995, p. 14, own translation). Roth means by this example that the systematic engineering design methodology is very effective when new products have to be found in a domain where many solutions already exist.

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<sup>1</sup> Abbreviations of the student groups:  $A_i$  – student of educational level  $i$  (Ausbildungsniveau, see Bender, 2004, pp. 124, 126), VG – experimental group (Versuchsgruppe), KG – control group (Kontrollgruppe).

Teil-aufgabe	1	Die Handkraft zur Entkorkung von Flaschen vergrößern								
Teil-funktion	2	$F_1 \rightarrow \boxed{\phantom{000}} \rightarrow F_2$			$F_2 > F_1$					
Effekte	3.1.1	Kraftzerlegung		3.1.3 Kraftsummierung		3.1.5	3.1.6	3.1.7	3.1.8	3.1.9
		Schneidend	Parallel	Schneidend	Parallel	Druckausbreitung	Reibung	Querkontraktion	Impulsübertragung	Rückstoß
Effekt-träger	3.1	1	2	3	4	5	6	7	8	9
Gestalt-ansatz	3.2	3.2.1	3.2.2	3.2.3	3.2.4	3.2.5	3.2.6	3.2.7	3.2.8	3.2.9
				—				—		—
(Prinzip-lösung)	3.2	Hebel			Hebel und Keil (Schraube)					
		3.2.2.1	3.2.2.2	3.2.1.1	3.2.1.2	3.2.1.3	3.2.1.4	3.2.1.5	3.2.1.6	

Figure 2. Solutions of the design task “increase the manual force for the removal of a cork” (Roth, 1995, p. 13)

## 4 DISCUSSION

This review presents many contradictory results, at least apparently, ranging from the methodology being effective and meeting targets, to inconclusive and to damaging for the design activity. This section elaborates on these results.

### 4.1 On the scientific signification of the industrial applications

The industrial applications of the systematic approach were all successful. But one can notice that almost all those works have been done by, or under the supervision of, the proponents of the systematic approach.

Collin was a research assistant and a PhD student under Rodenacker (Collin, 1969). Weber and Balken were also PhD students at Munich (Weber, 1978; Balken, 1981). The works of Schmidt and Hähn were done under the supervision of Beitz (Schmidt, 1973; Hähn, 1973). Hähn was research assistant under Beitz (Beitz, 1985, p. A8). Diekhöner and many of his colleagues were former students of Roth (Heymann, 2005, p. 420): they were advisers in the industrial projects reported in (Birkhofer et al., 1985, see Table 1 above), which were partially supported by the Federal Ministry of Research and Technology (Heymann, 2005, p. 420). Derhake received a PhD from Braunschweig University of Applied Sciences where Roth officiated (Derhake, 1990). Tonn was Professor at the Berlin University of Applied Sciences (Beitz and Fazar, 1992, p. A10). Tooten is Professor of machine elements and material sciences at Bochum University of Applied Sciences (Tooten, 1995, p. 217). Hales was a PhD student under the supervision of Wallace, who himself had participated in the translation and edition of Pahl and Beitz’ work (Wallace and Blessing, 2000, p. 3). Wiendahl worked at the Escher Wyss company where the VDI 2222 (1973/1977) was implemented, but had been previously chief assistant to Opitz, Professor at RWTH Aachen University and was well acquainted with the systematic approach (Heymann, 2005, p. 418).

The close relationship between the authors of the applications and the proponents of the systematic methodology seems to imply that most of these studies had the implicit goal to confirm the relevance of the systematic methodology, or at least to give recommendations on how to use it, rather than to try to ‘falsify’ it (Popper, 1980). This is corroborated by the fact that most publications are from the 70s to the 90s (references from Eder and colleagues, see Table 1, are mainly re-published applications).



Moreover, many publications do not mention possible methodological improvements or drawbacks; except from comments made by Eder and colleagues upon the re-published applications, and Franke (1979). This is current practice in science and especially relevant when the theory or methodology is at its infancy, not completely developed, and thus much more easy to reject because it does not have the same strength as the current way of designing. However this implies also that potential shortcomings might have been overlooked while trying to confirm that the systematic methodology indeed works. It can also reasonably be asserted that many cases have been edited so that they could be presented in a form that fits the systematic methodology process models, as the cases were also documented with an educational purpose. Many cases not reported are in effect only illustrative applications (e.g. Hubka et al., 1988), and doubtful cases have been excluded from the review.

But as for the scientific signification of the industrial applications, whatever the way the systematic methodology has been used, one cannot infer that the systematic methodology is not effective. One can even infer that for professional designers, at least designers that are very familiar with the systematic methodology such as the authors mentioned above, the systematic methodology leads to expected design results.

#### **4.2 On the effectiveness on the systematic methodology**

There are no clean-cut conclusions regarding the effectiveness on the systematic methodology. Nevertheless, the following points can be made.

The first and foremost goal of this paper was to assess whether the systematic methodology had critical shortcomings in regards with effectiveness, effectiveness being one of the critical elements that a methodology should possess as mentioned in the introduction. The systematic methodology may be problematic in terms of consistency and compatibility with the product development process, but it is not in term of effectiveness, in the sense that there is no overwhelming evidence that the methodology is not effective. *There is therefore no ground to dismiss it on that account.*

However, there is neither much evidence that the systematic methodology is significantly more effective than a designer not using it. *There is also not much ground for recommending the adoption of the systematic methodology regarding effectiveness.*

An exception might be for the improvement of already existing TSs, as the lever (Pahl, 1990) and cork (Roth, 1995) studies (see Figures 1 and 2 above) seem to imply. The reasons might be that the design problem is well defined, allowing for effective decomposition of the problem and variations in the solutions. The evaluation of alternatives can also be eased as many elements of information can be used to that end (assumptions from existing solutions, known bench tests, etc.).

There is an agreement among proponents and many opponents of the systematic methodology that it should not be followed rigorously but in a flexible manner. In its current form, the systematic methodology is however not suited to a flexible use: presented as a set of steps following a quite logical order, it is difficult, especially for the student, to devise one's own process. A recommendation would be to emphasize less on the process and more on pragmatic ways to use the different methods.

What the studies certainly show is that many other factors responsible for the final design quality (cf. Birkhofer, 1991, pp. 226ff), like the engineering designer's experience and motivation, dramatically influence the outcome. Methodology (systematic or not) is almost always presented as a cornerstone or as a pre-requisite for performing design of good quality. There is no doubt that an engineering designer need to possess knowledge about methods and tools in order to work effectively in an industrial setup. But maybe the importance of methodology and its associated process model need to be relativized in comparison to the other factors affecting effectiveness.

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