Design Flaws and Quality-Related Feedback in Product Development

vorgelegt von
Diplom-Ingenieur
Bruno Gries
aus Berlin

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Promotionsausschuss:

Vorsitzender: Prof. Dr.-Ing. Günther Seliger
Berichterin: Prof. Dr.-Ing. Luciënne Blessing, Technische Universität Berlin
Berichter: Prof. Dr.-Ing. Mogens Myrup Andreasen, Danmarks Tekniske Universitet

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Abstract

The subject of this thesis are design flaws, how different stakeholders in the affected products react to them and how design flaws may be corrected. It deals with the question of how to improve the quality of products by taking into account the expressed or implied need for a change in their design.

As a number of product examples show, this need is not always considered or understood by companies. These examples also illustrate that design flaws not only have a technological, but also a legal and an economic dimension.

Based on the perception that design flaws are a specific form of quality defect, existing concepts of quality and its management are reviewed. Yet, current research in this field proves to be an insufficient theoretical basis for interpreting, correcting and ultimately learning from design flaws.

Therefore, a generic model of design-related product quality is proposed which describes the interaction between designers, product attributes and the various stakeholders in a product. Based on this model, product quality is defined as the degree to which perceived product attributes match with expected attributes. Accordingly, a design flaw is defined as a design-related product attribute that impairs product quality.

An important aspect of the abovementioned model is feedback. It is shown that feedback is an important element of design and product development processes and that there are various potential sources from which companies might obtain quality-related feedback about their products after they have entered the market. However, existing studies give little detail on key questions related to design flaws.

A fundamental notion of this thesis is that a design flaw is the result of a design failure, i.e. the failure to achieve a sufficient level of product quality. Therefore, the conditions under which this kind of failure can occur are investigated, identifying four major failure modes: 1) misinterpreting the expectations of stakeholders, 2) poorly communicating product-related information to stakeholders, 3) not understanding the product as the stakeholders would and 4) failing to implement the product attributes as intended.

To complement the theoretical findings of this thesis, an exploratory study of 171 German companies was undertaken. It reveals deficiencies in post-project communication between manufacturing and design departments and identifies cases in which products were brought on the market despite the fact that their design flaws were known. It also shows that innovating implies successfully correcting design flaws, the latter being a challenge that companies need to face as a whole.

Zusammenfassung

Die vorliegende Arbeit befasst sich mit Konstruktionsfehlern, den Reaktionen derjenigen, die ein berechtigtes Interesse an den betroffenen Produkten haben (im Folgenden: Stakeholder) und damit, wie Konstruktionsfehler behoben werden können. Hierbei wird der Frage nachgegangen, wie die Qualität von Produkten gesteigert werden kann, indem die Notwendigkeit konstruktiver Änderungen berücksichtigt wird.

Wie eine Reihe von Beispielen zeigt, wird diese Notwendigkeit von Unternehmen häufig nicht erkannt. Diese Beispiele zeigen auch, dass Konstruktionsfehler nicht allein eine technologische, sondern auch eine rechtliche und wirtschaftliche Dimension aufweisen.

Davon ausgehend dass ein Konstruktionsfehler einen Qualitätsmangel darstellt, werden bestehende Qualitätsphilosophien sowie verbreitete Methoden des Qualitätsmanagements untersucht. Es zeigt sich jedoch, dass die Qualitätswissenschaft als theoretische Grundlage für die Beschreibung von (und letztlich den erfolgreichen Umgang mit) Konstruktionsfehlern allein nicht ausreichend ist.

Das in dieser Arbeit vorgestellte allgemeine Modell konstruktionsbezogener Produktqualität beschreibt die Wechselwirkung zwischen Konstrukteuren, Produktattributen und unterschiedlichen Stakeholdern. Basierend auf diesem Modell wird Produktqualität als Grad der Übereinstimmung zwischen erwarteten und wahrgenommenen Produktattributen definiert. Aus dieser Qualitätsdefinition leitet sich die Definition eines Konstruktionsfehlers ab: ein konstruktionsbezogenes Produktattribut, das die Qualität mindert.

Ein wesentlicher Aspekt des erwähnten Modells ist Feedback. Es wird gezeigt, dass Feedback in Konstruktions- und Produktentwicklungsprozessen eine bedeutende Rolle spielt und dass darüber hinaus zahlreiche Möglichkeiten existieren, wie Unternehmen qualitätsbezogenes Feedback über ihre Produkte erhalten können, nachdem diese auf den Markt gelangt sind. Es stellt sich jedoch heraus, dass im Hinblick auf die in dieser Arbeit untersuchte Fragestellung frühere Studien zu angrenzenden Themengebieten wenig aufschlussreich sind.

Dieser Arbeit liegt die Auffassung zu Grunde, dass Konstruktionsfehler das Ergebnis von Entwicklungsfehlern sind, und zwar solchen, die dazu führen, dass kein ausreichendes Maß an Produktqualität erreicht wird. Eine Untersuchung der Bedingungen unter denen diese Entwicklungsfehler auftreten können ergibt vier wesentliche Versagensmuster: 1) Fehlinterpretation der Erwartungen der Stakeholder, 2) Fehlkommunikation produktbezogener Information an die Stakeholder, 3) Fehlverständnis des Produkts und 4) Fehlimplementierung beabsichtigter Produktattribute.

Im Sinne der Vervollständigung der in dieser Arbeit theoretisch gewonnenen Erkenntnisse erfolgte eine explorative Studie 171 deutscher Unternehmen. Das Ergebnis zeigt Kommunikationsdefizite zwischen Fertigung und Konstruktion im Nachgang von Entwicklungsprojekten. Ferner lassen sich Fälle aufdecken, in denen Produkte auf den Markt gelangt sind, obwohl ihre Konstruktionsfehler bekannt gewesen sein müssten. Darüber hinaus deutet vieles darauf hin, dass Innovationsprozesse die erfolgreiche Behebung von Konstruktionsfehlern als Begleiterscheinung mit sich bringen und dass fernerhin der erfolgreiche Umgang mit Konstruktionsfehlern eine Herausforderung für das Gesamtunternehmen darstellt.

Contents

1 INTRODUCTION 1

1.1 General 1

1.2 Aims and Scope of this Work 2

1.3 Approach 3

1.4 Chapter Overview 4

2 EXAMPLES OF DESIGN FLAWS 7

2.1 General 7

2.2 The First Johnson & Johnson Cardiac Stents 7

2.3 The iPod nano 8

2.4 The Ford Pinto 9

2.5 The Audi 5000 10

2.6 Siemens 65-Series Mobile Phones 11

2.7 The NSU Ro 80 12

2.8 Discussion 13

3 PRODUCT QUALITY 17

3.1 General 17

3.2 Definitions and Concepts 18

3.3 Total Quality Management and Quality Methods 21

3.3.1 The Quality Movement 21

3.3.2 Total Quality Management 21

3.3.3 Quality Methods 23

3.3.4 Criticism 25

3.4 Quality Methods in Design 26

3.4.1 Quality Function Deployment 27

3.4.2 Failure Mode and Effect Analysis 29

3.4.3 Fault Tree Analysis 31

3.5 Q- and q-Quality 32

3.6 Discussion 34

4 DEFINING DESIGN FLAWS 37

4.1 A Generic Model of Design-Related Product Quality 37

4.1.1 Product Attributes 37
4.1.2 Stakeholders 39
4.1.3 Designers 40
4.1.4 Summary of Interactions 42

4.2 Definition of a Design Flaw 42

4.3 Discussion 43

5 DESIGN FLAWS AS A TRIGGER OF DESIGN FEEDBACK 45

5.1 General 45

5.2 Feedback as a Part of Design and Product Development 46

5.2.1 Feedback as a Part of the Design Process 46
5.2.2 Feedback as a Part of the Product Development Process 49
5.2.3 Studies of Feedback in Designing Organisations 52

5.3 Design Feedback After Product Development 53

5.3.1 Watchdog Organisations 54
5.3.2 Market Research and Customer Complaints 54
5.3.3 Internet Communities 56
5.3.4 Product Diagnostics 56

5.4 Discussion 57

6 DESIGN FLAWS AS A RESULT OF DESIGN FAILURE 59

6.1 General 59

6.2 Characteristics of the Design Context 60

6.2.1 Complexity 61
6.2.2 Dynamics 65
6.2.3 Intransparence 65

6.3 Human Factors in Designing 66

6.4 Design Failure 68

6.4.1 Design Error and Risk 68
6.4.2 Design Failure in the Generic Model of Design-Related Product Quality 72

6.5 Discussion 73

7 DESIGN FLAWS AS SEEN BY DESIGNERS: AN EXPLORATORY STUDY .. 75

7.1 General 75

7.2 Study Design 76

7.2.1 Considerations 76
7.2.2 Questionnaire Construction 78

7.2.3 Survey Implementation ... 79
7.2.4 Data Analysis ... 80

7.3 Product Characteristics ... 81

7.4 Characteristics of Design Flaws ... 83
7.4.1 Manifestations ... 83
7.4.2 Technological Domains ... 87
7.4.3 Magnitude ... 93

7.5 Characteristics of Design Feedback ... 96
7.5.1 Modes of Feedback ... 96
7.5.2 Customer/User Feedback ... 99
7.5.3 Feedback from Warranty Claims ... 100
7.5.4 Feedback from Manufacturing ... 102
7.5.5 Feedback from Product Tests During Development ... 106

7.6 Determinants of Successfully Correcting Design Flaws ... 111
7.6.1 Company-related determinants ... 112
7.6.2 Product-related determinants ... 113
7.6.3 Feedback-related determinants ... 117
7.6.4 Activity-related determinants ... 120

7.7 Discussion ... 126
7.7.1 Summary of the Findings ... 126
7.7.2 Alternative Explanations ... 128
7.7.3 Limitations of the Study ... 128
7.7.4 Conclusions ... 130

8 CONCLUSIONS ... 135

8.1 General ... 135
8.1.1 Summary ... 135
8.1.2 Contribution ... 136
8.1.3 Reflection on the Research Methods ... 137

8.2 Recommendations for Product Development ... 137

8.3 Suggestions for Future Research ... 140

APPENDIX A: TERMINOLOGY ... 143

APPENDIX B: QUESTIONNAIRE ... 145

REFERENCES ... 157

1 Introduction

1.1 General

Achieving given cost, time and quality targets is, from a company's perspective, the most important task of design. If the quality of a product is regarded as the degree to which required and actual product attributes match, it could be argued that the majority of all design and development activities ultimately serve the aim of ensuring product quality [cf. Pahl & Beitz 1996].

All too often, companies fail this aim. Whether small design flaw or catastrophic engineering disaster: in any case, the quality of the product (and inevitably its design) is questioned by those who are affected. Yet, products improve over time – not only in terms of performance and functionality, but also by not featuring the same design flaws as their predecessors. Petroski [1992] goes as far as claiming that many (if not most) products that we know today have a more or less long history of flawed designs. Considering the magnitude of this notion, surprisingly little is known about how designers learn from design flaws in both senses of the word "learn": getting to know that their products are flawed and utilizing this knowledge to develop a solution.

For understandable reasons, the philosophy of "doing it right for the first time" is prevalent in design [Wheelwright & Clark 1992, p. 226]. Error making is expensive. Poor design can cause delayed market entry, uncompetitive products and increased warranty costs. Product recalls cost companies millions. In 2000, Ford Motor Company announced a product recall of all Ford Explorer SUVs fitted with Firestone tyres after a large number of incidents involving tread separation repeatedly followed by tyre disintegration. More than 13 million tyres had to be replaced [Haig 2003]. According to conservative estimates, the costs of this action amounted to over 650 million US Dollars [Geiger 2001]. While Ford and Firestone blamed each other for design flaws in their respective products, the common view by outside observers is that the loss of over 250 lives and more than 3,000 serious injuries is the result of a combination of design flaws: the tyres being prone to tread separation and the Ford Explorer's handling being extremely difficult with a blown out tyre [Turner 2001].

Apart from these spectacular cases, there is reason to assume that many design flaws are noticed by e.g. users or customers but are never reported to those who are responsible for them: the designers. When detected during production or installation, design flaws are often "hot-fixed" without the designers ever knowing [Busby 1998].

By any means, poor design can put peoples' lives at risk [Hales 2003; 2005]. Therefore, "design responsibility" is all but a flowery phrase. Designers need to work to their best knowledge and in all conscience. Anything else would be highly uneconomical and unethical. While – unfortunately – avoiding design flaws altogether is impossible, missing the opportunity to learn from them would be highly uneconomical and unethical as well.

1.2 Aims and Scope of this Work

The overall aim of this research is to improve product development such that designers learn from their design flaws so that the quality of their products will improve. This work shall provide a better understanding of design flaws, their feedback and the factors that influence the ability of designers to correct them. Thus, design flaws may not be prevented, but prevented from being repeated. In particular, this contribution seeks to

- offer researchers a theoretical framework that relates the above phenomena and to
- provide practitioners with an insight into the actual factors that determine a designing organisation's capability of correcting design flaws, possibly learning from them.

In order to achieve the above aims, this study seeks answers to the following three research questions:

1. What is the nature of design flaws?
2. What is the nature of feedback about design flaws?
3. What influences the ability of designers to correct design flaws?

The scope of this contribution is on material products that are the outcome of a mechanical engineering design process in the widest sense. A *product* is defined as an item that satisfies a market's want or need [Gabler 1992, p. 2652]. According to the economic definition, however, a product is not necessarily material (e.g. a life insurance) which distinguishes it from a *good* [ibid, p.1483]. By fulfilling a purpose (satisfying someone's want or need), a product is similar to an *artefact* – yet, the latter is not necessarily the outcome of an engineering design process.

Design flaws can have various manifestations, reaching from catastrophic engineering disasters at the cost of thousands of lives to cases in which some product properties occasionally pose a minor annoyance to a small group of users. However, the scope of this work is not limited to safety-relevant design flaws. It rather focuses on how to improve the quality of current and future products by taking into account the expressed or implied need for a change in their design.

In the case of an engineering disaster, any need will soon be clear as great effort is usually taken to find the root cause. In the case of poor product quality, however, the picture is different: the need for a change in the design of a product is not always expressed (or: fed back) and if so, not always considered or understood by designing organisations.

This work does not claim to deliver a complete explanation for each and every aspect of design flaws and how they can influence design but to assist in a way of thinking that is more suitable to deal with this issue than existing approaches.

1.3 Approach

The approach taken in this thesis to achieve its aims and to answer the formulated research questions is generally based on the Design Research Methodology (DRM) proposed by Blessing et al. [1994; 1995; 2002; 2002]. DRM is a framework for the development of design support, i.e. methods, (computer) tools, guidelines, etc. By aiming to improve design in practice, DRM is rigorously goal-oriented. Figure 1-1 illustrates its individual stages.

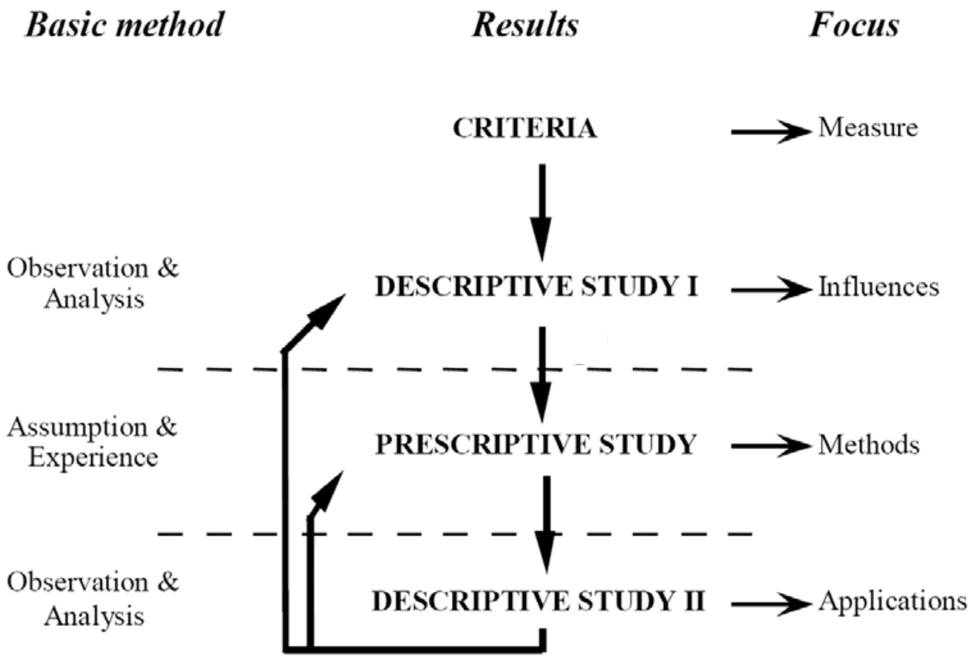

Figure 1-1 The DRM framework [Blessing 2002]

Each stage is inspired by the following fundamental questions [Blessing & Chakrabarti 2002]:

- **Criteria Definition Stage:** what do we mean by a successful product?
- **Descriptive Study I:** how is a successful product created?
- **Prescriptive Study & Descriptive Study II:** how do we improve the chances of being successful?

DRM puts a strong emphasis on determining criteria. It acknowledges, however, that the *overall success criteria* might be too difficult to assess. Therefore, *measurable criteria* must be formulated for which a (preferably close) link to the success criteria cannot only be assumed but needs to be made explicit.

As stated in 1.2, the overall aim of this thesis is to let designers learn from design flaws in order to improve the quality of their products. As this overall success criterion is indeed difficult to assess within the scope of this thesis, the measurable criterion shall be the success designers have in correcting design flaws. Thus, a successful product is a product that does not feature the same design flaw as its predecessor(s).

The primary aim of the Descriptive Study I is to identify which factors influence the formulated measurable criteria in what way. A common starting point is a literature review; when it does not provide enough detail, other means (e.g. observations, experiments, etc.) need to be considered.

In this thesis, an extensive literature study has revealed that current research provides too little detail on the influencing factors so that an empirical study, i.e. a mail survey of designers, was conducted.

As the paradigm of DRM is to change existing design practice for the better, no research can be complete without at least envisaging a new, improved situation. Therefore, even without conducting the Descriptive Study II (which is aimed at validating the developed support), there has to be at least “a description of the implications of the findings on the aim to improve design” [Blessing & Chakrabarti 2002].

The research presented in this thesis is more descriptive than prescriptive. No methods or tools are developed. However, as its descriptive results are close to what is necessary to develop design support, the areas of product development which need to be improved to leverage the overall success criterion are highlighted.

1.4 Chapter Overview

In accordance with the above approach, chapters 2 through 4 establish the measurable criterion “success in correcting design flaws”. Chapters 5 and 6 represent the literature study of the Descriptive Study I, which is complemented by the empirical study described in chapter 7. In chapter 8, implications for the improvement of product development are discussed. In summary, this thesis is structured as follows:

- **Chapter 2 “Examples of Design Flaws”** features six case studies of design flaws being revealed, fed back and eventually corrected – not only discussing their design-related implications but also their economic and legal magnitude. These examples also serve as an occasional reference in the subsequent chapters.
- **Chapter 3 “Product Quality”** investigates the relationship between design flaws and product quality. It contains an overview of current concepts of quality and describes existing managerial and design-oriented efforts to achieve quality.
- **Chapter 4 “Defining Design Flaws”** presents a generic model of design-related product quality which refines the findings of the previous chapter as to provide the necessary framework to define and interpret design flaws. The proposed model describes design-related product quality as an interaction between designers, product attributes and stakeholders, and design flaws as the result of a disturbance of this interaction.
- **Chapter 5 “Design Flaws as a Trigger of Design Feedback”** discusses the importance of feedback for design in general and for correcting design flaws in particular, focusing on the aspects of communication and learning. Various potential sources from which designers might obtain feedback about design flaws are identified in- and outside their companies as well as during and after product development.

- **Chapter 6 “Design Flaws as a Result of Design Failure”** investigates the conditions under which design processes can fail such that the resulting products are flawed. It focuses on the individual and process-related issues contributing to design failure, i.e. designers failing to define specific product attributes in a way that a sufficient level of quality is achieved
- **Chapter 7 “Design Flaws as Seen By Designers: An Exploratory Study”** describes the design and the results of an empirical study of designers in the German manufacturing industry. While the complete (i.e. descriptive) results of the survey are described in [Gries & Gericke 2005] and some of its results are discussed in [Gries et al. 2005], chapter 7 specifically aims at answering the questions left open by the theoretical findings so far.
- **Chapter 8 “Conclusions”** summarises the theoretical and empirical results of this thesis and discusses their relevance in the context of product quality, design feedback and design failure as treated in the previous chapters. Based on these conclusions, recommendations for product development are given.

2 Examples of Design Flaws

2.1 General

Many design flaws of everyday products are probably never reported to their designers. This might have various reasons. It could be that these flaws, while annoying, are too minor for those who are affected by them to care about finding someone to complain to. It could also be that some users find a work-around solution themselves.

Undoubtedly, there are many cases in which companies have reacted to customer feedback and had their designers develop a solution. When this happens smoothly, usually little of it becomes public as probably no company likes to admit that there was a design flaw in the first place.

Therefore, the following examples are not representative of design flaws, their feedback and the success companies have in correcting them. However, the examples are instructive inasmuch as illustrating some key issues related to design flaws which will be discussed at the end of this chapter.

2.2 The First Johnson & Johnson Cardiac Stents

In the mid 1990s, Johnson & Johnson (J&J) was the first company to introduce cardiac stents on the market [Finkelstein 2003]. These one-piece, expandable, cylindrical sleeves are primarily used with balloon angioplasty to open blocked coronary arteries (Figure 2-1). Stenting is a standard treatment nowadays, being a low cost and less invasive alternative to bypass surgery.

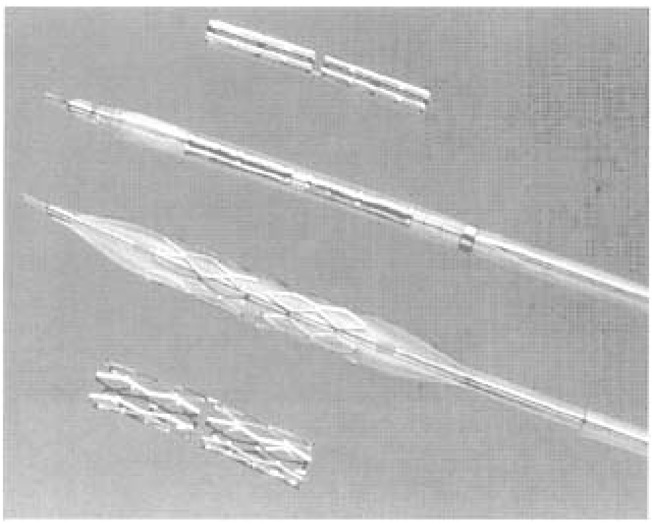

Figure 2-1 Palmaz-Schatz stent (source: Johnson & Johnson)

At its peak in 1997, J&J, through a clever patent and acquisition strategy, managed to achieve a market share of almost 95% which made the company the de-facto monopolist in angioplasty surgery supplies. By the end of 1998, J&J's market share reached 8%.

While business analysts argue that mistakes were made during the acquisition of Cordis, the company that actually developed the technology, and in marketing the product, Finkelstein [2003] concludes that the core problem was the design of the product:

- The width and rigidity of the stent made it difficult to insert it into the heart's fine and curved arteries.
- X-ray visibility was poor.
- The stent was only available in one length which forced cardiologists to insert two or more stents in certain situations.

The obvious reason why sales of J&J stents went into free fall was that Guidant Corp., a competitor in the field of coronary stents, had developed a product that overcame the shortcomings of the Palmaz-Schatz stent. Leading cardiologists, desperately waiting for such an improved product, used all of their influence on the US Food and Drugs Administration (FDA) to step up the approval process which eventually took only twelve days after Guidant filed the application. The poorly designed J&J product could only survive on the market because it was (for a limited time) the only one.

2.3 The iPod nano

Figure 2-2 shows the picture of an early "iPod nano" an ultra-small, pencil-thin MP3-player. Only four weeks after its launch in mid 2005, the first of eventually several class-action lawsuits was launched against the manufacturer, Apple Inc., following a rash of users complaining about scratched and/or broken screens. Concerning the scratches, the lawsuits alleged that the product was "too delicate for normal use". The lawyers claimed that Apple had launched the player regardless of knowing that a design flaw would limit its life: to reduce the thickness of the product, the polycarbonate layer which covers the screen and the controls, was made thinner than in previous models (that supposedly did not scratch that easily).

Figure 2-2 The scratched screen of an "iPod nano" (source: ipastudio.com)

Nevertheless, it is obvious that the scratching does not occur out of nothing, but is the result of some external impact – e.g. carrying the player in a jeans pocket as the picture in Figure 2-2 also shows. Given the small size of the product, it is understandable that people were tempted to do so. Apple therefore denied that there was a design flaw in the “nano” but, interestingly, started to “quietly” [Smith 2005] ship the product with a simple protective sleeve. The second generation of iPod nanos, introduced in late 2006, featured a scratch-resistant, brushed aluminium casing.

2.4 The Ford Pinto

In 1971, as a response to competition, especially from Volkswagen and Toyota, Ford Motor Company developed the Ford Pinto, the first American subcompact car. While the Pinto sold quite well in the early years, it caused major scandal when it was alleged that the car’s design made its petrol tank prone to leaking in the event of a rear-end collision. Accident reports revealed that even at relatively low speeds, the tank, when thrusted forward by the impact, would be punctured by bolts extruding from the differential housing and that the filler tube would easily rip off.

The actual scandal gained momentum when it was disclosed that Ford was well aware of this problem since the development phase of the Pinto and that the company allegedly decided against any design changes based on the reasoning that it would be cheaper to settle possible lawsuits for resulting damages, injuries and even deaths [Dowie 1977; Lee 1998].

During development, each crash test conducted at speeds over 40 km/h resulted in substantial damages to the car’s fuel system. Eventually, designers developed a whole array of solutions, ranging from mounting a plastic baffle in front of the differential housing in order to prevent the bolts from puncturing the tank to lining the tank with an internal rubber bladder. A complete redesign of the tank was also considered. However, a “saddle-type” tank (for which Ford even owned the patents), riding over the rear axle, was dismissed because such a design would have compromised trunk space, a vital competition factor in the market segment that the Pinto aimed at.

It is argued that none of these design measures were taken because they would have violated the two most important requirements for the new car, known as the “limits of 2,000” set by Lee Iacocca himself, then head of development of the Pinto. Even a small piece of plastic would have made the production of the product more expensive than $2,000 and probably heavier than 2,000 lbs. In fact, the comprehensive requirements list for the Ford Pinto did not contain a single safety-related requirement.

A leaked internal memo by Ford, containing the infamous cost-benefit analysis in Table 2-1, fuelled a media coverage that characterised Ford’s design decision as a cynical disregard for human lives in favour of profits. Major lawsuits, inconclusive criminal charges, and a costly recall of all 1.4 million affected Pintos followed.

Table 2-1 Cost-benefit analysis of design changes necessary to prevent crash induced fuel leakages and fires [Ford 1973]

Benefits		
180 burn deaths	$200,000 per death	$36,000,000
180 serious burn injuries	$67,000 per injury	$12,060,000
2,100 burned vehicles	$700 per vehicle	$1,470,000
		$49.5 million
Costs		
11,000,000 cars	$11 per car	$121,000,000
1,500,000 light trucks	$11 per truck	$16,500,00
		$137.5 million

It must be noted, however, that the memo referred to the company's model range in general and not to the Pinto in particular. Also, the estimated legal costs of $200,000 per burn death were taken from a publication of the US National Highway Traffic Safety Administration (NHTSA). Therefore, the case was much less clear-cut than traditionally assumed [Schwarz 1991].

2.5 The Audi 5000

In April 1986, owners of an Audi 5000 (the US version of the Audi 100; Figure 2-3), filed a class-action lawsuit against the manufacturer, demanding up to $12 million in compensatory and $18 million in punitive damages [Huber 1991]. The litigants' lawyers claimed that the Audi's design allowed for "sudden acceleration" as their clients consistently reported that their car would surge forward uncontrollably without even its brakes being able to bring it to a stop [Csere 1987]. The results: material damage, injuries and in one case the loss of the life of a six year-old boy. His mother stated that when she was waiting in her driveway for her son to open the garage door, the car, upon switching the automatic transmission from "Park" to "Drive", leaped forward for no reason. Supposedly, applying the brakes to the maximum extent showed no effect.

Figure 2-3 The 1981 Audi 5000s (photo: Audi of America)

In the court trials that followed, none of the potential causes alleged by the plaintiffs' lawyers and their hired experts (malfunctions in the car's engine management, transmission, cruise control, etc.) could be substantiated; all explanations were dismissed as far too unlikely and/or not evident. Most convincingly, however, the defendant, Audi of America, was able to demonstrate that the power of the car's drivetrain (and in fact, the power of any car's drivetrain) would under no circumstances be sufficient to overcome its brakes.

Audi, in 1987, nonetheless recalled 250,000 '5000' models built between 1978 and 1986 to implement two major design changes. One design change concerned the arrangement of the pedals. The accelerator pedal was moved farther away from the brake as it was concluded (by the courts, the NHTSA – and common sense for that matter) that the incidents were caused by pedal misapplication, i.e. driver error. The other change was adding a shift-lock mechanism to the gear selector. Since most incidents occurred when drivers mistakenly stepped on the accelerator instead of the brake when shifting out of "Park", the shift-lock device blocks the movement of the gear lever unless the brake is firmly applied.

However, from a legal point of view, the issue of "sudden acceleration" was all but settled. In a 1988 trial, the plaintiff (who, by the way, failed to react to Audi's recall), admitted to, at least partly, standing on the wrong pedal when his '79 Audi 5000 went out of control. The jury – whether interpreting Audi's 1987 recall as a tacit admission of guilt or not – eventually found the company guilty, basically ruling that the manufacturer had failed to leave sufficient distance between the pedals. The case, which was settled on $114,000, became precedence.

While from a technical point of view, nothing has ever been wrong with the Audi 5000, the company paid millions in damages and settlements. Its sales dropped from 73,000 cars in 1985 to 23,000 units in 1988, almost putting an end to Audi's North America operations.

This example shows that the economic impact of legal affairs surrounding a product's quality is often less a result of the costs of the lawsuits themselves but of dwindling sales as a consequence of a damaged reputation. In this context, Sullivan [1990] has described how negative "spillover" effects also affected other Audi models of that era.

2.6 Siemens 65-Series Mobile Phones

It was more of a coincidence that a Siemens technician noticed the defect shortly after market launch in August 2004 [Kröger 2004]: the melody that the newly developed 65-series mobile phones (C65, CX65, M65, S65 and SL65) would play upon being switched off was found to be so loud that in case the handset was held close to the user's ear, it might cause hearing damage. This scenario was not too unlikely because the 65-series firmware would run the same shutdown routine if the phone's battery ran empty amidst a phone call.

Siemens issued an immediate consumer warning, advising users to disable the switch-off melody in the phone's settings [Cloer 2004]. However, retailers and network operators also reacted: they imposed a complete sales stop on all affected models [Bremmer 2004].

Two weeks later, during which a new firmware had been developed and tested and each of the already manufactured handsets had been taken out of its packaging to perform the upgrade, the crisis, it seemed, was overcome. The new firmware was offered to be downloaded from the Internet and a company spokesperson (in allusion to the Mercedes-Benz A-Class [Töpfer 1999]) self-critically admitted: "This was our moose test".

Yet, the mobile phone division of Siemens, amidst a struggle against its declining market share and suffering from years of losses, never recovered from this "final blow". It was eventually sold to BenQ Corporation and went bankrupt in mid 2006.

2.7 The NSU Ro 80

The "Ro 80" (Figure 2-4), which was built between 1967 and 1977, was the first mass-produced car with a twin-rotor Wankel engine [Korp 1993; Dubbel 2001]. It is today considered as one of the cars that were most ahead of their time. Apart from the revolutionary (pun not intended) engine concept, the Ro 80's specification listed

- a semi-automatic transmission,
- front wheel drive,
- a fully independent suspension with MacPherson struts for the front and a semi-trailing arm suspension for the rear suspension,
- four disc brakes,
- automatic seat belts and
- a car body with a drag coefficient of $c_w = 0.355$.

While all of these features are quite commonplace in today's cars, in the late 1960's, they set a whole new automobile agenda. Consequently, the NSU Ro 80 received rave reviews, also being voted "Car of the Year" in 1968.

Figure 2-4 The NSU Ro 80 [Korp 1993]

Unfortunately for the manufacturer, the car, i.e. its engine, soon developed a reputation for being unreliable it could never get rid of. Shortly after market launch, a stream of customer complaints reached the company, especially concerning poor performance, strange noise, starting problems and stalling. NSU's warranty policy at that time was extremely generous. To boost customer confidence in the new engine, the warranty was valid for 30,000 km or 18 months, whichever came first. Furthermore, dealers were encouraged to replace defective engines rather than to repair them, whereupon each dismantled unit had to be sent back to the factory for damage analysis.

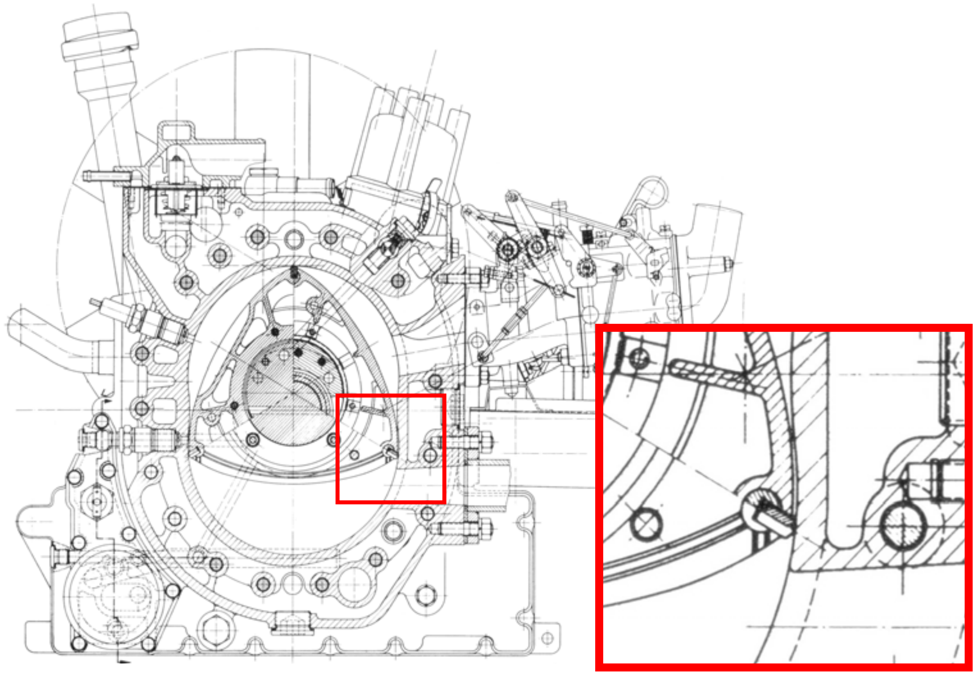

Figure 2-5 Section drawing of the Ro 80 engine (rotor tip seal highlighted) [Korp 1993]

This "autopsy" [Korp 1993, p. 109] revealed that most reported problems were caused by worn rotor tip seals (see Figure 2-5) which eventually were replaced by re-designed seals made of Ferro-TiC® (a bonded titanium carbide material, produced by powder metallurgy technology). However, poor understanding of the Wankel engine by dealers and mechanics lead to the situation that temporarily 35% of the returned engines were actually functional or just suffering from minor defects (one engine only had a clogged idle nozzle).

By the 1970 model year, most problems were resolved, but the damage to the car's reputation and, more importantly, the financial damages were irreversible. NSU's generous warranty policy for the Ro 80 lead to the situation that, simply put, about each unit built between 1967 and 1970 was sold with two engines for the price of one. The complex technology of the car's Wankel engine caused average warranty costs of DM 1,400 – compared to DM 75 for an Audi 100 of that time [Korp 1993, p. 118]. NSU was acquired by Volkswagen in 1969.

2.8 Discussion

The product examples in this chapter show that design flaws can reach from minor annoyances to serious safety dangers and that they affect (and have affected) different kinds of products in different eras. The examples also show that for companies, the consequences of design flaws can be considerable as a result of decreased competitiveness, increased warranty costs, legal claims, etc. Yet, all of the above design flaws were eventually corrected – in the cardiac stent example, however, by another company (see 2.2).

Many more examples could be given, like the space shuttle “Challenger”, the early Intel Pentium processors and the Mercedes-Benz A-Class.

What the examples have in common is that at a certain point in the product life cycle, there has been the situation that certain stakeholders indicated their discontent with the product, prompting a reaction from the companies:

- In the cardiac stent example, there was negative feedback from surgeons – which, however, did not cause J&J to design a second generation stent due to lacking competition (see 2.2).
- Similarly, buyers of the iPod nano (see 2.3) would have liked Apple to have designed the product with a scratch resistant surface, which the company decided not to do.
- In the case of the Ford Pinto, it was the (design!) engineers who discovered the dangers in the car’s design and therefore advocated safety-relevant changes, which were, however, dismissed by management for cost reasons (see 2.4).
- Audi 5000 owners believed that their car was unsafe. The manufacturer, trying to avoid any more bad publicity, decided to make changes to its design despite the fact that driver error caused the accidents (see 2.5).
- Similar to the Ford example, the design flaw of the Siemens 65-series mobile phone (see 2.6) was known to the manufacturer before any end-user became aware of it. Unlike the US automaker, however, Siemens voluntarily decided to inform the public and to work out a solution (see 2.6).

The question with the last example is what would have happened if Siemens had developed a new firmware but otherwise maintained a low profile regarding the issue, i.e. waiting for the first customers to complain. It is likely that the company would have opted for this strategy had they anticipated the sales stop imposed by retailers – a stakeholder which might not have been taken into account or if so, whose reaction was not anticipated.

Some of the examples deal with the question of product misuse. Hales and Gooch [2004, p. 206] comment: “Design engineers can no longer assume that only reasonable people will be using their products. Plaintiff’s lawyers have seen to it that product must be designed to cater to the most extreme use of products, almost to the point where it has become ridiculous. Is it really a designer’s problem if someone gets injured while using a rotary lawn mower to cut a hedge?”.

The case of the “sudden acceleration” of the Audi 5000 was in fact quite simple: no technical defect was to blame, but drivers trying to brake the car using the accelerator pedal. Misuse that lead to certain problems with the NSU Ro 80 was less obvious. Apart from the worn rotor tip seals, many engines were obviously destroyed by a lack of oil, some showed combustion chambers flooded with fuel and a few cars suffered from inexplicable transmission failures.

Korp [1993] concludes that some drivers ignored the instruction manual, thus being unaware of the fact that a) the car’s Wankel engine had a higher oil consumption, needing more frequent replenishment than a comparable piston engine, b) when starting the engine, the accelerator should not be applied and c) a semi-automatic transmission is not a fully automatic transmission – some owners constantly drove the car in third gear which was possible thanks to car's torque convertor.

The third and most recent example, the iPod nano, can be considered a borderline case. While it is comprehensible that carrying such a device in a jeans' watch pocket will increase the likelihood of scratches (which are therefore user-caused), owners obviously regarded this as a way of using the product it was actually intended for "as demonstrated by Steve Jobs […] when he launched it" [Arthur 2005]. In fact, the Apple CEO pulled the player out of his own jeans pocket when he presented the product to the public.

As has been pointed out, the legal pressure that is put upon manufacturing companies, especially in countries like the United States, can be immense. There is no doubt that a product's quality has a direct impact on aspects of product liability and warranty. However, both product liability and warranty are in fact legal concepts (Figure 2-6).

As most jurisdictions in the world uphold the inviolability of property, health, and life, manufacturers shall be held liable if their products put these values at risk, which is the basic idea behind product liability. Above that, buyers of a product have the right to obtain a product that fulfils its intended purpose and complies with its warranted properties. Still, there are product attributes influencing customer satisfaction that are beyond the scope of law, such as usefulness, innovation and prestige.

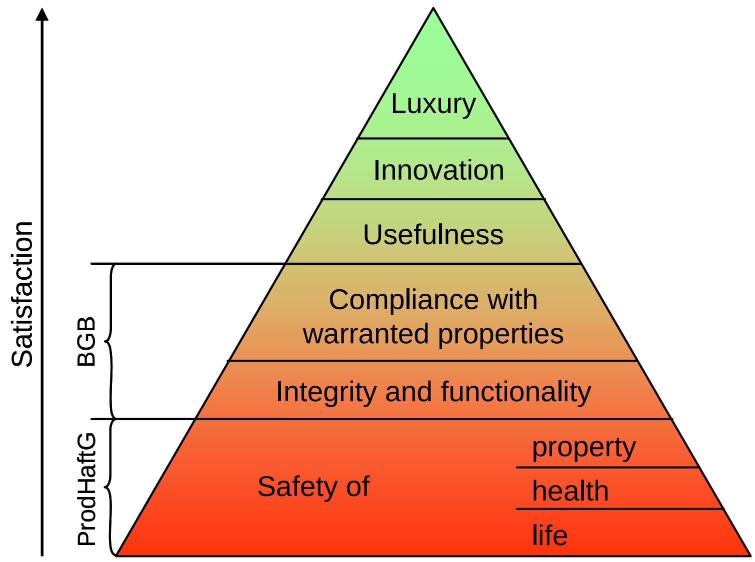

Figure 2-6 Aspects of product quality as covered by (German) law[1]. Note the similarity to the Maslow Pyramid (after: [Linß 2002])

Regardless of "Junk Science in the Courtroom" [Huber 1991] and the observation that lawsuits benefit "no one but the trial lawyers" [Hesseldahl 2005], taking a legal approach to understand product quality can be problematic. While the legal action that was taken against Ford was justified, Schwarz [1991] points out that the Pinto, given the total number of units

[1] ProdHaftG = Produkthaftungsgesetz (Product Liability Law); BGB = Bürgerliches Gesetzbuch (German Civil Code)

built, was not more fire-prone than other cars of that time. What remains undisputed is the fact that the company could have avoided the product liability lawsuits.

The important question is: can that be said for the case of the Audi 5000's "sudden acceleration"? In other words: did the company have a fair chance of foreseeing what eventually happened to its product? The same applies to Apple's iPod nano, although the legal battle was about warranty rather than product liability.

The already mentioned borderline character of this case is illustrated in Figure 2-6 as it cannot be clearly said whether scratch resistance is a warranted property of a MP3 player (in which case legal claims would be admissible) or simply a matter of usefulness. As the latter turned out to be the case (Apple eventually won the legal battle), one important fact becomes clear: it is not necessarily unlawful to design products that disappoint their buyers.

3 Product Quality

3.1 General

The products that served as examples for design flaws in the previous chapter had one thing in common: they did not satisfy the needs of those dealing with them. It can therefore be assumed that their quality was poor.

Poor product quality is probably more easily recognised than good one. Products satisfying the wants or needs of their stakeholders (cf. definition in 1.2) is considered normal. In contrast, a situation in which something breaks, cannot be assembled, or simply does not function in the expected way calls for attention.

The economic dimension of poor product quality is considerable. In the United States, deaths, injuries and property damage from consumer product incidents amount to more than $700 billion annually [CSPC 2005]. Literature states the expenses to correct quality faults to be as high as up to 20% of the sales volume [Harrington 1987]. When companies face quality problems, they are advised to take action. As Figure 3-1 shows, the need for such action in some sectors even seems to have increased over the years.

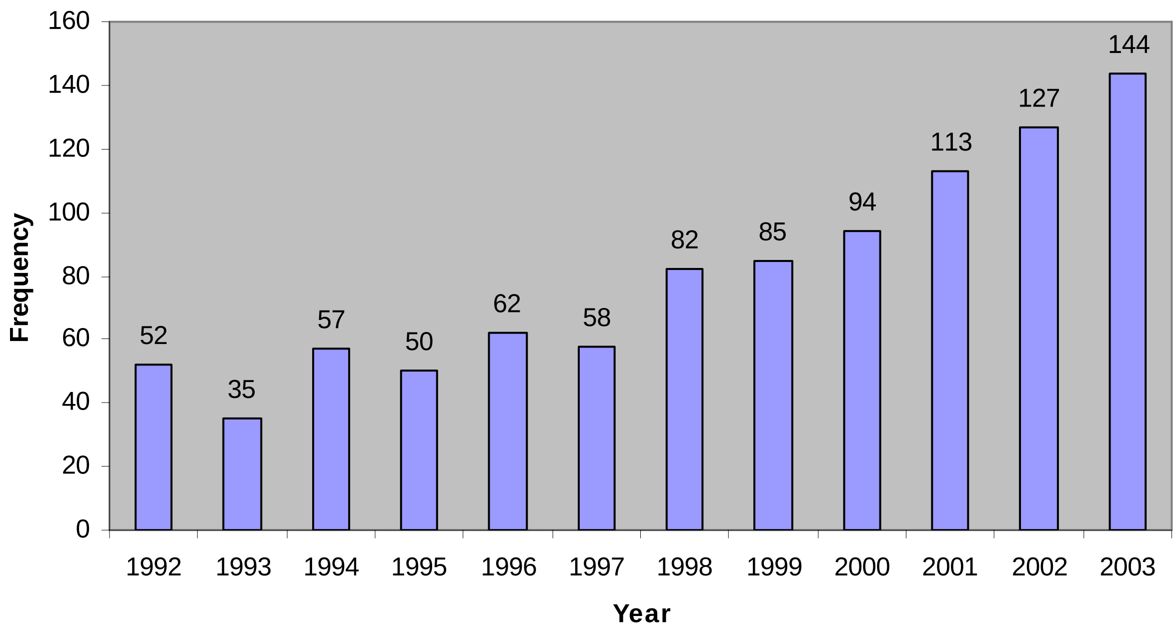

Figure 3-1 Development of car recalls in Germany (Source: German Federal Motor Transport Authority)

3.2 Definitions and Concepts

The term “quality” is widely encountered in literature as well as everyday life. Quality is “created”, “measured” and “controlled”. Companies boast their “quality products” and consumers are becoming increasingly “quality aware”. However, as many authors admit, defining quality is difficult. The American Society of Quality (ASQ) gives following definition: “A subjective term for which each person has his or her own definition.” Masing [1988] states that it will never be possible to implement a commonly accepted concept of quality among millions of individuals working in different disciplines. This multitude of disciplines (design, manufacturing, marketing, sales, etc. – each of which necessary to create a product) is probably the reason why there is no universal definition of quality.

Therefore, each definition of quality can only be seen as a statement that represents some underlying concept of or approach to quality. Garvin [1984] identifies five such approaches:

1. **The transcendent approach:** proponents of this approach regard quality as absolute and universally recognisable, often equating it with excellence.
2. **The product-based approach:** quality is something directly measurable. Accordingly, the quality of a mobile phone, for instance, can be determined by its battery lifetime and weight.
3. **The user-based approach:** quality is defined as the ability of a product to satisfy the wants or needs of the consumer.
4. **The manufacturing-based approach:** definitions that follow this approach regard quality largely as conformance to specifications.
5. **The value-based approach:** these definitions take affordability into account, implying that quality highly depends on the costs that are necessary to achieve it.

While Garvin points out that different definitions bear the potential for conflict, he stresses that differing perspectives are actually necessary for companies to be successful, i.e. that it is dangerous to rely on one definition of quality alone. Regardless of the approach taken, any definition of quality (see Table 3-1) at least implies that quality is determined by two factors:

- some specific product attributes
- some stakeholder that evaluates (or rather: passes judgement on) these attributes

When it comes to specific product attributes, it can be argued that any attribute of a product (cf. definition in 1.2), whether material or non-material, measurable or non-measurable, is a potential determinant of product quality. Garvin [1984; 1987] suggests that there are eight dimensions of product quality:

- performance
- features
- reliability
- conformance
- durability

- serviceability
- aesthetics
- perceived quality

Table 3-1 Definitions of quality according to the five approaches of Garvin [1984]

Approach	Definition	Source
Transcendent	"A direct experience independent of and prior to intellectual abstractions" "[…] even though quality cannot be defined, you know what it is"	Robert M. Pirsig
Product-based	"Differences in quality amount to differences in the quantity of some desired ingredient or attribute"	Lawrence Abbott
User-based	"Your customers returning, not your products"	Unknown
	"Fitness for use"	Joseph M. Juran
	"Quality: Whatever the customer says it is."	Richard F. Gerson
Manufacturing-based	"Conformance to specifications"	Philip B. Crosby
	"The degree to which a set of inherent characteristics fulfils requirements"	ISO 9000:2005
Value-based	"The loss a product imposes on society after it is shipped"	Genichi Taguchi
	"High Quality is the composite of quality attributes that provides the intended functions with the greatest overall economy"	Armand V. Feigenbaum

Similarly, Feigenbaum [1991] states that quality is determined by a spectrum of quality attributes such as reliability, serviceability, maintainability, attractability, etc. Examples for quality-determining characteristics of service-like products are reliability, responsiveness, assurance and empathy [Parasuraman et al. 1988].

Mørup [1993] observes that "Apart from the (paying) customer and the end user, there are a lot of other interested parties or 'stakeholders' in the product who should be considered in product development". Examples would include manufacturers, marketers, service and repair personnel, etc. Juran and Gryna [1993] extend the meaning of an existing term: "A customer is anyone who is impacted by your products or processes – either inside or outside your organisation".

A model that describes the relationship between specific product attributes and their perception by customers (in the traditional sense) has been proposed by Kano et al. [1984]. According to the Kano Model, an attribute can also be a (tangible) product feature. Three major types of product attributes are distinguished (see Figure 3-2):

- **Basic/Threshold attributes:** also referred to as "must-be" attributes, product attributes that fall into this category must be present in order for the product to be successful. Still, even if these attributes are implemented perfectly, no level of achievement will lead to above-neutral customer satisfaction. Therefore, the term "dissatisfiers" is also often used. An example would be the SMS feature of a mobile phone.
- **One-dimensional attributes:** these characteristics (also called performance or linear attributes) correlate directly to customer satisfaction. Increased achievement leads to increased customer satisfaction and vice versa. Product price is a typical one dimensional attribute (or e.g. weight and battery lifetime to keep on the mobile phone example).
- **Attractive attributes:** customers get great satisfaction from these attributes (also sometimes called "exciters" or "delighters") – and might be willing to pay a price premium. However, satisfaction will not decrease (below neutral) if these attributes are not fully achieved or, in the case of product features even lacking altogether. Attributes that are "attractive" in the sense of Kano (e.g. the video-call feature of a mobile phone) are often unexpected by customers and can be difficult to establish as needs up front.

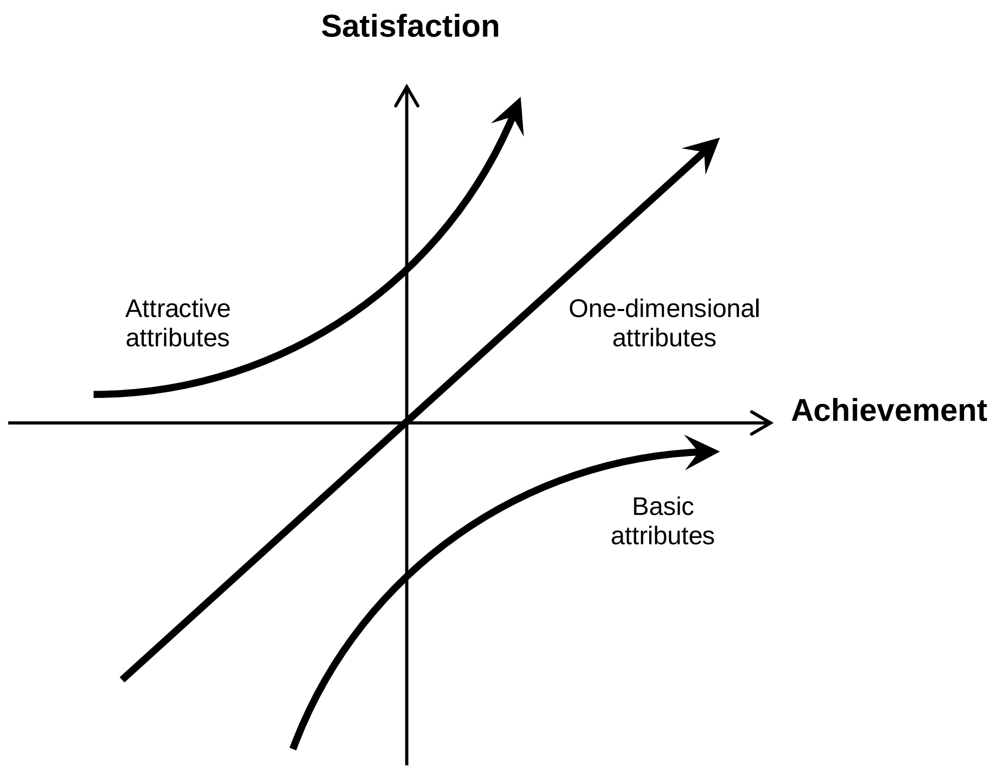

Figure 3-2 Attractive, one-dimensional and basic product attributes in the Kano Model [after Kano et al. 1984]

3.3 Total Quality Management and Quality Methods

3.3.1 The Quality Movement

Historically, efforts in achieving quality within organisations roughly went through the following phases:

- quality inspection and statistical quality control (until mid 1960s)
- quality assurance (mid 1960s until mid 1980s)
- quality management (until today)

In the beginning of this “Quality Movement” [Garvin 1988], the primary concern was on detection and control. The emphasis was on product uniformity and avoiding scrap and rework. The transition from inspection to statistical quality control was marked by the introduction of statistical tools and techniques.

In the mid 1960s, there was growing awareness that inspecting or controlling quality is not sufficient. Instead, all departments, but especially design, became responsible to assure quality throughout the entire production chain. Proven methods became part of “quality programmes” or “quality systems” to prevent defects.

Today’s management-oriented concepts, e.g. “Total Quality Management”, view quality as a competitive opportunity rather than a problem that needs to be solved. By putting a stronger emphasis on market and consumer needs, companies have shifted from a mainly product- and manufacturing-based to a more user-based quality approach.

In the following, the main methods of managing and achieving quality in companies shall be discussed.

3.3.2 Total Quality Management

Total Quality Management is defined by the Union of Japanese Scientists and Engineers (JUSE) as

> “[…] a set of systematic activities carried out by the entire organization to effectively and efficiently achieve company objectives so as to provide products and services with a level of quality that satisfies customers, at the appropriate time and price.” [JUSE 2006].

More so, TQM maintains to be a comprehensive management strategy capable of meeting the challenges of modern corporate governance by following a holistic approach that considers process-, personnel- and customer-related aspects [Rothlauf 2001]. Within the TQM framework

- **“Total“** refers to the involvement of all individuals within the value creation chain,
- “**Quality”** includes the quality of processes and products as perceived by external as well as internal stakeholders while
- **“Management”** is responsible for creating a corporate culture that enables all of the above through leadership.

Seghezzi [2003] characterises the philosophy behind TQM as follows:

- Appropriate consideration of all stakeholders with a focus on the customer.
- Better use of the knowledge of all employees in connection with individual and organisational learning.
- Continuous improvement in small steps but also in radical leaps.
- Quality responsibility of individuals as well as of teams
- Process-oriented work style.

Kanji and Asher [1996] give following account of TQM, emphasising the importance of continuous improvement: "[..] all work is seen as 'process' and total quality management is a continuous process of improvement for individuals, groups of people and whole organisations. What makes total quality management different from other management processes is the concentrated focus on continuous improvement. Total quality management is not a quick management fix; it is about changing the way things are done within the organization's lifetime"

The abovementioned long-term aspect of TQM is also referred to as "never-ending journey" [Seghezzi 2003].

In Europe, one of the strongest promoters of TQM is the European Foundation for Quality Management (EFQM)[2]. Its prestigious Excellence Award is given to organisations that stand out of their competition in the following categories – which can therefore be interpreted as the "virtues" of TQM [EFQM 2005]:

- Leadership and Constancy of Purpose
- Customer Focus
- Corporate Social Responsibility
- People Development and Involvement
- Results Orientation
- Management by Processes and Facts
- Continuous Learning, Innovation and Improvement
- Partnership Development

The evaluation of an organisation's achievement is based on the EFQM Excellence Model, a "non-prescriptive" (sic) framework that consists of nine components (Figure 3-3). Five of these are "Enablers" and four are "Results". "Enablers" describe what an organisation does leading to "Results" which are used to measure how well the organisation performs in any of the above categories. In a process of innovation and learning, feedback from "Results" shall help to improve "Enablers".

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[2] www.efqm.org

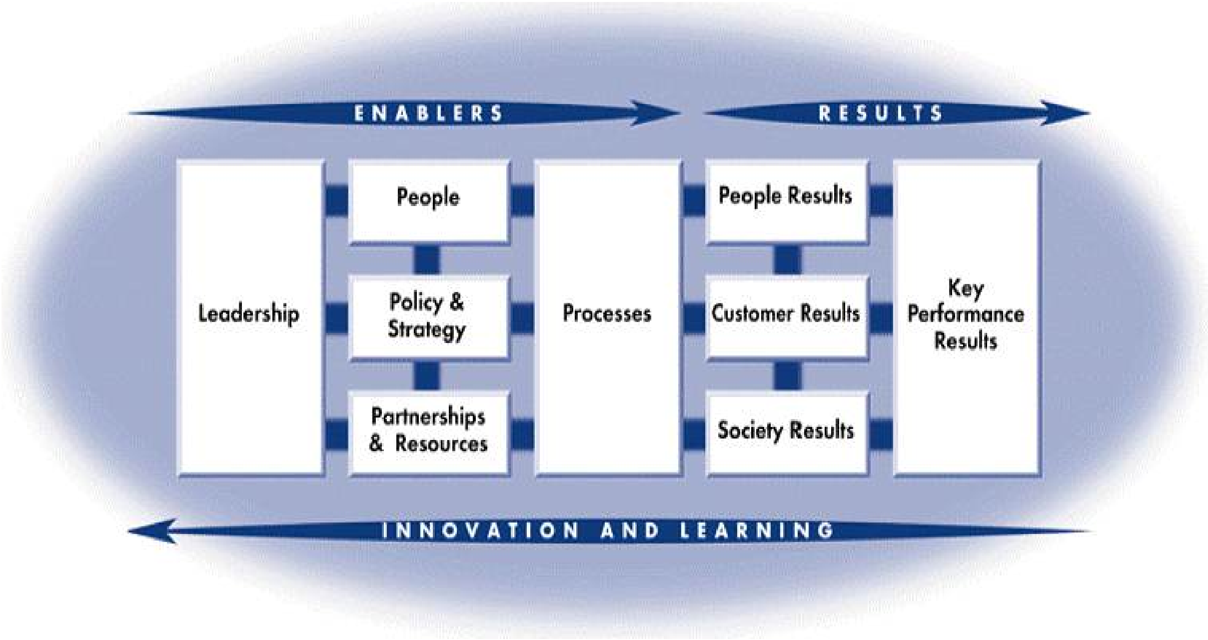


Figure 3-3 The EFQM Excellence Model [EFQM 2005]

3.3.3 Quality Methods

TQM literature suggests quite a lot of methods and tools that shall be used in practice to achieve quality. Some of the more commonly mentioned are the "Seven Basic Quality Tools" (Q7) pioneered by Ishikawa [1980] which were later supplemented by the "Seven New Management and Planning Tools" (M7; also called "Seven New QC Tools" or "New 7") [Mizuno 1988; Nayatani 1994]. Rothlauf [2001] identifies three main "sub-systems" of TQM: Just-in-Time (JIT), Benchmarking and Kaizen, whereas Kanji and Asher [1996] list 100 methods which they classify according to the following categories:

- Management methods
- Analytical methods
- Idea generation
- Data collection, analysis and display

An even more comprehensive compilation of quality methods can be found in [Tague 2005] where 113 tools plus 35 variations are identified in categories that are partly similar to the ones in [Kanji & Asher 1996]:

- Project planning and implementing
- Idea creation
- Process analysis
- Data collection and analysis
- Cause analysis
- Evaluation and decision-making
- "Mega-tools"

Table 3-2 contains an overview of methods commonly found in TQM literature. Details on these methods can also be found in e.g. [Seghezzi 2003] or [Kamiske & Brauer 2006].

Table 3-2 Overview of common quality management methods

	Method	Category [Kanji & Asher 1996]	Category [Tague 2005]
"TQM sub-systems" [a]	Just-in-time (JIT)	M	–
	Benchmarking	M	I, A_p, A_d
	Kaizen	M	–
"Seven Basic Quality Tools" [b]	Cause-and-effect diagram (Ishikawa/Fishbone chart)	A	A_c
	Check sheets	D	P, A_d
	Control charts	–	A_d
	Histograms	D	A_d
	Pareto charts	M	A_d, A_c
	Scatter diagrams	D	A_d, A_c
	Run charts	–	A_d
"Seven New Management and Planning Tools" [c]	Affinity diagrams	M	I
	Relationships diagrams	M	P, I, A_p, A_c
	Tree diagrams	D	P, A_p, A_c, E
	Matrix diagrams	D	P, A_p, A_c, E
	Matrix data analysis	D	–
	Arrow diagrams	M	P
	Process decision programme charts (PDPC)	M	P
Other	Quality Function Deployment (QFD)	M	MT
	Brainstorming	I	I
	Failure Mode and Effect Analysis (FMEA)	A	A_p, A_c
	Fault Tree Analysis (FTA)	A	A_c
	Error proofing/Poka-Yoke	M	A_p
	Balanced scorecard	–	P, A_d
	Statistical Process Control (SPC)	D	–
	Design of Experiments (DOE)	–	A_d
	Bar charts	D	A_d
	ISO 9000	M	MT
	Mind-mapping	I	P, I

M: management methods; **A**: analytical methods; **I**: idea generation; **D**: data collection, analysis and display; **P**: project planning and implementing; $\mathbf{A_P}$: process analysis; $\mathbf{A_D}$: data collection and analysis; $\mathbf{A_C}$: cause analysis; **E**: evaluation and decision making; **MT:** "Mega-tools"

[a] [Rothlauf 2001]; [b] [Ishikawa 1980]; [c] [Mizuno 1988; Nayatani 1994]

Westkämper [2001] distinguishes methods, tools and principles of QM. He states that in general, methods can often only be assigned to a specific phase of the product life cycle (Figure 3-4), whereas tools and principles are universally applicable.

<table>
<tr><th></th><th>Definition</th><th>Design / development</th><th>Production planning</th><th>Production</th><th>Use</th></tr>
<tr><td rowspan="9">Methods</td><td colspan="3">QFD</td><td rowspan="6"></td><td rowspan="7"></td></tr>
<tr><td colspan="2">Product FMEA</td><td rowspan="3"></td></tr>
<tr><td rowspan="2"></td><td>Design FMEA</td></tr>
<tr><td>Design reviews</td></tr>
<tr><td colspan="3">Fault tree analysis / run charts</td></tr>
<tr><td rowspan="4"></td><td></td><td>Process FMEA</td></tr>
<tr><td colspan="3">Design of Experiments</td></tr>
<tr><td rowspan="2"></td><td>Supplier evaluation</td><td>Sampling</td><td>Complaints mgt.</td></tr>
<tr><td>Capability approval</td><td>SPC</td><td>Field data analysis</td></tr>
<tr><td>Tools</td><td colspan="5">Seven Basic Quality Tools / Seven New Management and Planning Tools</td></tr>
<tr><td>Principles</td><td></td><td colspan="3">Error Proofing / Poka Yoke</td><td></td></tr>
</table>

Figure 3-4 Methods, tools and principles of QM in different phases of the product life cycle [after Westkämper 2001]

3.3.4 Criticism

It should not be left unmentioned that TQM is subject to considerable controversy. Even the "bottom line", i.e. the economic benefit of quality management is recently being doubted. While some studies, especially the often cited one by Hendricks and Singhal [1997], conclude that companies practicing TQM outperform their competitors, more recent publications, e.g. [York & Miree 2004], argue that effective quality management "comes along the ride" of already successful firms.

There is also some criticism about (total) quality management originating from the design community. Moss [1996], for instance, describes TQM as "A laudable intent but hardly a program for specific actions." Hosnedl [1997] comments that "Methods for controlling quality, such as TQM, go a long way towards increasing the quality of work in the pre-production phases, especially in designing." He also points out theoretical and terminological deficiencies. Mørup's research [1993] "[…] has not been able to identify TQM as a separate research area. Since no consistent theoretical basis for TQM has been found either, TQM still appears to be based on fragments of what theories the different methods under the TQM umbrella have to offer." He concludes that TQM

- overrates specifications and planning,
- overlooks the fact that quality is synthesised, having obscure, naive conceptions of design,
- focuses on problem solving only,
- overrates management's role,
- is prone to the risk of bureaucracy and
- ignores linkages between activities.

In addition to these theoretical reservations, Andreasen and Hein [1998] observe that in general practice, TQM has not helped designing companies in improving the quality of their products. Their findings show “[…] a fragmented picture of islands of efforts and a weak understanding of basic quality concepts between designers.”

3.4 Quality Methods in Design

As pointed out in section 3.1, any concept of product quality refers to actual product attributes. Design, arguably having the greatest influence on the attributes of a product, has therefore an important – if not the most important – influence on its quality. Pahl and Beitz [1994; 1996] assert that marketable product quality starts with design, affirming that their systematic approach prepares designers for their quality responsibility.

Dertouzos [1989] observes: “The key […] will be to make further progress in […] ‘design for quality’ techniques. The challenge here is for product-development teams to arrive at a product design that has been systematically optimized to meet customers’ needs as early as possible in the development project. The design must be robust enough to ensure that the product will provide customer satisfaction even when subject to the real conditions of the factory and customer use. The more problems prevented early on through careful design, the fewer problems that have to be corrected later through a time-consuming and often confusing process of prototype iterations.”

The importance of an early prevention of quality problems within the product development process is illustrated in Figure 3-5: the “Rule of Tens” suggests that the costs for fixing a quality problem increase by a factor of ten at each major stage following the design stage. Therefore, fixing a quality problem at the customer could be 1,000 times more expensive than correcting it in the design phase. In this context, it should be mentioned that 80% of all quality problems have their roots in design, development and planning [Masing 1988].

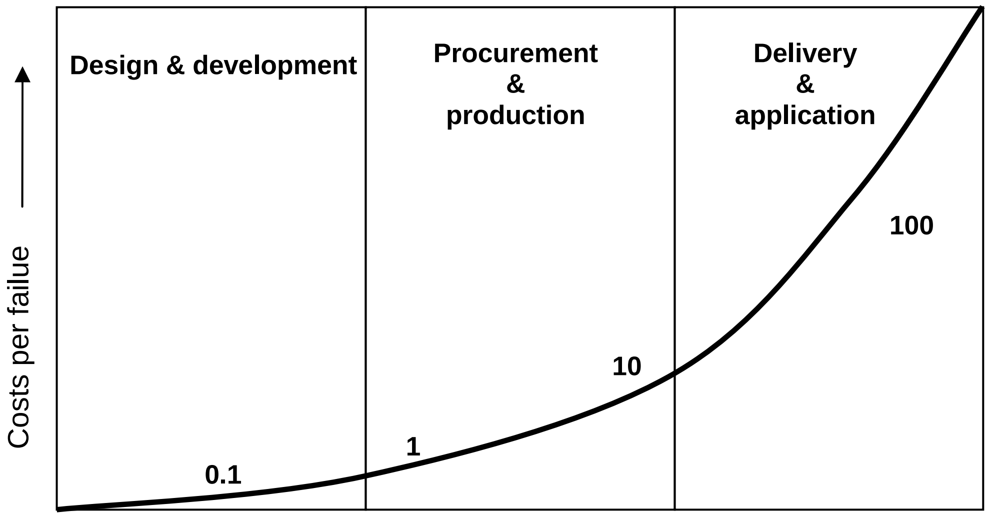


Figure 3-5 “Rule of Tens”of failure costs after [VDI 2247]

According to [VDI 2247], the aims of development and design in quality management should be to

- ensure product safety and product reliability,
- prevent and if necessary systematically handle design faults,
- identify and resolve unnecessary levels of safety, thus increasing performance, reducing costs and improving economic efficiency,
- keep schedules and
- ensure economic efficiency.

To achieve these aims, the guideline proposes the use of the following quality methods in the design process:

- Quality Function Deployment (QFD)
- Failure Mode and Effect Analysis (FMEA)
- Fault Tree Analysis (FTA) and derivates
- Design Reviews
- Quality Assessment
- Design of Experiments (DOE)
- Statistical Tolerancing

As QFD, FMEA and FTA are probably most commonly mentioned in design-related literature[3], a brief description of these methods is given in the following, focusing on their application in the design process.

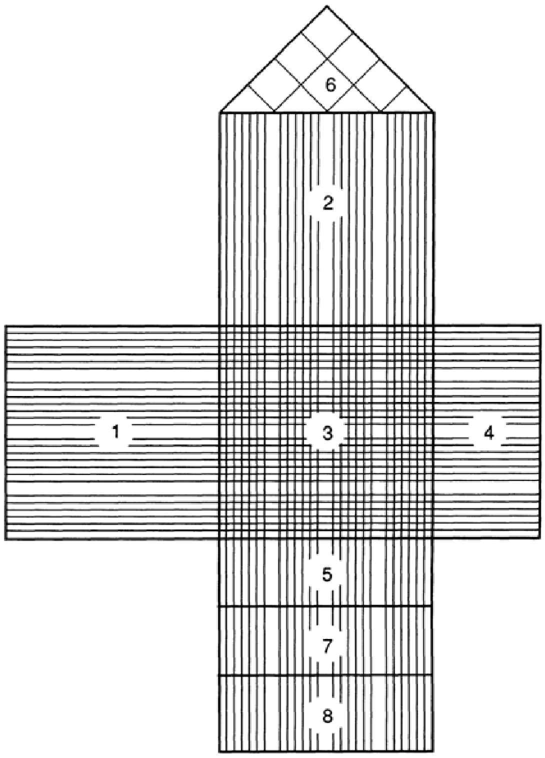
3.4.1 Quality Function Deployment

QFD is a technique that originated in Japan in the late 1960s [Akao 1997] and became popular in the United States in the early 1980s where it was further developed by e.g. Clausing [1994] and King [1989]. Its main purpose is to help translate customer requirements ("what") into company-specific measures ("how"). More specifically, it aims at facilitating the correct and complete identification and formulation of customer requirements and their implementation in terms of quality targets and product features by the responsible company departments.

The main tool of QFD is the "House of Quality" (HoQ) which, in its most basic form, consists of two matrices or "rooms" (Figure 3-6). The central matrix (3) displays the correlation between the "what" (1) and the "how" (2), in other words: the potential of the measures to fulfil the requirements. The "roof" (6) of the HoQ is a triangular matrix representing the interrelation (i.e. compatibility) of measures where potential target conflicts can be identified.

[3] e.g. [VDI 2247; Harms & Salewsky 1994; Streckfuss 1994; Pahl & Beitz 1996; Hosnedl et al. 1997; Ehrlenspiel 2003; Hering et al. 2003; Clarkson & Eckert 2005]; with a special focus on QFD: [Wheelwright & Clark 1992; Clausing 1994]

The rooms below and right of the correlation matrix are used for optional (e.g. benchmarking) analyses.



"Rooms" of the HoQ:

1. Customer needs and wishes ("what")
2. (Design) Measures / requirements ("how")
3. Correlation of (1) and (2)
4. Benchmarking of products from a customer perspective
5. Benchmarking of products from a technical perspective
6. Interrelations/conflicts of measures
7. Priorities: customer weight (1), importance (3), and expected difficulty of each measure
8. Definite quantification of requirements (value and spread)

Figure 3-6 House of Quality [after Clausing 1994]

Typically, the correlations are specified as "weak", "medium" or "strong", while there can be "strong negative", "negative", "positive" or "strong positive" interrelations. QFD is often referred to as a multi-stage process where the "how" becomes the "what" of a subsequent stage (Figure 3-7).

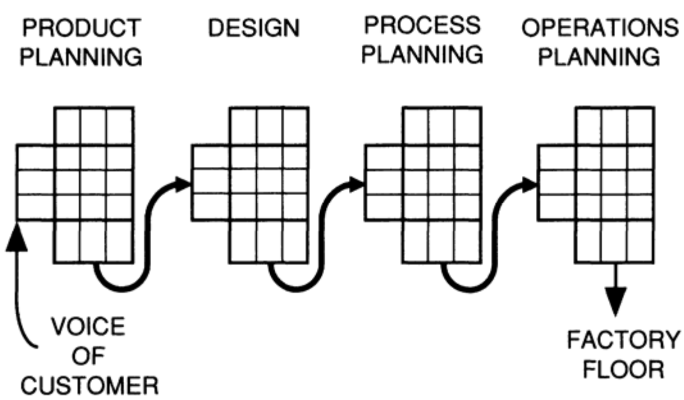


Figure 3-7 QFD as a multi-stage process [Clausing 1994]

Successful QFD requires [VDI 2247; Streckfuss 1994]:

- Distinct customer orientation during development
- Integration of all company departments
- Support from management
- Proficient moderation, especially in the introductory phase
- Efficient teamwork
- Use of further intuitive solution finding methods (e.g. brainstorming, gallery method, etc.)

Usually, the following results can be expected from (successfully) applying QFD [VDI 2247; King 1989; Wheelwright & Clark 1992; Clausing 1994; Streckfuss 1994]:

- Clear understanding of the customer requirements
- Consensus about identified solutions
- Earlier beginning of the development phase
- Few changes
- Complete documentation of the individual steps
- Profitable products
- Satisfied, or even enthusiastic customers

According to King [1989], it is even possible to achieve "Better designs in half the time". There is, however, also criticism about QFD, mainly concerning the complexity of the method and the necessary effort to carry it out [Streckfuss 1994]:

- Experience shows that even for a small product, a session to build a single HoQ can last between one and three days.
- The number of evaluable correlations grows quadratically, rendering it impossible to analyse all of them. Identifying important correlations, however, requires experience.
- The same difficulty applies to the "roof". In addition, interrelations between measures are often even harder to interpret than correlations.
- The paperwork can be arduous.

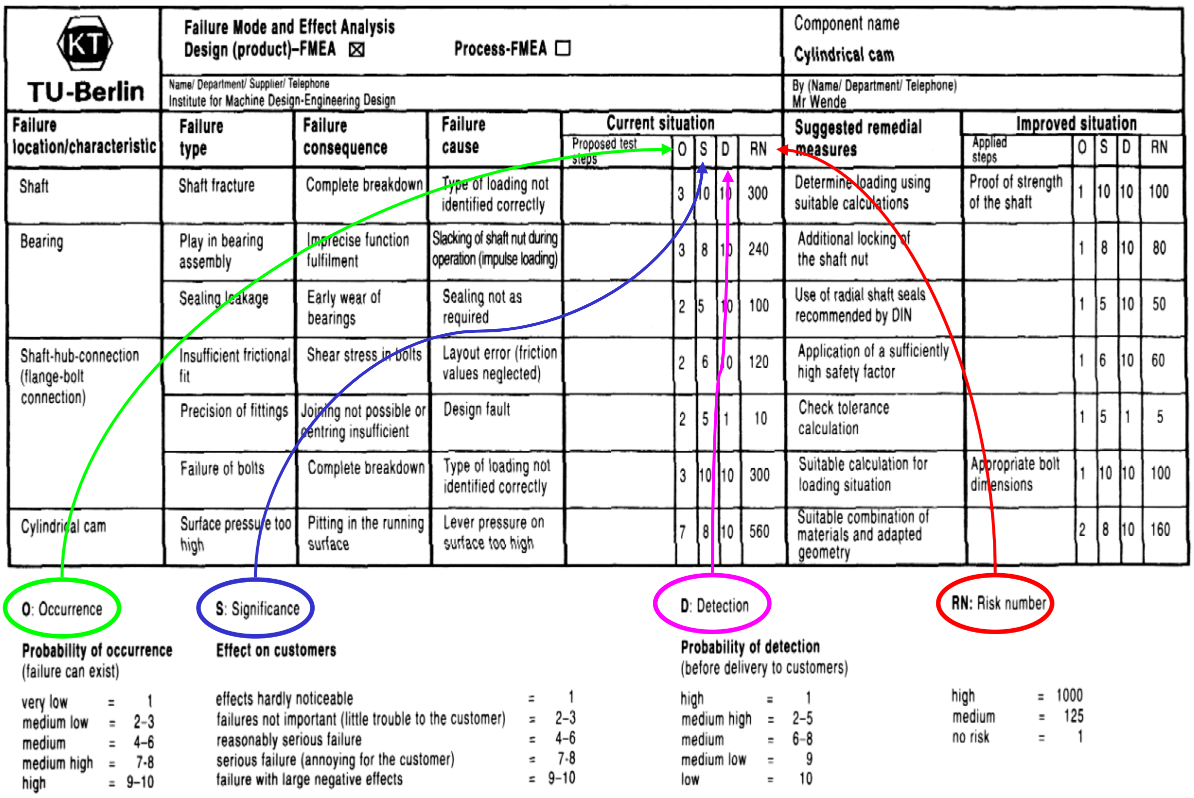
Wheelwright and Clark [1992] report that "Many users of QFD have horror stories about design teams that literally fill up wall after wall with matrices so complicated that no one understands them. The organization's time and energy is absorbed in the minutiae of nuts and bolts that no one concentrates on those design parameters that are most crucial in driving customer attributes […]".

3.4.2 Failure Mode and Effect Analysis

Originally developed by the US military in 1949 as a method to classify "failures according to their impact on mission success and personnel/equipment safety" [MIL-P-1629], FMEA is a method that examines potential failures in products, processes or systems. Its goal is to avoid or limit risk. Today, it is standardised e.g. in [DIN EN 60812]. There are three major types of FMEA:

- **Process-FMEA:** carried out to identify potential failures in e.g. manufacturing or service processes
- **System-FMEA:** analysing the sub-systems as part of a larger overall system (e.g. a chemical plant), concentrating on failures which may result from their interaction and problems that could arise at the interfaces.
- **Design-FMEA:** similar to a system-FMEA but usually carried out on product or component level. As it can be difficult to draw a clear line between the two, system- and design-FMEA are also sometimes combined under the term “Product-FMEA” [Müller & Tietjen 2000].

During a Design-FMEA, the product is broken down into (preferably all) potentially failing entities (i.e. components, assemblies, parts; but also functions). Figure 3-8 shows an example of a form that could be used in a Design-FMEA.



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Failure Mode and Effect Analysis
Design (product)–FMEA ☒ Process-FMEA ☐

Component name: Cylindrical cam

Name/ Department/ Supplier/ Telephone: Institute for Machine Design-Engineering Design

By (Name/ Department/ Telephone): Mr Wende

Failure location/characteristic	Failure type	Failure consequence	Failure cause	Current situation: Proposed test steps	O	S	D	RN	Suggested remedial measures	Improved situation: Applied steps	O	S	D	RN
Shaft	Shaft fracture	Complete breakdown	Type of loading not identified correctly		3	10	10	300	Determine loading using suitable calculations	Proof of strength of the shaft	1	10	10	100
Bearing	Play in bearing assembly	Imprecise function fulfilment	Slacking of shaft nut during operation (impulse loading)		3	8	10	240	Additional locking of the shaft nut		1	8	10	80
	Sealing leakage	Early wear of bearings	Sealing not as required		2	5	10	100	Use of radial shaft seals recommended by DIN		1	5	10	50
Shaft-hub-connection (flange-bolt connection)	Insufficient frictional fit	Shear stress in bolts	Layout error (friction values neglected)		2	6	10	120	Application of a sufficiently high safety factor		1	6	10	60
	Precision of fittings	Joining not possible or centring insufficient	Design fault		2	5	1	10	Check tolerance calculation		1	5	1	5
	Failure of bolts	Complete breakdown	Type of loading not identified correctly		3	10	10	300	Suitable calculation for loading situation	Appropriate bolt dimensions	1	10	10	100
Cylindrical cam	Surface pressure too high	Pitting in the running surface	Lever pressure on surface too high		7	8	10	560	Suitable combination of materials and adapted geometry		2	8	10	160

Figure 3-8 Example of an FMEA form [Pahl & Beitz 1996]

For each entity (failure location/characteristic) taken into consideration, the failure type, consequence and cause is identified. In the subsequent section, a risk number (RN) is assigned, which is the product of the estimated likelihood of occurrence (O), significance for the customer (S) and probability of detection (D). Each factor can take a value between 1 (very low likelihood of occurrence, effects hardly noticeable for the customer, high probability of detection) and 10 (high likelihood of occurrence, failure with large negative effects and low probability of detection). Failures with a RN > 125 as well as those for which O > 8 or C > 8 or D > 8 are considered critical. The resulting RNs indicate the priority for formulating remedial measures. The rightmost part of the FMEA form leaves room to document the improved situation by noting applied steps and new values for O, S and D. Over time, the information stored in the FMEA forms can serve as valuable source of information as to the effectiveness of specific quality measures [Pahl & Beitz 1996].

A Design-FMEA should be carried out by a multidisciplinary team with members not only from design and development, but also e.g. manufacturing (planning), purchasing, sales, quality control, customer service, etc. as causes and measures can involve any stakeholder.

However, the usefulness of FMEA is limited as it can usually cover only major failure modes in a product or system. Identifying failure modes involving multiple failures or failure chains is very difficult. Industrial practice has also shown that a successful FMEA, especially with complex products and processes, can require considerable time and cost efforts, and needs meticulous planning and preparation.

3.4.3 Fault Tree Analysis

FTA is based on the principle of causality which states that each event can be traced down to at least one cause. The procedure is deductive: for each fault, all possible causes leading to the fault shall be identified, recursively establishing the fault tree (Figure 3-9). Boolean expressions indicate whether all causes (&) or any cause (≥ 1) are necessary for an event to occur.

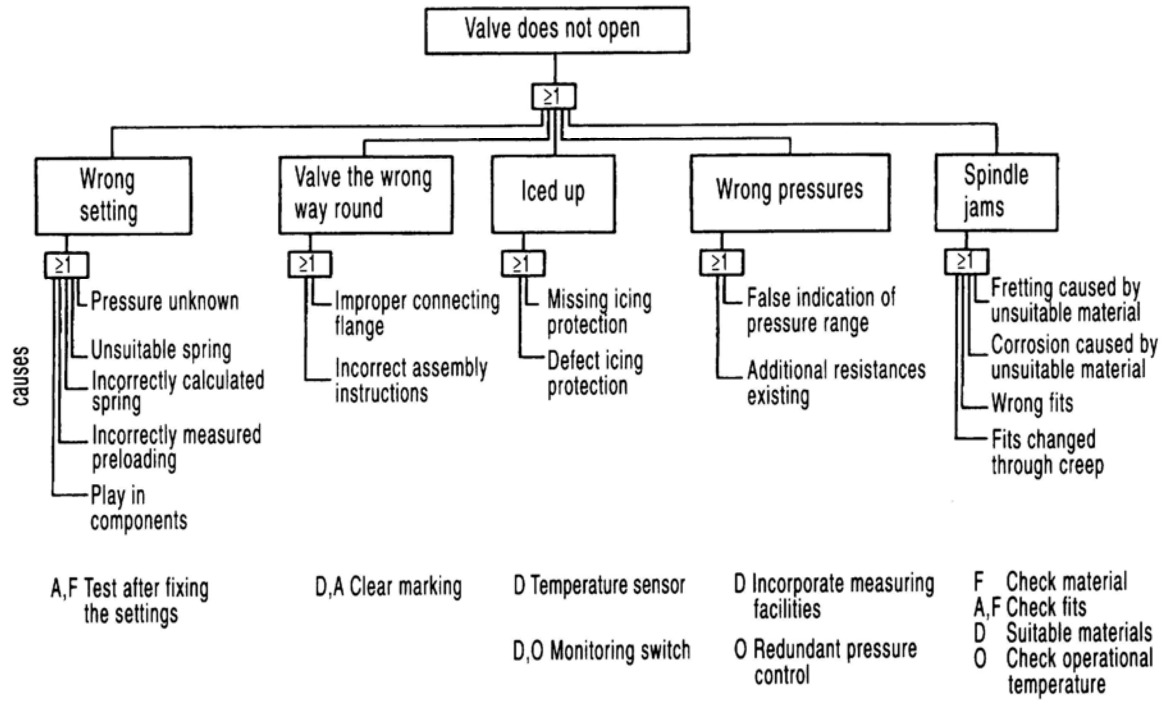

Figure 3-9 Fault tree containing the causes leading to the failure of a valve. Below: identified remedies[4] [Pahl & Beitz 1996]

[4] grouped according to the involved departments: D = design; P = production; A = assembly; O = operation; F = formal procedure required.

Pahl and Beitz [1996] propose a systematic (if not rigorous) approach based on negating the functions as provided by the function structure of the product, allowing it to perform an FTA already in the conceptual stage of design. The fault tree in the above figure is therefore one sub-tree of the fault "Valve does not limit pressure", which is the negation of the valve's assumed function "limit pressure".

The greatest benefit that can be obtained from performing an FTA is the possibility to identify and document complex failure modes. However, the implied top-down approach cannot always be strictly followed as newly identified causes can make it necessary to rearrange the fault tree. Also, unlike with a an FMEA, no information as to the prioritisation of failures is given. Clausing [1994] therefore suggests to iteratively combine both methods until consistency is achieved. Finally, fault trees can become very complicated which can make the use of specialised software tools necessary [Thompson 2005].

3.5 Q- and q-Quality

Andreasen and Hein [1998], in advancing Mørup's concept of Design for Quality (DFQ) [1993], propose a framework for life cycle oriented quality efforts. Their criticism of TQM notwithstanding (see 3.3.4), this framework is intended to support – not replace – existing approaches by linking proven methodologies and efforts together and creating a common quality mindset. To begin with, they refer to two main types of quality [Mørup 1993]:

- **Q-quality ("big Q"):** the *external stakeholders*' qualitative perception of the product.
- **q-quality ("little q"):** the *internal stakeholders*' qualitative perception of the product (in relation to their product-related tasks).

External stakeholders are e.g. customers, end-users, approval authorities and sales and service professionals not affiliated with the manufacturer of the product. Internal stakeholders include all company-internal functional areas, e.g. design, manufacturing, quality control and logistics.

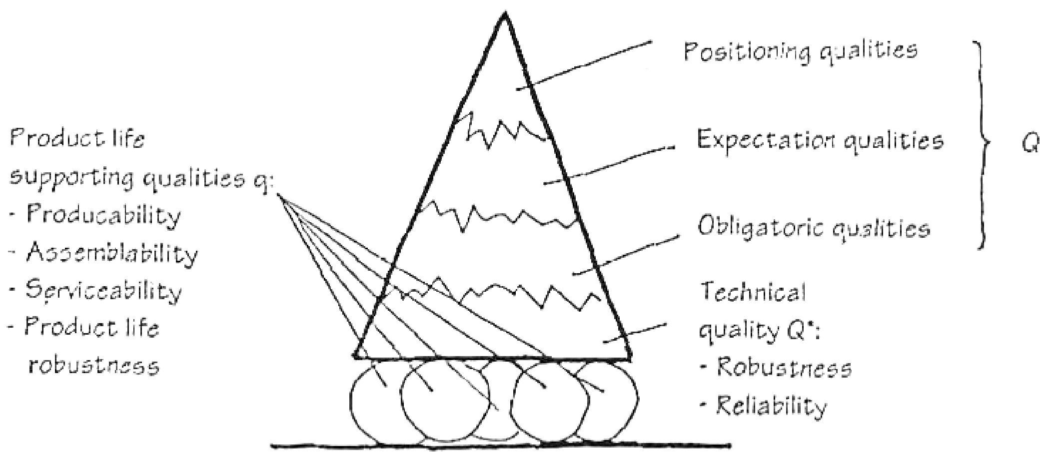

Figure 3-10 q-, Q- and Q*-qualities [Andreasen & Hein 1998]

Figure 3-10, using a pyramid as a metaphor, shows examples of product properties contributing to q- and Q-qualities. Furthermore, it introduces Q*-quality which, as a subset of

Q-quality, relates to product properties like reliability and robustness. This so-called technical quality Q*, while not necessarily appreciated by all external stakeholders, is the “enabler” of Q-quality of which Andreasen and Hein distinguish three types:

- **Obligatory qualities:** based on product properties which must be present and must have a minimum level with regard to the competitive situation.
- **Expectation qualities:** based on product properties which are unique to the company and express its image.
- **Positioning qualities:** based on properties which give the product its competitive edge.

A proposed framework for life cycle oriented quality efforts is illustrated in Figure 3-11. According to this framework, there are three distinct quality dimensions: the quality of the design, the quality of the produced product and the quality of the individual product in use. With regard to each dimension, a company must understand

- how to specify, implement and verify q- and Q-qualities,
- the chain phenomena related to specification, design, and making of quality, as well as
- the final product’s qualities and quality influencing parameters, not only from its use but also from e.g. distribution and service.

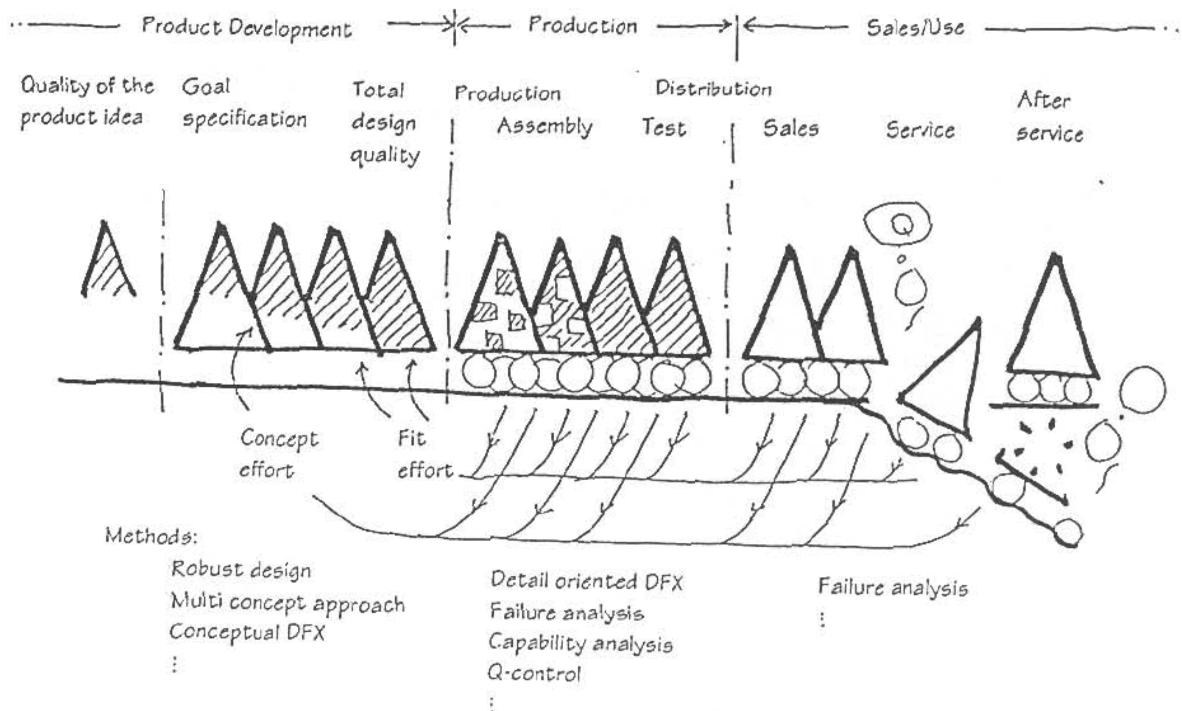

Figure 3-11 A framework for life cycle oriented quality efforts [Andreasen & Hein 1998]

This understanding not only implies anticipation but also learning (as the feedback arrows in Figure 3-11 suggest). To assure the quality of the design, the following steps are necessary:

1. Identification and articulation of Q-elements
2. Creation of product concepts which carry these Q-elements
3. Detailing in order to ensure Q*, technical quality
4. Conceptualisation and detailing to ensure q-quality

In industrial practice, however, Andreasen and Hein have often observed causes like the following that prevent leveraging life cycle oriented quality efforts:

- Companies being at the limit of their knowledge when new technologies are introduced in new markets
- Changes leading to flaws because the original solution is not well understood
- A lack of structured learning which impedes the ability to foresee flaws
- Feedback from customer detected errors being processed too slowly
- Inexperienced designers performing design reviews or being allowed to choose design concepts

3.6 Discussion

The definitions and concepts of quality addressed in 3.1 suggest regarding design flaws as quality defects. This does not imply, of course, that every quality defect is a design flaw. As design is directed towards creating a product and a product is defined as an item that satisfies someone's need (cf. 1.2), it is advisable to follow a user-based quality approach [Garvin 1984] to design flaws[5]. Two important aspects of quality, product attributes and stakeholders, are also key to understanding design flaws. This issue has already been touched on in chapter 2. However, the attributes that troubled the users, dealers and mechanics of the example products, largely elude the quality attributes proposed by e.g. Garvin [1984; 1987] and Feigenbaum [1991] (see 3.1).

Kano's model of how different attributes influence the satisfaction of one particular stakeholder – customers – is not quite suitable as a model for design flaws either. It is based on the state of the product at the time customers buy it. At that time, an attractive attribute, which was possibly unexpected, will certainly increase satisfaction. However, a subsequent decrease of the same attribute – e.g. as the result of a design flaw – will likely have a more negative effect as the absence of the attribute in the first place.

When regarding design flaws as a special form of quality defect, it suggests itself to consider current approaches and methods to achieve quality. The holistic philosophy of TQM, especially its involvement of all stakeholders in a product and its recognition of a need for continuous improvement seems to be highly suited not only for preventing design flaws but also correcting them.

[5] Note that e.g. "Conformance to specifications" or "The degree to which as set of inherent characteristics fulfil requirements" (manufacturing-based approaches in Table 3-1) were not at all the problem in the example in 2.4.

Yet, an analysis of the methods proposed by TQM literature reveals that in general, quality is still largely treated as a statistical and metrological issue which poorly reflects the holistic "spirit" of TQM. In particular, few methods could be found which would be useful for assessing the quality of products once they have entered the market (e.g. complaints management; see Figure 3-4). Most common quality methods are preventive in nature which includes QFD, FMEA, and FTA, methods with a traditionally strong link to product development (see 3.4).

The question whether these design-related quality methods would have prevented any of the design flaws exemplified in chapter 2 is of course speculative and probably irrelevant. They could be, however, useful for documenting design flaws and thus – in terms of not repeating them in a follow-up design – helpful for correcting them. Design flaws revealing new, unknown customer requirements or unexpected interactions between design measures could be displayed in a HoQ (see 3.4.1). Similarly FMEA (see 3.4.2) and FTA (see 3.4.3) could be used in a "documentation mode", making the collected information available for future generations of products. Anyhow, experience from design flaws can serve as a valuable input for any of these methods in future design projects.

Within the framework of life cycle oriented quality [Andreasen & Hein 1998], design flaws in the final product are an opportunity to verify (a lack of) q- and Q-qualities and to understand the parameters that influence them. Therefore, design flaws could be a key element in meeting the authors' demand for learning in DFQ (see 3.5).

All criticism aside (see 3.3.4), TQM reflects companies' increased commitment to quality as a strategic issue. If applied prudently, both TQM and DFQ are invaluable for preventing design flaws. At the same time, this emphasis on prevention – in theory and practice – might have left a "blind spot" on situations where this goal could not be met. In order to leverage the potential that both concepts hold, it is necessary to apprehend quality defects, i.e. design flaws, as a starting point for continuous improvement.

4 Defining Design Flaws

4.1 A Generic Model of Design-Related Product Quality

In the previous chapter, it was concluded that a design flaw is a specific form of quality defect. However, it was also pointed out that current research – not so much about the concepts but rather about the achievement of quality – provides an insufficient theoretical basis for describing, understanding and ultimately dealing with design flaws.

Therefore, the aim of this section is to further refine of the previous findings in order to arrive at a generic model of design-related product quality which can be used as a framework for the definition and interpretation of design flaws.

This model describes the interactions between three elements. Two of which, *product attributes* and *stakeholders*, have already been addressed. Both play a role in existing concepts of (achieving) product quality. The third element of the model are the *designers*. These three elements shall be discussed in the following sections before their interactions are summarised in 4.1.4.

4.1.1 Product Attributes

Many authors have pointed out that there are different dimensions along which products can be described. Hubka and Eder [1996, p. 112] generally distinguish between the "internal" and "external" properties of a technical system (Figure 4-1).

Internal properties are under the direct control of the designers. These properties include "general design properties" like strength, stiffness and hardness, "elementary design properties" such as form, dimensions and materials, as well as "design characteristics" like the technological principle.

External properties, on the other hand, are those properties that "the customer can see and judge" [ibid.] and that designers must generate by means of establishing the internal properties. Hubka and Eder identify 11 classes of such external properties, e.g. "operational properties" like reliability, safety and maintainability, "manufacturing properties" e.g. quality control and testing, and "aesthetic properties" which include form, colour and sound.

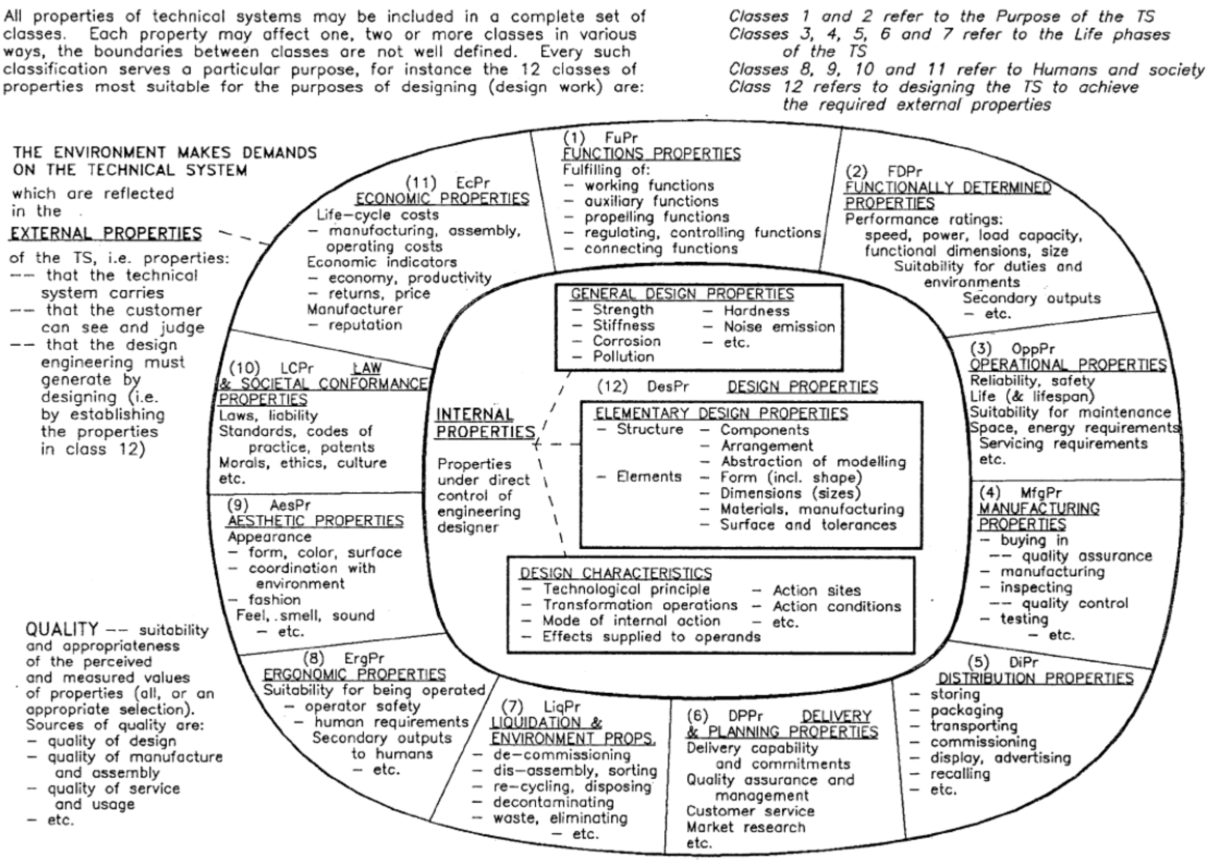

Figure 4-1 **Internal and external properties of technical systems [Hubka & Eder 1996]**

Wheelwright and Clark [1992], using the gear system of a photo camera as an example (see Figure 4-2), describe the relationship between "design parameters" and "customer attributes", concepts that are similar to the internal and external product properties in [Hubka & Eder 1996]. They state that the vector of design parameters influences the customer attributes which in turn should be the basis for choice and evaluation.

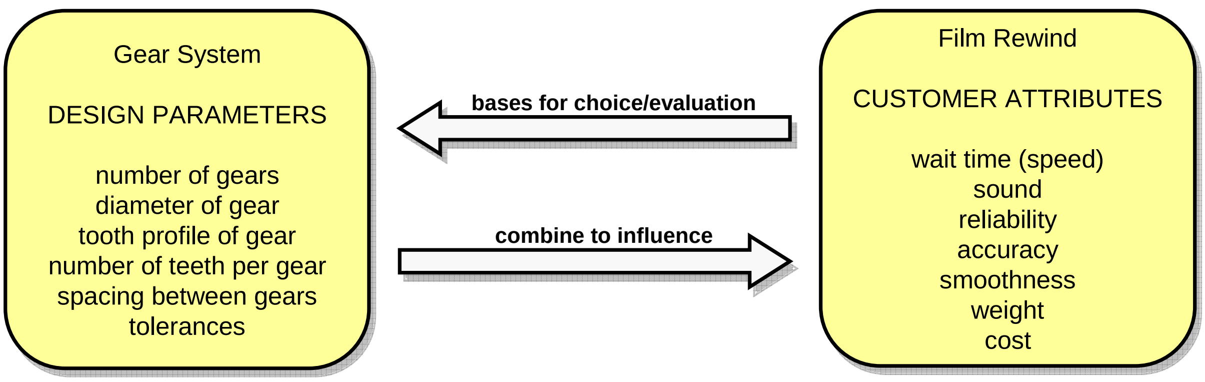

Figure 4-2 **Design parameters and customer attributes [Wheelwright & Clark 1992]**

In this thesis, a distinction is made between *product properties* and *product attributes*. Product properties are similar to “internal properties” [Hubka & Eder 1996] or “design parameters” [Wheelwright & Clark 1992] in that they are directly determined during design and that they represent the dimension along which designers usually describe a product. Also, product properties are objective [cf. Gudnason 1987 in Mørup 1993, p. 90] which means that their assessment is largely independent from individual influences.

Product attributes, while being determined by the product properties, are highly subjective. In this thesis, a product attribute can be any aspect of a product that is of interest for a specific stakeholder. Depending on the stakeholder, however, product attributes can be identical with product properties. Tolerances and sizes, for instance, are of vital interest for manufacturers. Apart from these quite objective measures, product attributes can still be as elusive as “prestige” or “coolness”.

The examples in chapter 2 have shown that stakeholders care about various product attributes. In the stent example discussed in 2.2, “stiffness” and “shape” were the product properties that lead to the stent’s product attributes “X-ray visibility” and “ease of insertion” – both found to be poor by surgeons. Similarly, the product property “surface hardness” of the iPod nano (see 2.3) determined its product attribute “scratch-resistance”. In the case of the NSU Ro 80 (see 2.7), the engineers eventually succeeded in adjusting a whole range of properties of the engine such that the product attribute “reliability” became acceptable.

4.1.2 Stakeholders

Any definition of quality discussed so far (see 3.1) at least implies the existence of an entity whose legitimate interests or needs are supposed to be met. Consequently, these stakeholders, as they are referred to in the generic model being described in this chapter, not only include the buyers or users of a product but also government authorities (e.g. the FDA and the NHTSA), retailers and repair personnel[6]. Apart from these *external stakeholders*, many functions within a company also fulfil the role of a stakeholder. Such *internal stakeholders* can be e.g. manufacturing, logistics, customer service but also marketing and sales (see 3.5).

Whether internal or external, different stakeholders usually have different (if not contradicting) interests related to the product. These interests and needs are reflected by the expectations that the stakeholders set into the product attributes.

According to Mørup [1993], consumers expect benefits, i.e. desirable consequences from using a product. He states: “A customer evaluates product attributes and benefits in terms of his own values, beliefs, and his knowledge about and past experiences with similar products” [Mørup 1993, p. 93]. In a similar context, Hales and Gooch [2004, p. 205] observe that “The expectations of customers and users change with time, not always in a predictable fashion”.

As mentioned above, product attributes are subjective, i.e. different stakeholders ascribe different meanings to the same product attribute as a result of dissimilar values, beliefs and experiences. Another factor that adds to the subjectivity of product attributes is the fact that they are perceived.

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[6] as highlighted by the examples in chapter 2

In cognitive psychology, perception is the process of acquiring, interpreting, selecting and organising sensory information [Wessells 1982; Anderson 2005]. The common underlying view is that our mind maintains a schema of how our world functions. Schemas of dynamic systems are often referred to as *mental models* [several sources in Wickens et al. 2004, p. 137]. They determine our understanding of how systems, e.g. products, work and behave. Mental models, however, are not static but are constantly being updated by our perceptions. The cognitive approach to perception holds that these perceptions are strongly affected by our expectations – which, in turn, are determined by our mental model [Goldstein 1996, p. 24].

4.1.3 Designers

The final element of the generic model of design-related product quality are the designers. Their task is to define the product's properties as such as to ensure that the product's attributes meet the interests of its stakeholders (which can be seen as the essence of design [cf. Pahl & Beitz 1996, p. 1]).

In doing so successfully, designers need to perceive (cf. 4.1.2) the product's attributes – ideally in the same way as the stakeholders. This is usually difficult for two main reasons: the first reason is that the product attributes designers perceive are not final yet. They typically belong to a product that is still under development. Therefore, designers can often only anticipate its attributes. The second reason is that designers naturally have a more sophisticated mental model of the product and thus a better understanding of the product than any other group of individuals.

Designers cannot reasonably fulfil their task unless they know the stakeholders' interests in and expectations of the product. This information, transmitted by what is often referred to as the "voice of the customer", typically serves as the basis for the requirements list in a design project [Schmidt-Kretschmer et al. 2006]. However, as the iceberg metaphor in Figure 4-3 suggests, the voice of the customer is only the explicit subset of his or her true needs or interests. Indirectly, complaints and warranty claims also express the expectations of stakeholders, possibly those that were not made explicit earlier.

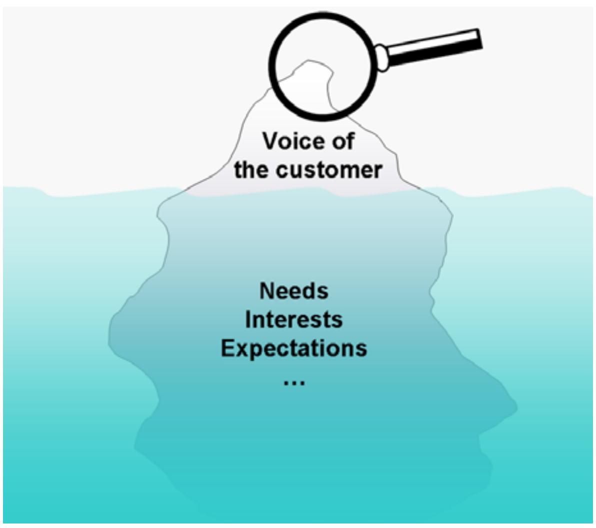

Figure 4-3 The voice of the customer as the proverbial "tip of the iceberg" [after Schmidt-Kretschmer et al. 2006]

In opposite direction of the voice of the customer, i.e. from designer to stakeholder, there is a communication of product-related information. This communication can take the form of instructions but also technical support and training. The product itself is also a carrier of information. In addition, applying instruction and warning labels/signs is a common means to provide safety, one of the three basic principles of embodiment design[7] [Pahl & Beitz 1996, p. 217]. Products should be designed to provide information about their purpose and about the correct operation and intended use [ibid.].

Figure 4-4 shows the photograph of a rental bicycle[8]. The sticker (which translates to "No kickstand") was attached to all bicycles when shortly after the service was launched, many customers accidentally broke off this part – which is only an ornament but looks exactly like the actual kickstand mounted on the other side.

Figure 4-4 Warning sticker on a rental bicycle

[7] clarity, simplicity and safety
[8] www.call-a-bike.de

4.1.4 Summary of Interactions

Figure 4-5 summarises the interactions between *product attributes*, *stakeholders*, and *designers*, giving a graphical representation of the generic model of design-related product quality.

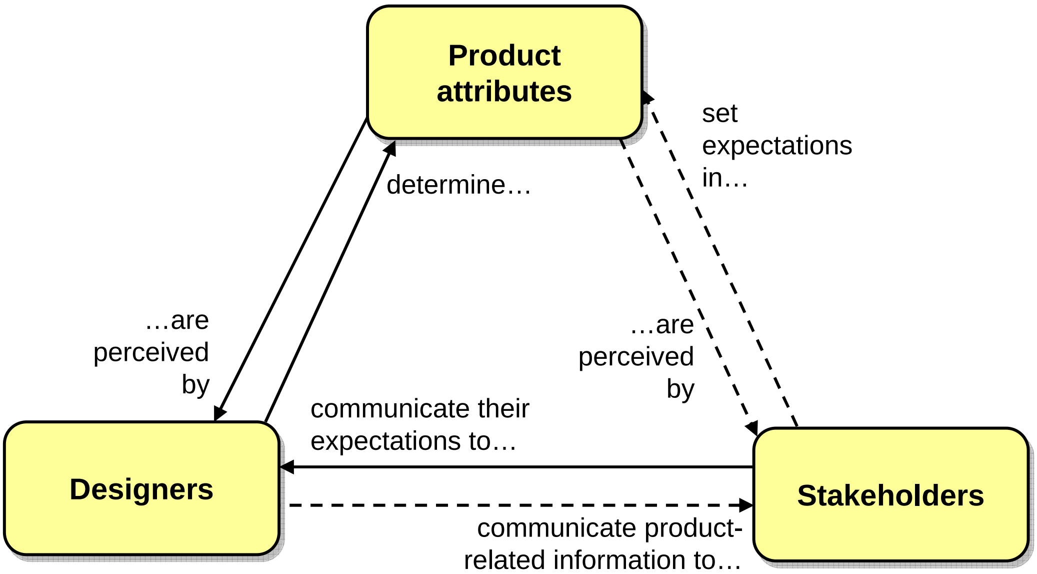

Figure 4-5 Elements and their interactions within the generic model of design-related product quality (solid lines indicate the focus of this research)

Internal or external stakeholders *set expectations in* certain product attributes. The way these product attributes *are perceived by* them – just like their expectations – is determined by their mental model which encompasses values, experiences and beliefs. Thus, the stakeholder's mental model not only tells him or her what to expect but also how and where to look for it.

By influencing product properties, designers (more or less directly) *determine* the product's attributes. These product attributes *are perceived by* the designers – however, due to different mental models not necessarily in the same way stakeholders perceive them.

In the model, it is assumed that stakeholders *communicate their expectations to* the designers. From this "voice of the customer", designers derive the requirements for a design project. Likewise designers *communicate product-related information to* the stakeholders, e.g. in the form of instructions, warning labels, trainings – and, of course, through the product itself.

4.2 Definition of a Design Flaw

Before a definition of a design flaw can be given, a (working) definition of product quality is required. In keeping with the generic model of design-related product quality introduced in this chapter, the following definition is used:

"Product quality is the degree to which perceived product attributes match with expected attributes"

Product quality is therefore described by the Stakeholder-Product domain of the model. As such, the above definition follows a user-based approach (cf. 3.1). However, it allows to give the following definition of a design flaw:

"A design flaw is a design-related product attribute that impairs product quality"

Thus, a design flaw is a design-related product attribute whose perception does not match the expectations of a stakeholder.

According to the above definition, product quality is determined by two (not mutually exclusive) factors: a) the mental model of the stakeholder which defines his or her expectations and b) the stakeholder's perception of the product attributes, i.e. the way in which the he or she makes sense of the product attributes in terms of his or her mental model (cf. 4.1.2).

Factor a) played a role in all examples of design flaws in chapter 2. In all cases, expectations in product attributes like e.g. X-ray visibility, scratch resistance, fire safety, etc. were disappointed. Two examples, in addition, demonstrate the influence of factor b). Some drivers of an Audi 5000 (see 2.5) experienced a level of safety that did not match their – justified – expectations. Similarly Ro 80 owners rightfully expected their car to accelerate faster while constantly driving in third gear. In both cases, the stakeholders' perception was incorrect as such as their mental model ascribed their experience to the product and not to their own behaviour.

4.3 Discussion

The generic model of design-related product quality proposed in this chapter provides the necessary framework for a definition and interpretation of design flaws. As all models, however, it can only deliver a simplified representation of some specific aspects of the phenomenon it tries to describe – or, to quote the British statistician George Box: "All models are wrong – but some are useful". Therefore, the model's limitations shall be addressed.

To begin with, it is of course not only designers that define a product's quality but also e.g. manufacturing, maintenance and also marketing [cf. e.g. Ulrich & Eppinger 2004, p. 3].

While it can still be assumed that design has the strongest leverage on product quality (see Figure 3-5) as all relevant product properties (and hence all product attributes) are defined at that stage, the question is: what is not a design flaw? In fact, and especially based on the model, this question is not too easily answered. Although exact figures are not available, experience shows that it is relatively hard to find quality defects which are positively, solely manufacturing-based. Even in these cases, one could (almost) always argue that better design could have prevented the manufacturing glitch, e.g. by ensuring that only the correct parts fit each other. Therefore, a per se distinction between design- and build quality[9] seems questionable.

By strict interpretation, the definition of a design flaw used in this thesis would exclude the possibility of intentional misuse or gross negligence by stakeholders. According to the definition of product quality in 4.2, quality can also be poor if expectations in product attributes are irrationally high or if their perception is impaired due to the ignorance of the stakeholders. Given a certain amount of common sense, however, these possibilities should – hopefully – not carry too much weight.

[9] as e.g. in the renowned annual "J.D. Power Initial Quality Study" of cars (www.jdpower.com/corporate/)

Notwithstanding its limitations, the model highlights certain aspects of product quality which, in the context of design flaws, need to be further explored.

The Stakeholder-Product domain of the model, as far as consumers and their expectations in and perception of product attributes are concerned, is well covered by marketing science. In companies, marketing probably also plays a more important role in communicating product-related information, especially to customers, than design does. Advertising, for instance, can be interpreted as an activity directed towards influencing the mental model of customers. Thus, design efforts to adjust the product's attributes to the expectations of the customers are often complemented by marketing efforts to adjust the customer's expectations to the attributes of the product.

In accordance with the design-oriented scope of this thesis, the following chapters will focus on three particular aspects of the generic model of design-related quality (see Figure 4-5):

1. How product attributes are perceived by designers
2. The manners in which stakeholders communicate their expectations to designers
3. The way designers determine the product attributes as a result of 1. and 2.

Both designers perceiving their products during product development as well as stakeholders voicing their interests in the product are aspects of design feedback which is the topic of chapter 5, especially when the cause of this feedback is a design flaw.

The last item on the above list motivates chapter 6 which deals with the question what limits the ability of designers to avoid design flaws.

5 Design Flaws as a Trigger of Design Feedback

5.1 General

Feedback, in its most general sense, can be defined as information about actions leading to "knowledge of results" [Busby 1997]. More specifically, it is a "process in which part of the output of a system is returned to its input in order to regulate its further output" [WordNet 2005].

The scientific concept of feedback has its roots in cybernetics, the science of the abstract principles of organisation in complex systems [Heylighen & Joslyn 2001]. It studies the communication and control (thus involving feedback) in systems of all kinds: e.g. physical, technological, biological, ecological, psychological, social and any combination of those (e.g. sociotechnical and economic systems).

Regardless of the system, two main types of feedback mechanisms are distinguished:

- *positive feedback* (the fed back input increases the output) and
- *negative feedback* (the fed back input decreases the output).

Bipolar feedback incorporates both effects, usually in order to keep the output on a desired level. Examples in which these feedback mechanisms are applied or can be observed exist in a number of areas (Table 5-1).

Table 5-1 Examples of feedback in different areas

Feedback \ Field	Engineering	Nature	(Organisational) psychology
Positive	Power steering	Greenhouse effect	Praise
Negative	Electromagnetic brake	Pupillary reflex	Blame
Bipolar	Cruise control	Predator-prey interaction	Training, coaching, customer surveys

In (organisational) psychology, feedback plays an important role in learning, communication and motivation, both of individuals and groups. As far as learning is concerned, feedback is closely linked to the concept of *reinforcement*. This key concept of learning theory describes a process in which the consequences of a behaviour influence the likelihood of its future occurrence. In this context, feedback by e.g. a superior or coach is an important carrier of reinforcement [Holling & Liepmann 2004]. In learning theory, feedback is sometimes distinguished as *intrinsic* or *extrinsic*. While intrinsic feedback is defined as the immediate result of an individual experience, extrinsic feedback incorporates some external event or communication with another person.

McKenna [2000] emphasises the importance of feedback together with active listening as a key factor in successful communication within organisations. To increase the effectiveness of the feedback process, Robbins [1991] suggests that it should be (among other things):

- **specific:** no general statements about the recipient's performance should be made; instead, feedback should relate to a specific behaviour or incident.
- **timely:** it has been found that the more recent the incident, the more likely it is that (both positive and negative) feedback will have an effect.
- **impersonal:** especially important when negative feedback is given, remarks should not be misinterpretable by the recipient in a way that he or she feels disrespected as a person.
- **goal-oriented:** whenever possible, feedback should relate closely to the goals the recipient has agreed to achieve.

Semmer and Udris [2004] implicate that feedback about goal achievement is essential for ensuring that the process of goal setting has a positive effect on performance and Holling and Liepmann [2004] state that the effectiveness of feedback is especially high when it is perceived and accepted as very precise. The acceptance depends on e.g. the perceived expertise, power and/or attractiveness of the feedback source.

Survey feedback is a popular organisational change and development technique designed not only to collect empirical data, but (after analysing and summarising it) to present the results to the individuals who took part in the process [McKenna 2000; Gebert 2004]. As a method for organisational development, survey feedback has been found to be helpful for management to understand what employees think about an issue and effective in building trust between both groups [Pasmore 1978 in McKenna 2000]. Furthermore, the motivation of organisation members, having dealt with their own situation as a part of survey feedback measures, is observably increased [several sources in Gebert 2004].

In accordance with the general findings of learning theory, feedback that is given too frequently can lose its effect or even be counterproductive as feedback recipients might stop reflecting their own behaviour [Holling & Liepmann 2004].

5.2 Feedback as a Part of Design and Product Development

5.2.1 Feedback as a Part of the Design Process

In design, there are many opportunities to obtain feedback, the more so as design is usually a team activity. In keeping with the above definitions and concepts of feedback, a lot of activities within the design process aim at gaining "knowledge of results" in order to regulate the "further [design] output".

The TOTE model by Miller et al. [1960], mentioned e.g. by Pahl and Beitz [1996] as a fundamental thinking pattern in design, is in fact a cybernetic model of problem solving through self-correcting feedback loops. The "Test–Operation–Test–Exit" sequence after which it is named is shown in Figure 5-1: after the initial state is analysed, the appropriate operation is performed. If a renewed test proves a satisfactory change of the initial state, the procedure is exited. If not, another operation is performed and the sequence repeated. More complex problem solving processes can be modelled by linking any number of TOTE sequences.

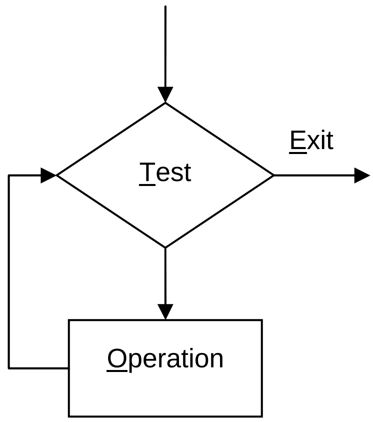

Figure 5-1 Flowchart of the TOTE model [Miller et al. 1960]

The Design-Build-Test cycle in (design) problem solving proposed by Wheelwright and Clark [1992] can be seen as an extension of the TOTE model applied to design. They emphasize that problem solving is an iterative learning process which follows the steps shown in Figure 5-2. After the problem is framed by identifying the gap between the current design and the targets, alternatives are generated and built. Note that the outcome does not have to be physical. The testing that follows can as well be performed with e.g. CAD models (or even take place by applying selection or evaluation methods on "paper" concepts). Upon evaluating the results, the cycle is either repeated or, if the goals are met, terminated.

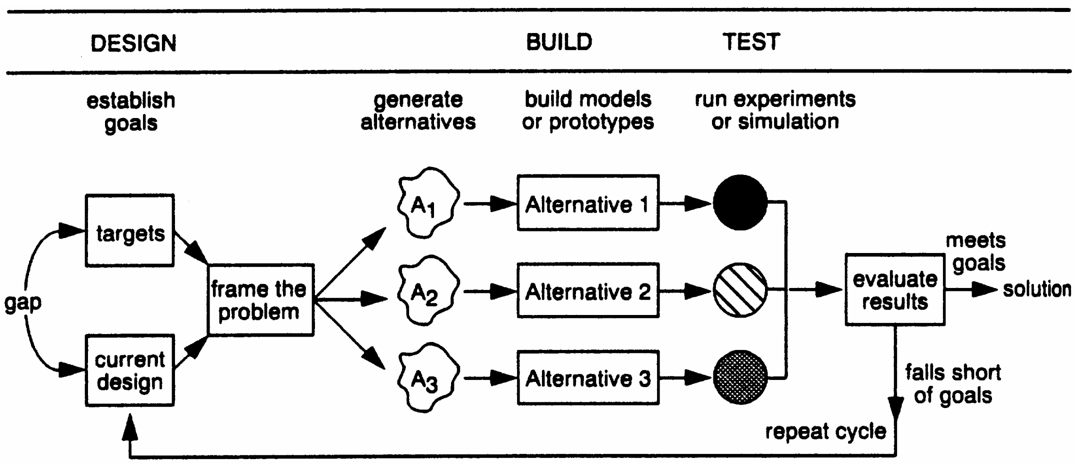

Figure 5-2 Feedback in the Design-Build-Test cycle in problem solving [Wheelwright & Clark 1992]

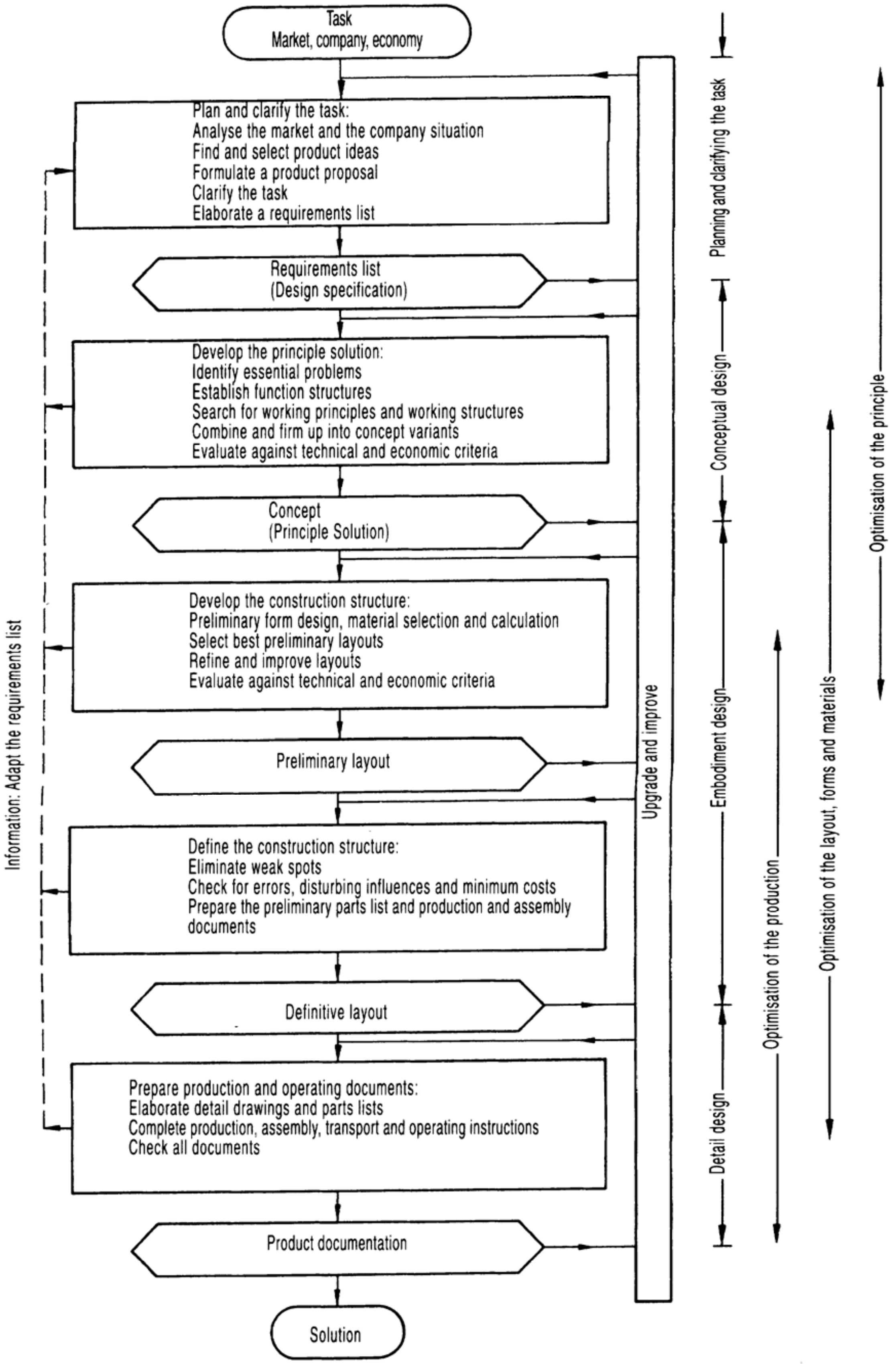

Figure 5-3 Feedback (dashed lines) during the process of planning and designing [Pahl & Beitz 1996]

On the scale of an overall design process, Pahl and Beitz [1996], describing the "flow of work during the process of planning and designing", emphasize that the requirements list, i.e. the outcome of the task clarification phase, needs to be continuously updated in the subsequent phases of conceptual, embodiment and detail design. This "information feedback loop" [ibid.], initiated e.g. in design review meetings, is shown as dashed lines in Figure 5-3.

5.2.2 Feedback as a Part of the Product Development Process

So far, feedback has been regarded in the context of the design process, i.e. the process that leads from an idea or a need to a product description. In this section, the scope is expanded to the product development process which also begins with an idea or a need, but also includes the necessary activities to launch a physical product. Thus, stakeholders like e.g. marketing and manufacturing come into play.

Designers might already have received feedback from these groups when applying intuitive methods for finding design solutions (e.g. Brainstorming, Method 635, or the Gallery Method) where including non-designers is in fact strongly encouraged [Pahl & Beitz 1996]. The same applies to the FMEA methodology (see 3.4.2). Now, these stakeholders are confronted with the (physical) outcome.

The involvement of company-internal stakeholders like marketing, sales, manufacturing, etc. is the core of approaches like simultaneous/concurrent engineering [Ehrlenspiel 2003] or integrated product development [Andreasen & Hein 2000].

According to Ehrlenspiel [2003], the (back) flow of information from functions like the above is a major rationale behind simultaneous engineering. He emphasizes that product development, in order to realise product attributes like safety, manufacturability, and environmental friendliness, cannot only be "feed-forward" in nature, but, where necessary, needs to consider feedback from stakeholders who might be better able to judge these attributes. A common means to obtain this feedback are design reviews where all stakeholders meet to assess the results thus far (usually, however, only internal stakeholders attend these meetings). Ehrlenspiel gives the example of a designer using CAD to define the product properties (i.e. sizes and distances) of a car interior. Using simulation techniques like Virtual Reality (VR), the product attribute of interest, spaciousness, can be assessed – also by other stakeholders.

Such short feedback loops, however, cannot always be realised. In practice, the situation is more like in Figure 5-4. The thick, grey arrows symbolise the forward flow of information necessary to develop a product. The thin, black arrows represent the information that is fed back from stakeholders like production planning, sales, service, etc. This feedback can be personal (consulting, teamwork, job rotation), paper-, or IT-based .

Ehrlenspiel states that ideally, this feedback is already present and considered at the design stage. If not, design flaws – i.e. the product not meeting the expectations of e.g. manufacturing, service or in the worst case: the end-user – are likely to trigger feedback which will become part of unplanned iterations [Ehrlenspiel 2003, p. 181].

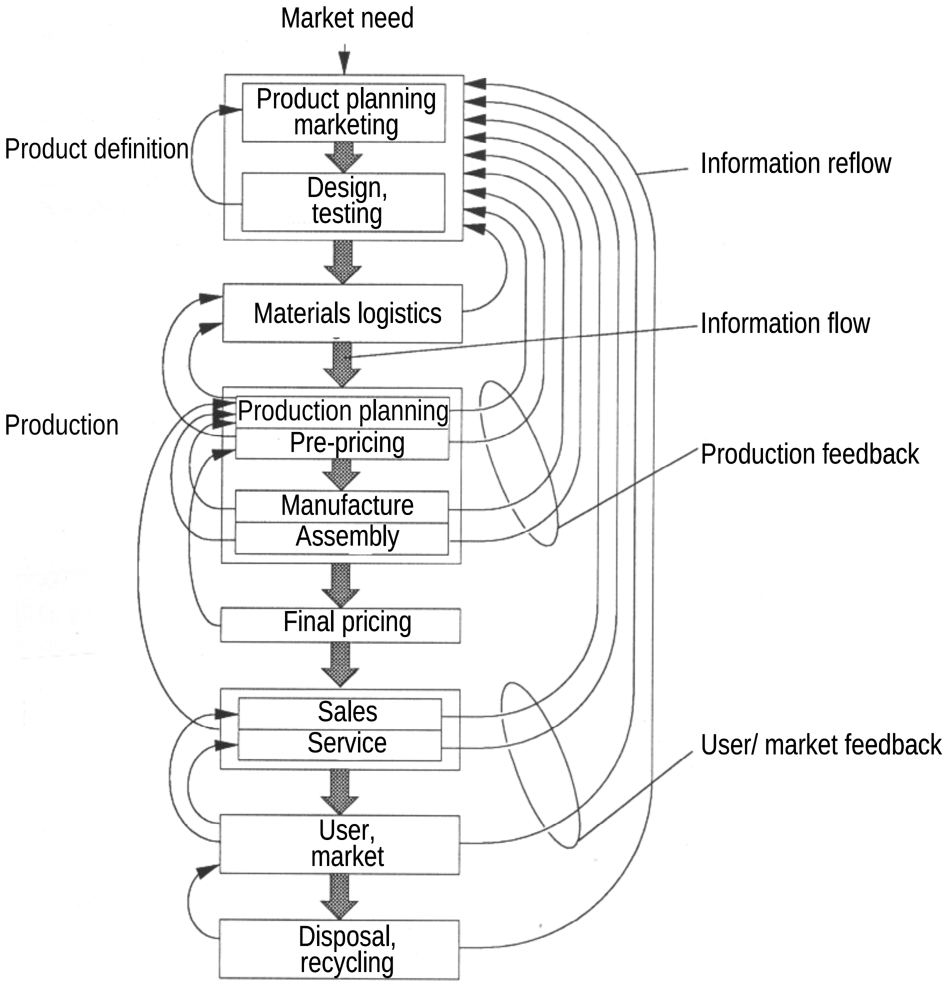

Figure 5-4 Feedback loops during and after product development [after Ehrlenspiel 2003]

Feedback from "downstream functions" is also a key success factor in the concept of "cross-functional integration" [Wheelwright & Clark 1992]. Figure 5-5 shows four different modes in which upstream (i.e. design) and downstream (e.g. manufacturing) functions can interact.

Mode 1 represents a strictly sequential processing of activities (like – unintentionally – implied in Figure 5-4). In Mode 2, the downstream group begins its work concurrently with the upstream group but has no information about the design until the very end of the upstream process. Design only receives feedback in modes 3 and 4. The major difference between the two modes is that in mode 3, designers receive feedback that is based on general knowledge and engineering judgment of e.g. manufacturers, whereas in mode 4, in which upstream and downstream functions communicate *and* work simultaneously, the feedback that designers receive may be related to real and current issues. For instance, designers could learn that the design of a part *could* cause problems with manufacturing (mode 3) or that it *does* cause problems with manufacturing (mode 4).

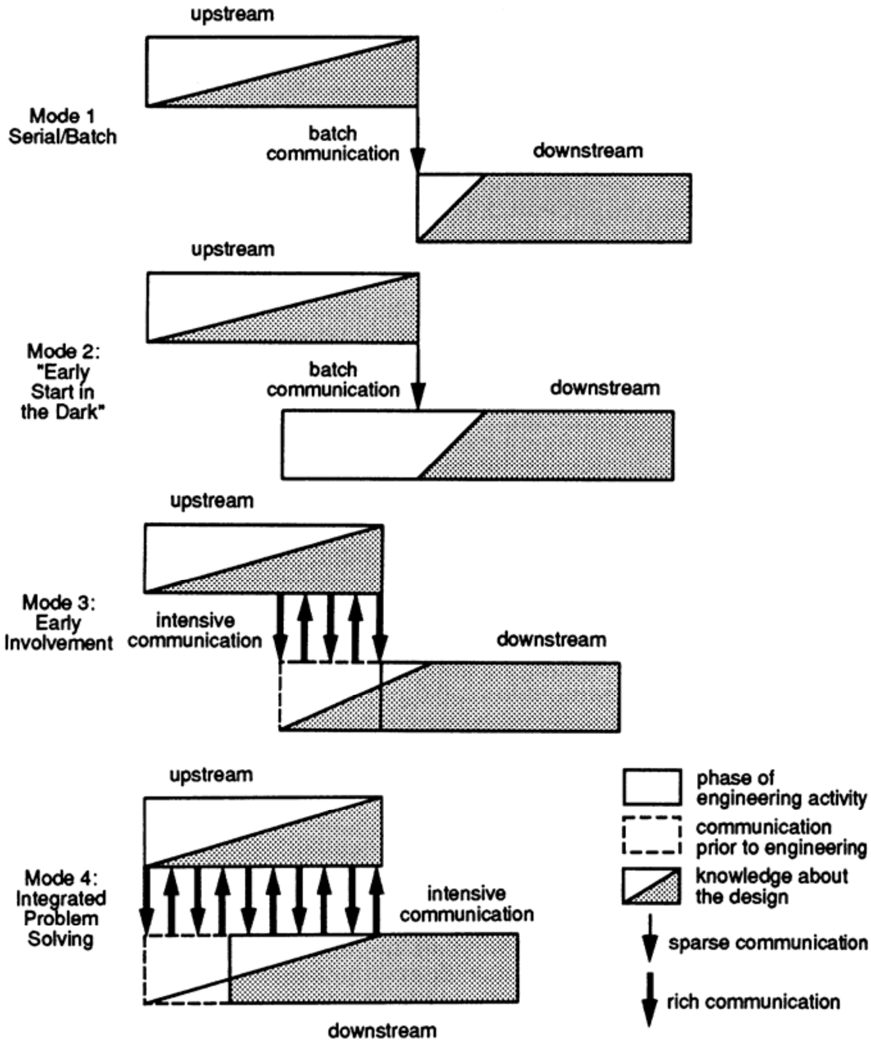

Figure 5-5 Communication between downstream to upstream functions in different modes of cross-functional integration [Wheelwright & Clark 1992]

The integration of external stakeholders – i.e. customers and users – in the product development process is usually achieved by a closer cooperation of design and marketing. However, Reinicke [2004] has proposed a methodology of directly integrating potential users of the product in design activities like task clarification, idea generation, embodiment, evaluation, etc. Thus, her user integration framework goes beyond mere concept testing.

In concept testing, as described by e.g. Ulrich and Eppinger [2004], a response from potential customers[10] in the target market is solicited e.g. to gather information as to how to improve a product concept or which of two or more concepts the company should pursue. It can be done at different levels of concept concretion, ranging from verbal descriptions to fully functional prototypes.

Concept testing is therefore closely related to prototyping which the above authors define as "an approximation of the product along one or more dimensions of interest". These dimensions can be visual appearance, performance, functionality and so on. Wheelwright and Clark [1992] emphasize the importance of prototypes because they provide an opportunity for

[10] not necessarily users as in [Reinicke 2004]

feedback and learning: “As a result of that feedback, individual functions as well as the broader organization can learn the degree to which choices made thus far are likely to achieve the intended results, what refinements still need to be made, and what work remains for project completion”.

5.2.3 Studies of Feedback in Designing Organisations

The study of Schmidt-Kretschmer, Gries, and Blessing [2006] supports the above statement by Wheelwright and Clark [1992], particularly in terms of necessary refinements. They analysed the amount of feedback that was given during a specific product development process by accumulating the entries into the used error-tracking system over time (74 weeks). While there was relatively little feedback in the early phase, it surged at the moment prototypes of the product became available.

Ehrlenspiel [2003] analysed the communication flows between the members of a development project for a heating device. The project lasted 57 months. In its final phase, each member was asked to log all conversations they had over a period of two weeks. The logs contained the time, duration, cause and partner of the conversation. Figure 5-6 illustrates the result for the indicated team member, in which

- the width of the arrows represents the total duration of all conversations,
- the direction of the arrows shows who initiated the communication and
- the numbers next to the arrows specify the total number of conversations held.

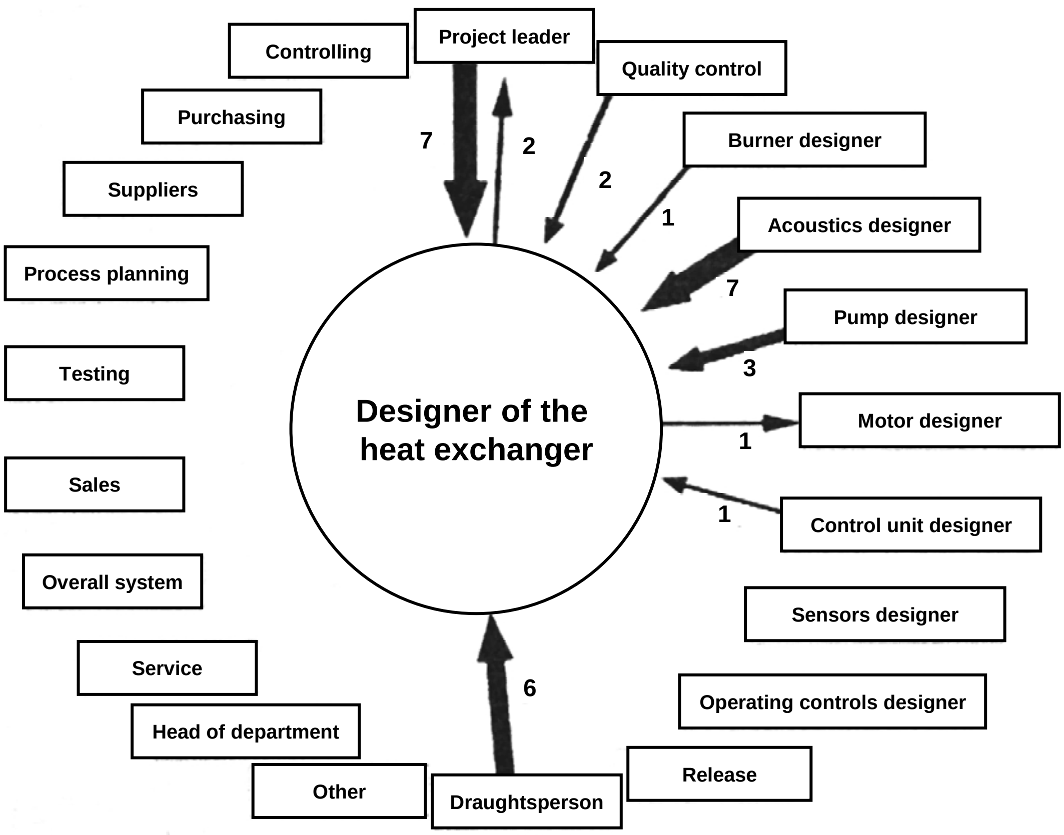

Figure 5-6 Communication flow between team members from the perspective of one designer [after Ehrlenspiel 2003, p. 169]

Most of the time, the designer in Figure 5-6 received feedback. Interestingly, it was found that this individual's reluctance to initiate any communication kept his colleagues' willingness to give feedback to a minimum. Had he been more eager to share his information, he would have benefited by receiving even more feedback in turn.

Some of the most extensive studies of feedback in designing organisations have been conducted by Busby [1997; 1998]. His research took place in five companies with between 30 and 300 staff that developed and manufactured offshore industrial equipment. The data was obtained from interviews with individual designers as well as focus groups involving staff from other functions and verbatim transcripts of post-design reviews. It was, however, purely qualitative in nature. The studies were based on the following considerations.

Design affects individuals in- and outside a company. Usually, there is little chance for designers to get a picture of these effects. Depending on the product, there may be long delays between designing it and seeing it in use. Also, as companies grow, they develop structures that distance designers even more from the outcome of their work (e.g. product support departments) in seeking a balance between competing effects: being sensitive to stakeholder needs but not being distracted by claims that are illusory or transient.

Busby's two key findings were that

- most of the feedback designers received was ineffective partly because the communication channels used were unreliable and that
- negative feedback predominated which lead to dissatisfaction among designers and discouraged any feedback-seeking behaviour[11].

When feedback was given, it often happened that non-designers proposed specific design changes instead of describing the actual problem. In doing so, communication channels were used that disregarded the preferences of most designers who favoured e.g. e-mail.

Busby states that on the whole, feedback is more a motivational than an informational issue also as – according to his observations – the absence of data on products in use was seen as a problem of lower significance. In summary, he concludes that problems with feedback arise from:

- limitations of individual performance,
- defects in organisational design,
- the characteristics of the task structure and
- the common misbelief that feedback is feed-forward by nature.

5.3 Design Feedback After Product Development

Companies continue to obtain feedback about their products even long after the product development process is completed. While these channels are normally not seen in a design context, they are a potentially valuable source of information whether certain quality targets have been met or not.

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[11] cf. the behaviour of the designer in Figure 5-6

5.3.1 Watchdog Organisations

In the EU, the General Product Safety Directive 2001/95/EC (GPSD) aims at protecting both consumer health and safety from risks posed by non-food products. Under the GPSD, measures to be taken by member states include imposing conditions prior to the marketing of a product, requiring that a product be marked with warnings concerning any risks, banning temporarily or definitively the supply, the offer to supply or the display of a product and ordering producers and distributors to withdraw a product, recall it from consumers and destroy it. All these measures shall be taken in close cooperation with manufacturers and distributors. To help enforce the GPSD, 'RAPEX'[12], the Rapid Exchange of Information System has been installed [EU 2005].

In the US, the mission of the Consumer Product Safety Commission[13] is to protect the American public from "unreasonable risks of serious injury or death from more than 15,000 types of consumer products under the agency's jurisdiction". The commission develops voluntary standards with industry, issues and enforces mandatory standards and bans consumer products, if necessary. In 2005, the CPSC, in cooperation with the manufacturers, initiated 397 product recalls involving 67 million product units [CSPC 2005]. Organisations with similar authority but different target products include the National Highway Traffic Safety Administration (NHTSA), the Food and Drug Administration (FDA) and the Federal Aviation Administration (FAA). (Note the role that the first two organisations have played in the examples in chapter 2).

Therefore, companies selling their products in the European Union, the United States (or in fact most industrialised countries) have a reasonable chance of receiving feedback from any of these watchdog organisations if their products are flawed in a way that they pose a safety risk.

Independent non-government and non-profit consumer organisations like Stiftung Warentest[14] in Germany, or Consumers Union[15] in the US test and compare hundreds of consumer products each year and make the results accessible to the consumers through their own publications. Notably, as part of Stiftung Warentest's testing process, results are always fed back to manufacturers prior to publication to give companies the chance of verifying the results and giving a comment.

5.3.2 Market Research and Customer Complaints

Similar to the abovementioned non-profit organisations, marketing research companies also gather data on product quality, but usually by means of customer feedback. They are either commissioned by client companies or conduct their research independently, selling the results to interested firms in the target industry sector (syndicated research). A quite eminent example for the latter approach is J.D. Powers and Associates. This firm is probably best known for its car customer satisfaction tests in the US and UK. Via online surveys, owners of

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[12] ec.europa.eu/consumers/dyna/rapex/rapex_en.cfm
[13] www.cpsc.gov
[14] www.stiftung-warentest.de
[15] www.consumersunion.org

about 130 different cars can voice their opinion and give ratings on a whole range of criteria. Based on this data, studies like the “Initial Quality Study” or the “Vehicle Dependability Study” are published to companies (but not the general public).

In general, customer surveys, when related to a product as above, can be seen as an active solicitation of design feedback by the company. However, most current literature deals with them mainly as an instrument to measure customer satisfaction, focusing on services rather than products [see e.g. Gerson 1993; Hayes 1998]. Ofir and Simonson [2001] observe that “Indeed, customer satisfaction measurement is today perhaps the most common type of marketing research performed by companies.” However, in their study the authors point out that customers suspecting that they will be asked to participate in a survey (which has become increasingly common, e.g. when staying at a hotel or buying car) are strongly negatively biased. By and large, however, customer satisfaction surveys exhibit a clear positivity bias [Peterson & Wilson 1992].

Unlike customer surveys, which are “perhaps best characterized by their lack of definitional and methodological standardization” [ibid.], customer complaints can be regarded as a valuable source of unsolicited (and therefore much less “filtered”) feedback [Barlow & Møller 1996].

Goodman [1999], in summarising the findings of his previous studies, states that for large ticket items (e.g. a PC or a car) on average 50% of consumers will complain to a front line person (e.g. the car dealer), but only 5%–10% will escalate their complaint to a corporate level (e.g. the car company). While problems that result in monetary loss lead to higher (front line) complaint rates (up to 75%), poor quality of a product only accounts to a likelihood of between 5% and 30%.

Wirtz and Tomlin [2000] propose the concept of an integrated customer feedback system (CFS) to systematically gather, analyse and disseminate various types of feedback. This system consists of the following elements:

- service indicators, standards and performance targets
- feedback collection tools and feedback process management
- a reporting system
- a service recovery system
- an IT system
- a team learning system
- an effective organisational structure (also within the overall company)

Concerning the last element, the above authors point out that the most effective organisational structure for managing a CFS is a centralised customer feedback unit (CFU) acting as the “owner” of the system. Such a CFU does not have to be large; Wirtz and Tomlin have successfully implemented such an unit in an organisation with around 2,000 employees which consisted of one manager and one support staff.

5.3.3 Internet Communities

In recent years, Internet communities have attracted the attention of companies as they offer an inexpensive opportunity to obtain feedback about their products that is less obtrusive than customer surveys and at the same time not necessarily as negatively biased as complaints. The latter, of course depends whether e.g. a web site is thought of as a "fan-club", a (neutral) source of customer information or even a means of "customer revenge" as highlighted by Prosser [2007]. In connection with the design flaw of the iPod nano (see 2.3), angry users created the web site www.scratchedipods.com which was, however, eventually closed down due to legal pressure from Apple.

Already in the mid-1990s, Finch and Luebbe [1997] studied the conversations of subscribers to a listserve[16] about fly fishing, also discussing the potential of this (indirect) feedback to e.g. improve the design of fishing rods. The current phenomenon of "blogging" offers interesting chances of building communities between companies and users. Turcotte et al. [2005] have found in their study that corporate blogs offer a unique possibility to collect valuable feedback. They observe a "viral effect": companies that utilise the knowledge that they gain from their blogging activity are better able to satisfy the needs of their user community which in turn appreciates it by participating more actively.

Sawhney, Verona and Prandelli [2005] investigated how the Internet can serve as a platform for collaborative innovation with customers. They contrast the traditional perspective of customer/user integration in product development (cf. 5.2.2) against what they see as the emerging perspective of co-creation facilitated by the Internet. The authors outline a variety of Web-based mechanisms for customer collaboration and propose a framework for classifying these mechanism in terms of the nature of the collaboration and their applicability in the new product development process (NPD). They conclude that while the potential that the Internet offers is promising, there is still a need for systematisation as well as for adapting and integrating processes like marketing, customer relationship management and support.

5.3.4 Product Diagnostics

Several approaches exist to obtain feedback by diagnosing products during or after their use phase. Edler [2001] proposes a framework for utilising field data in product development and service. He defines field data as all data that is generated in connection with the use of the product by the customer, e.g. operating hours, downtimes, fuel consumption, etc. The "Life Cycle Unit" developed by Grudzien [2002] would solve some of the technical challenges of obtaining that field data although its purpose is rather to facilitate disassembly and remanufacturing. As the latter has been identified as "[…] another opportunity for the collection of product failure data […] which can lead to improved design for future new unit production." [Haynsworth & Lyons 1987], the implications for design processes exploiting information from disassembly as part of product recycling have been discussed in [Gries & Blessing 2003].

[16] Basically a mailing list where replies to a mail are usually sent to all subscribers; the predecessor of web-based user forums.

5.4 Discussion

In this chapter, it was shown that design, design flaws and feedback are closely related – not only as design involves problem solving (and thus learning) but also intensive communication with stakeholders in and outside the companies.

In theory, design feedback fulfils three major criteria for effective feedback in general as it is specific, impersonal and goal-oriented (see [Robbins 1991] in 5.1). Design feedback is specific because it relates to some property or attribute of the product being designed. In that manner, it is impersonal as well. Also, it is goal-oriented as all designers adhere to the goal of creating a product. In practice, however, the effectiveness of design feedback – especially when triggered by design flaws – is challenged by the following issues:

An immediate issue is the timeliness of design feedback. As a general principle, feedback will loose its effectiveness when it is given too late [Robbins 1991]. However, many (if not most) design flaws are detected after the design process is completed in which case the design team might have been disbanded.

Also, there is the danger of "finger pointing". Hales and Gooch [2004] observe: "When an engineering failure occurs, and the excitement over 'what broke' dies down, the hunt for who to blame and who is going to pay becomes a main focus." Hence, design feedback can be all but impersonal, the more so in connection with (supposed) design flaws.

Finally, there is a challenge inherent to the process of designing: any design feedback, whether positive or negative, needs to be interpreted in a way that designers can adapt their "output", i.e. their ability to modify the product attributes according to the feedback. This means that – in case of feedback about a design flaw – learning that a certain product attribute is undesirable not necessarily provides any insight into how to fix the problem.

As has been shown in 5.2, a common method to obtain design feedback is the integration of internal and external stakeholders in the design process. While this feedback is important, it is different from unsolicited feedback, especially in connection with design flaws. By integrating stakeholders in the design process, designers might profit from the expertise and experience of these groups. However, as long as the product still does not exist, any feedback about its flaws will be of limited use. Some design flaws can only be assumed and not all flaws might be identifiable.

Therefore, tapping the potential of unsolicited design feedback about products in use is vital. As Wheelwright and Clark [1992, p. 21] observe: "Additional time to secure feedback on the most recently introduced generation and to learn about market development and emerging customer preferences may mean the difference between winning and mediocre products".

As pointed out in 5.3.2, many companies actively solicit feedback from their customers, e.g. by means of surveys. Most research in this area focuses on how to measure the satisfaction with a product. However, (solicited) feedback about low satisfaction with a product can only be the starting point for the search for any design flaws.

Alas, unsolicited feedback about design flaws is basically a complaint and therefore tends to be regarded as unwelcome by most companies. Whether design consequences are drawn or not, the reaction to sue consumer rights group when they identify design-related quality defects, while comprehensible from the perspective of (reputation) damage control[17], illustrates how delicate this issue can be.

Another challenge inherent to complaints about design flaws is that there is little that a company can do right away to correct it in following what is considered good practice in complaint management [Barlow & Møller 1996, p. 52]. From that perspective, ironically, companies – having the chance to improve the design of their product – would benefit more from complaints than the customer who might have to keep using the product unless the design flaw constitutes a warranty case or can be remedied by a software upgrade.

In conclusion, research on design feedback – especially when triggered by design flaws – is fragmentary. Although the issue of feedback is recognised in many models of designing (see 5.2.1 and 5.2.2), little is known about unsolicited feedback about products on the market. Although literature about customer satisfaction and complaints exists, it does not deal with the design-related issues of this phenomenon. The studies consulted in 5.2.3 dealt with design-feedback that was not necessarily related to design flaws and came from company-internal stakeholders. It is also unclear to what extent the results are representative of other products and companies.

Hence, more research is needed to explore the nature of design feedback in terms of

- who exactly is giving and who is receiving feedback,
- which channels are used to communicate feedback to the designers of the products and
- how these issues are connected to the design flaws.

[17] Goodman [1999] has shown that twice as many consumers tell others about a bad experience than about a good experience.

6 Design Flaws as a Result of Design Failure

6.1 General

In chapter 4, a design flaw has been defined as a design-related property of a product that impairs its quality if quality is defined as the degree to which expected product properties match with perceived product properties. In chapter 5, the importance of obtaining feedback in design has been discussed, looking at the relationship between designers and stakeholders. The focus of this chapter is on designers and the process of design itself, elaborating on a fundamental notion of this thesis: that a design flaw is the result of a design failure – i.e. the failure to achieve a sufficient level of product quality.

To understand the phenomenon of design failure, it suggests itself to look at what is usually seen as design success. Throughout literature, the common view is that a successful design process is one that leads to a successful product. [Blessing 1994] contains an extensive overview of descriptive studies that have investigated the correlation between a product's success and the various influences on its design process. The success measures of these studies are, by and large, market success and the product's quality (however especially the latter may be defined). Ulrich and Eppinger [2004] argue that the ultimate goal of product development is profitability. They suggest product quality and cost as well as development time, cost and capability as related dimensions. The authors in [Wheelwright & Clark 1992] define the success of product development projects according to the performance measures given in Table 6-1.

Table 6-1 Performance measures for development projects [after Wheelwright & Clark 1992]

Performance Dimension	Measures	Impact on Competitiveness
Time-to-market	• Frequency of new product introductions • Time from initial concept to market introduction • Number started and number completed (actual vs. plan) • % of sales coming from new products	• Responsiveness to customers/competitors • Quality of design - close to market • Frequency of projects - model life
Productivity	• Engineering hours per project • Cost of materials and tooling per project (actual vs. plan)	• Number of projects – freshness and breadth of line • Frequency of projects – economics of development
Quality	• Conformance – reliability in use • Design – performance and customer satisfaction • Yield – factory and field	• Reputation – customer loyalty • Relative attractiveness to customers – market share • Profitability – cost of ongoing service

Quality, as expressed by the measures given above, is seen as one of three performance dimensions. As pointed out earlier, the quality of a product mainly depends on its design.

So if design success is determined by the level of quality that a product achieves, it is reasonable to argue that lacking quality is a sign of design failure.

6.2 Characteristics of the Design Context

One central question to be discussed in this chapter is: What influences the likelihood of design processes to fail in a way that the resulting products may be flawed? The influences on the design process as a whole are commonly referred to as *design context*. Figure 6-1 shows the generic process model used to describe the characteristics of design in [Blessing 1994]. The model centres around the *design process* which consists of *stages*, *activities*, and *strategies* that transform a *problem* into a *full product description*. In this model, it is the *environment*, the *organisation* and the *designer* which define the context on a macro- and microeconomic, corporate, project and personal level respectively.

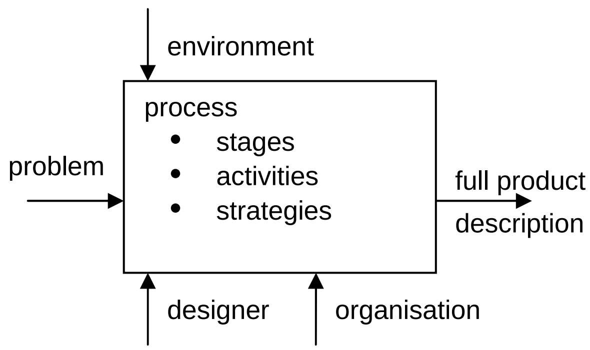

Figure 6-1 Generic process model of design [Blessing 1994]

Similarly, Hales and Gooch [2004] see influences on different levels of resolution (Table 6-2). Each of these 23 influences is characterised by individual contributing factors (not listed here) so that the overall design context is described by a total of 98 of these.

Table 6-2 Influences on the design process on different levels of resolution [Hales & Gooch 2004]

Level of resolution	Influences
Macroeconomic	culture, science, random influences
Microeconomic	market, resource availability, customer
Corporate	corporate structure, corporate systems, corporate strategy, shared values, management style, -skill and -staff
Project	design task, -team, -tools and team output
Personnel	knowledge, skills, attitude, motivation, relationships and output

However, the above authors regard the *design task* – the closest equivalent to the *problem* in Blessing's model – as part of the design context, being an influence on project level (see Table 6-2). As such, they characterise the design task using (organisational) *magnitude*, (technological) *complexity*, *novelty*, *production quantity*, *technical risk*, and *urgency* as contributing factors.

Badke-Schaub and Frankenberger [2004] state that the engineering design process is subject to influences from the task, the individual, the group and the environment (Figure 6-2).

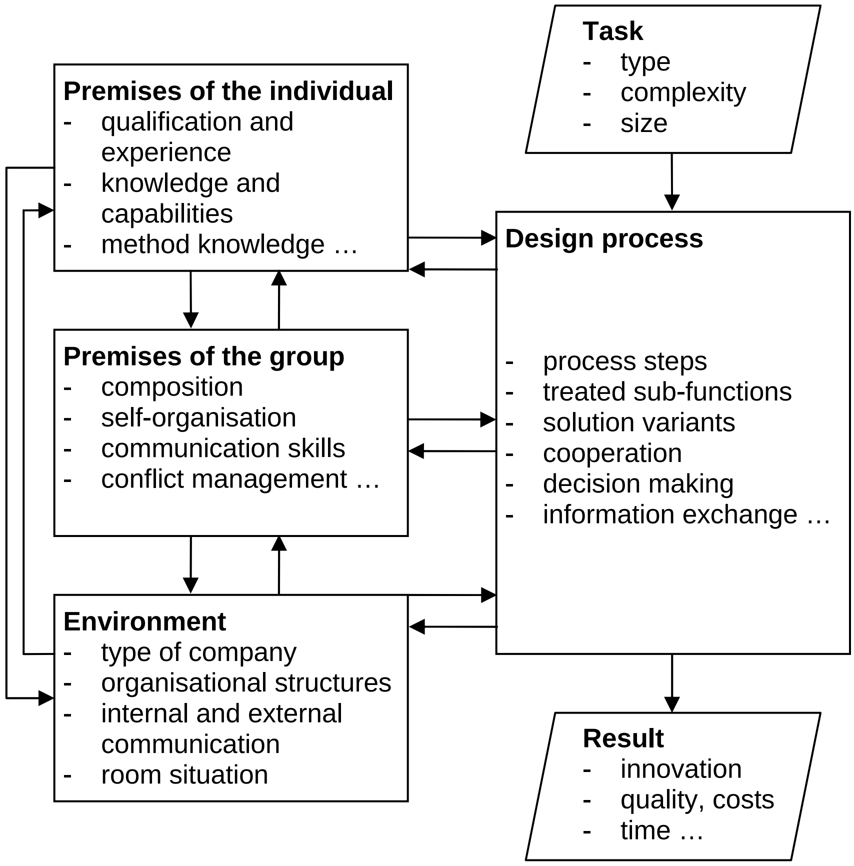

Figure 6-2 Influences on the design process after [Badke-Schaub & Frankenberger 2004]

Regardless of how authors describe the design context, i.e. the sum of influences that act upon the design process, those who participate in this process perceive it as complex, dynamic and intransparent [Gries & Blessing 2006]. These characteristics (see also [Bender 2004] and [Schroda 2000]) shall therefore be discussed in more detail below, whereas the issue of human factors is addressed in section 6.3.

6.2.1 Complexity

Depending on the scientific discipline, there are different definitions of complexity. Probably the most general one would be that complexity is the property of a system or a model that makes it difficult to understand as a whole. Pahl and Beitz [1996] describe complexity in (design) problem solving as the existence of many differently interrelated elements. Considering that problem solving is only part of design and, as pointed out before, there are up to nearly 100 different factors contributing to the various influences on design [Hales & Gooch 2004], it becomes clear that design is indeed complex.

Today's design processes are more complex than ever due (but not limited) to the factors addressed in the following.

1. Newly Available Technologies and Tools

The spectrum of technical solutions to a specific design problem that designers have to consider is continuously becoming larger. An example are LEDs which, due to their improved light output and newly available colours (especially white) have become increasingly popular in areas ranging from domestic lighting to the automotive sector, where they will soon be usable in headlights. With the advent of mechatronics, which is "[…] not a distinctly defined, and hence separate, engineering discipline but is an integrating theme within the design process" [Bradley et al. 1991], many product functions that were formerly based on purely mechanical solution principles are realised today by a mix of mechanics, electronics and software (e.g. fly-by-wire control of airplanes).

The same applies to the – nowadays usually IT-based – design tools. While progress has been made in terms of making the systems more user-friendly, the sheer feature list of a modern parametric 3D CAD application can be intimidating. The increased importance of industry- or even company-specific third-party add-ons for e.g. machining, moulding or cabling has lead to the consequence that new designers, while being proficient in the base CAD software[18], need to be trained in the use of the add-ons.

Also, as design research progresses, there is an increasing number of available methods and methodologies. While many of these certainly mean (or mean to be) a progress in terms of effectiveness and efficiency of certain design tasks, retaining an overview becomes increasingly difficult. As a consequence, supporting designers in providing them with the right methods at the right time seems to have become a little discipline of design research of its own – see e.g. [Zanker 1999; Bichlmaier 2000; Ponn & Lindemann 2005], [Meißner et al. 2005], or [Meißner & Blessing 2006a; b; c].

2. Design Processes Becoming More Interdisciplinary and More Distributed

Approaches to design like simultaneous/concurrent engineering, integrated product development, etc. all mark a renunciation of what could be called "Design Taylorism", i.e. the division of a task into smaller subtasks that departments handle successively – the common design process until the 1970s [Hales & Gooch 2004]. As already discussed in 5.2, today it is common that designers are required to collaborate with, e.g. manufacturers, marketers, psychologists and software developers. Ulrich and Eppinger [2004] describe a typical mix of disciplines as illustrated in Figure 6-3.

[18] which, given the number of different systems available on the market today, cannot be taken for granted

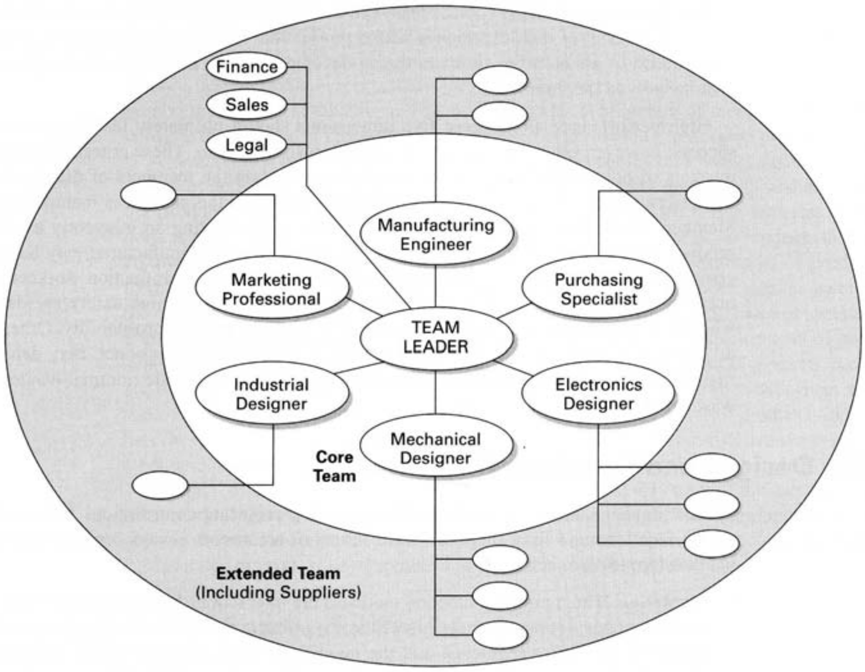

Figure 6-3 Typical composition of a product development team for a modestly complex electromechanical product [Ulrich & Eppinger 2004]

As Figure 6-4 shows, the development departments of many companies are no longer dominated by mechanical engineers. Instead, specialists with a background in new areas, e.g. electronics and software, have joined the team.

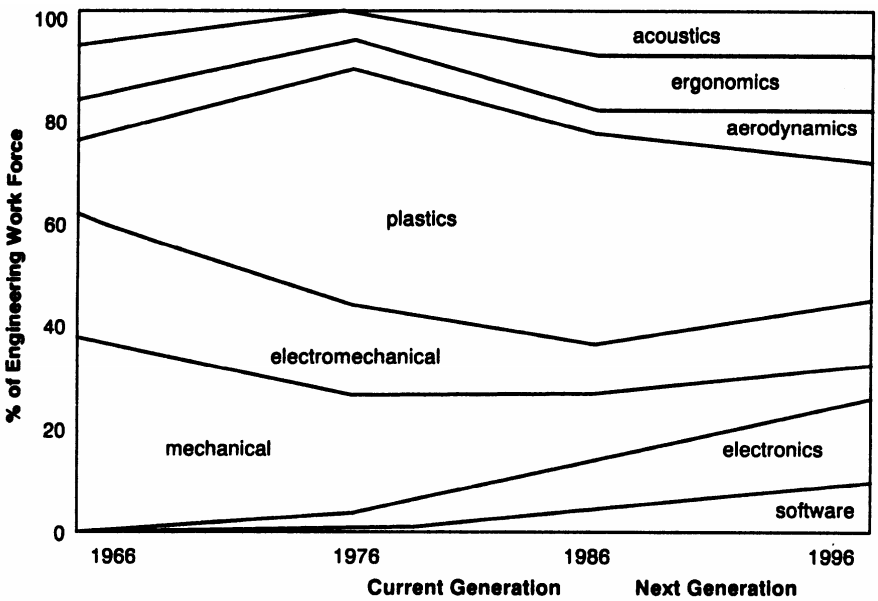

Figure 6-4 Distribution of engineering disciplines in the design department of a manufacturer of vacuum cleaners [Wheelwright & Clark 1992]

In recent years, the supplier landscape, especially in the aerospace and automotive industry, has shifted dramatically as original equipment manufacturers (OEMs) are outsourcing more and more of their development activities. Suppliers that a few decades ago manufactured only parts or assemblies (e.g. gearboxes) to the specifications of the OEM, today develop whole systems (e.g. complete drivetrains). While the OEMs are “relieved” of that task, their designers need to collaborate more closely with their external counterparts than in the past.

As a result of globalisation, design teams are increasingly often distributed around the world. Therefore, designers working on the same project may have to do so in different countries and in different time zones. Effective communication and collaboration not only requires special tools but often also intercultural skills.

Baumgärtner [1999] analysed 60 cases of collaboration projects between engineering consultants and their German, Indian and Italian clients in the automotive industry. He found that the most important characteristics of successful collaboration projects relate to experience in terms of the relationships between the parties, to the understanding of the culture and to the project goal definition.

3. Increased Product Diversity

To better meet market demands, the product portfolios of many companies have become increasingly diverse in recent years. This development was largely made possible by the use of platform and family strategies. Fiil-Nielsen et al. [2005] define *product platforms* as “the scheme by which companies consciously aim to introduce one or more families of products, while utilizing the commonalities within these families for mass-production.” A *product family* is therefore the instantiation of a product platform. The authors point out that developing and implementing product platforms is still a complex task as a trade-off between commonality and variety of the necessary product modules needs to be found.

Mortensen et al. [2005] identify six levels describing the platform character of product development projects. At the lowest level, companies develop each product independently, making no formal decisions as to any platform architecture whatsoever. At the highest level, an integrated development of not only the architecture, but also of related business processes takes place.

4. Extended Scope of Design

Another factor that has added to the complexity of design processes is that today, apart from ensuring function, quality and costs, designers also have to consider aspects such as social values and environmental issues. A strategy to meet this challenge, which has lately attained a lot of attention by academia and industry alike, is the concept of product/service-systems (PSS) [McAloone & Andreasen 2002; Matzen et al. 2005; Matzen & McAloone 2006].

A PSS aims at changing business models from being based on selling physical products alone to offering a combined product/service, thus providing value to the customer [Matzen et al. 2005]. Thereby, the company retains ownership of the physical product while providing the customers what they really want: the actual functionality of the product [McAloone & Andreasen 2002].

However, McAloone and Andreasen [2002] conclude: “The broadening of scope of both the development task, the relationship to the physical artefact and to the business, increases the complexity of the product development process immensely and calls for new competencies in product development.”

6.2.2 Dynamics

In systems theory, the dynamics of a system describe its temporal behaviour. Persistent changes to the design context (e.g. the elements that contribute to the complexity of design discussed above) are a normality in industry. Since design is normally a team activity, these changes happen with or without the individual designer's participation, making it a highly dynamic process [cf. Ulrich & Eppinger 2004, p. 6]. What furthermore adds to the dynamics is time pressure due to a fiercer competition and shorter development cycles[19].

Taking a more business-oriented perspective, Wheelwright and Clark [1992, p. 29] describe how evolving technologies, markets and legislations represent "moving targets" for product development. Focusing on new but immature solutions (as well as ignoring technological trends), wrongly predicting market developments or overlooking legislative changes has put many development projects in trouble. In that case, the problems compound themselves, as projects begin to "drift" in order to meet the targets.

6.2.3 Intransparence

In design, it is typical that decisions have to be made without all necessary information being available. When, for example, different solution variants are evaluated, many of their properties (not to mention their attributes) are only estimated or even unknown. Knowing that the situation is intransparent makes decisions difficult, whereas greater danger might lie in designers not being aware of any intransparence, i.e. "not even knowing that they do not know" all they need to make a reasonable decision.

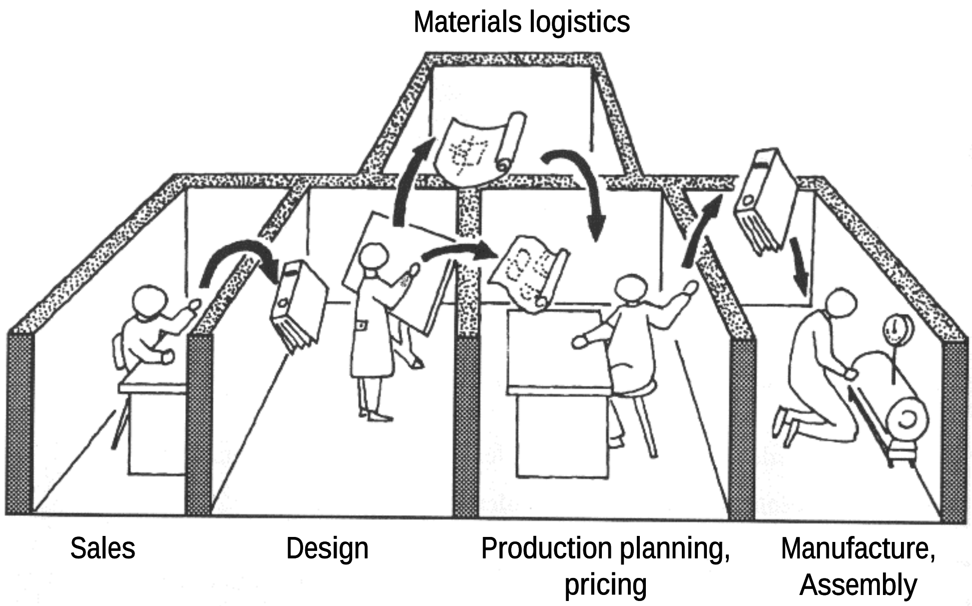

Figure 6-5 "Over-the-wall" approach in product development after [Ehrlenspiel 2003]

Organisationally, the situation in many companies is similar to the situation depicted in Figure 6-5. Following an "over-the-wall" approach, members of e.g. sales, design, production

[19] See [Blessing 1994, p. 86] for a review of research on the influence of time pressure on designers.

planning, materials management, and production, have no insight into the activities of the others, creating an environment in which designers are unlikely to receive useful design feedback – at least timely (see also Figure 5-5).

6.3 Human Factors in Designing

In this section, a closer look shall be taken at the factors that influence the individual capability of those involved in the design process to deal with its complexity, dynamics and intransparence. This look is taken not so much from the perspective that these human factors (e.g. knowledge, skills and experience) are *part* of the design context, but rather the personal requisites for consisting in it.

Wheelwright and Clark [1992] identify technical, organisational, and commercial skills or knowledge that not only designers but also (executive) managers should have in order to turn product development projects into a success (see Table 6-3). At all hierarchical levels, the importance of education and training but also leadership is emphasized. The authors stress the need to provide training of design methods not only on project- or team leader level but for all team members.

Table 6-3 Skill and knowledge requirements for successful product development after [Wheelwright & Clark 1992, p. 331]

Development participants	Skill or knowledge requirements		
	Technical	Organisational	Commercial
Senior corporate managers	Understand key technical changes	Recognise importance of creating a rapid learning organisation; lead and provide vision	Identify strategic business opportunities
Business unit managers	Understand depth and breadth of technology	Train and select leaders; champion cross-functional teams; adapt career pathing	Target key customer segments; architect product families and generations
Team leaders	Provide breadth of capabilities; comprehend depth requirements	Select, train, and lead development team; recognise importance of attitudes and secure functional support	Champion concept definition; competitive positioning
Team members	Use new tools and apply technologies	Integrate cross-functional problem solving; create improved development procedures	Operationalise customer-driven concept development; refine concept based on market feedback

Beitz and Helbig [1997] conducted a survey of German companies into wanted qualification profiles of product developers resulting in the identification of the “Five Pillars of Qualification” (Figure 6-6). Accordingly, methodical competence based on expert knowledge and skills related to this area has the highest significance, whereas professional and systems competence are regarded as less important, basic knowledge and skills being sufficient.

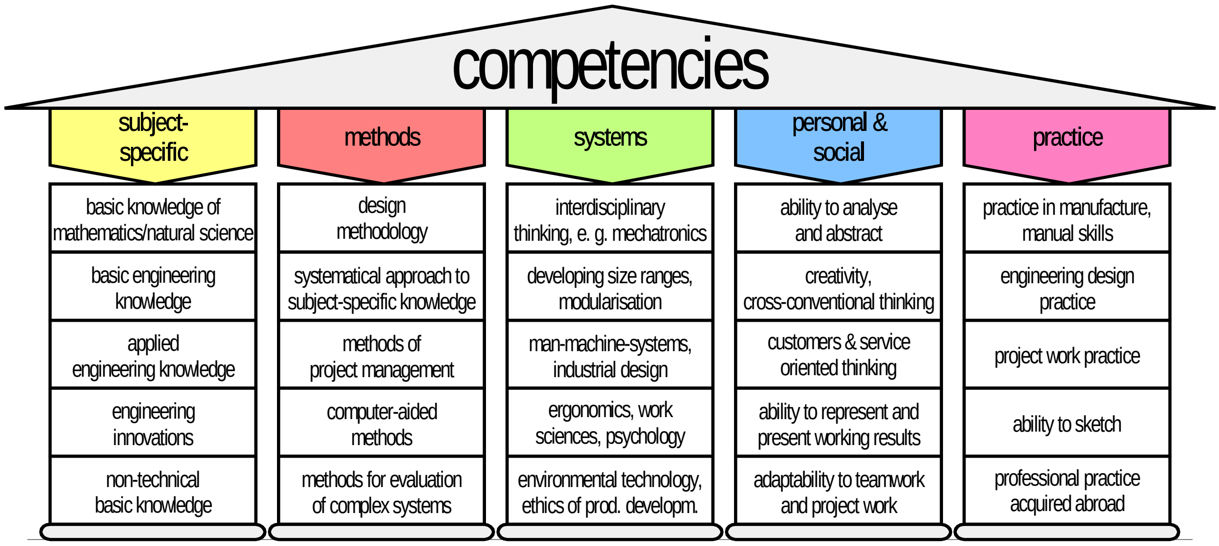

Figure 6-6 The Five Pillars of Qualification of product developers after [Beitz & Helbig 1997]

In a non-participatory observational study of ten development projects in four different companies, Badke-Schaub and Frankenberger [2004] investigated how "critical situations" were handled in a design context. They define a critical situation as a state in which there is a high likelihood that the subsequent process will be positively or negatively influenced. In their studies, they focused on five types of critical situations.

Table 6-4 contains the success factors that were identified, indicating which critical situation benefits from which factor. Each success factor belongs to one of four major areas of competence (cf. Figure 6-6).

Table 6-4 Individual success factors and their influence on critical design situations [after Badke-Schaub & Frankenberger 2004]

Area of competence	Success factor	Benefiting critical situation				
		T_a/T_d [a)]	S_f [b)]	S_a/S_d [c)]	M_d [d)]	M_c [e)]
Professional	Experience	●	●	●	○	○
Social	Assertiveness	●	○	○	○	●
	Social knowledge	○	○	○	○	●
Methodical	Method knowledge	●	○	○	○	○
	Quality standards	○	○	●	○	○
Personal	Self-evaluation	○	●	○	●	○
	Open-mindedness	○	●	○	○	●

[a)] target analysis and target decision; [b)] solution finding; [c)] solution analysis and solution decision; [d)] disruption management; [e)] conflict management.

Assertiveness, when understood as the ability to implement own interests without violating the rights of others, has been found to be crucial for conflict management (achieving win-win situations and acceptable compromises) as well as for target analysis and target definition which often involve conflicting interests. Also, s*ocial knowledge*, as part of social competence, is important in terms of knowing the roles, responsibilities and sometimes the peculiarities of individuals within the organisation. In the area of methodical competence, *method knowledge*, while beneficial especially for target analysis and definition, is still deemed less crucial than high personal *quality standards* which determine the accuracy and care of solution analysis and solution definition. Adequate *self-evaluation*, i.e. the ability to correctly judge own skills and knowledge, as well as *open-mindedness* turn out to be the significant success factors in the area of personal competence. However, the authors of the study point out that the most dominant success factor of all is *experience*, also as it represents the knowledge designers have accumulated in living through the previously mentioned success factors.

In an experimental setting, Fricke [1993] observed 26 individual designers solving a design assignment originally devised by Dylla [1991] (embodiment of a swivelling wall mount for an optical device). In his study, Fricke identified the following psychological characteristics of designers producing good solutions:

- a good spatial sense,
- solid design expertise and (several years of) design experience, as well as
- a high level of heuristic competence.

The latter is defined by the author basically as the ability to plan the necessary steps for solving an unknown problem, to identify sub-problems and their importance and to control the own action accordingly.

Günther [1998], using the same design assignment as Fricke and Dylla, found a highly significant relationship between design experience and quality of the solution in a similar experiment with 18 designers.

6.4 Design Failure

It was shown so far that design takes place in an environment that designers perceive as complex, dynamic and intransparent. Individuals in such an environment are likely to fail [Dörner 2005], designers being no exception [Gries & Blessing 2006]. Before addressing the issue of design failure, however, two concepts closely related to this phenomenon – error and risk – shall be discussed in the following section.

6.4.1 Design Error and Risk

Without doubt, there is a lot that can go wrong in design. Badke-Schaub and Frankenberger [2004] observe that despite all efforts to support designers with guidelines, methods, checklists and IT-based tools, the results show errors, shortfalls, or simply blunders. Clausing [1994 p. 287] estimates that during the development of a complex product 10 million decisions are made and points to the fact that an error rate of 0.01% theoretically results in

1,000 mistakes. Above all, Ulrich and Eppinger [2004, p. 7] comment that often organisational realities in companies prohibit design success.

McMahon, Cooke and Coleman [1997] propose a classification of design errors according to how and where they occur. As to the "how", they distinguish sources of error in design activities and in communication (Table 6-5).

Table 6-5 Sources of error in design activities and communication [after McMahon et al. 1997]

Area	Source or error	Examples
Design activities	Inappropriate technique	Method does not match required precision; use of elastic analysis where elastic-plastic is required
	Activity not carried out completely	Insufficient number of iterations in an analysis; excessive reliance on assumed data values
	Method error	Error from limitation in the technique used (e.g. arising ftom an assumption of linearity in an analysis)
	Activity not carried out	Failure to carry out a particular design evaluation
	Slip occurs in carrying out activity	Typographical error in preparing a drawing; transcription error (e.g. incorrectly read dimension)
	Combinatorial Failure	No failure in individual activities, but error from interaction between several activities
	Time delay	An analysis that takes so long that results are not available in time for some other activity
	Process failure	Computer error or breakdown
	Deliberate error	Falsification of results
Communication	Encoding error	Incorrect communication standard used or error in use of the standard
	Loss of signal	Poorly reproduced drawing; file inadvertently deleted
	Noise on signal	Poorly reproduced drawing; telephone conversation in a noisy room
	Decoding error	Incorrect communication standard used; user fails to understand the notation
	Incomplete communication	Incomplete system standards (e.g. communication between CAD systems).

The locations of design errors (the “where”) include pieces of information pertaining to “explicit” and “implicit” product attributes [McMahon 1994 in McMahon et al. 1997]. They are shown in Table 6-6.

Table 6-6 Locations of design error in information relating to a specific artefact [after McMahon et al. 1997]

Location of errors in information relating to a particular artefact	Examples
Functional requirement	Incorrectly interpreted/changed client requirements; incorrect reference to standard and code
External influences on the artefact, e.g. applied loads	Loads poorly or incompletely understood; incorrect understanding of customer application
Explicit attributes – e.g. dimensional parameters, material properties, etc.	Dimensional error on drawing; incorrectly specified or inappropriate material
Implicit attributes – characteristics and behaviour of the artefact subjected to the external influences	Incorrect performance estimate; excessive uncertainty in durability evaluation; inappropriate FEM result
Specified values of implicit attributes that the design is to achieve	Incorrectly transcribed standard value; incorrectly understood/changed client requirement
Constraints on these values of explicit parameters	Incorrect dimensions for external design envelope; incorrect specification of external interface
Expression defining the **utility** of design	Omitted, incorrectly stated or poorly understood utility function

Busby also conducted some research into human error in the engineering design process [2000], characterising typical failures in design activity [2001]. He interviewed 22 staff in a company that designed complex plant, asking them to recall specific episodes of design error which for the study he defined as an outcome that was

- unexpected,
- unfavourable and
- not entirely attributable to chance or circumstances.

As the focus was on the design process, the above outcome did not have to affect the product. In fact, most of the 86 errors that were analysed in the study were detected early enough that the product was not flawed. A total of 19 different activities in which errors occurred were identified which were managerial or technical in nature. For the 12 technical activities, a total of 57 different “fundamental” causes were found. The (purely subjective) analysis of these fundamental causes lead to 17 “instrumental elements” of the fundamental causes, e.g. “change in the problem or requirement”, “interdependence among subtasks”, or “performance under time pressure”.

More recently, Saariluoma et al. [2006], reasoning that design errors are one of the main sources of risk in design, conducted a survey of 294 Finnish designers. 72% worked in small and mid-size companies with less than 250 staff, 28% in larger companies. 8% held a position equivalent to a CEO, 47% were project leaders and 44% worked as project members.

For a total of a 39 factors, the participants were asked to state to what extent each factor would negatively affect reaching the design goals. This statement should be made by assigning a value between 1 (very little) and 4 (very much).

A principal components analysis (PCA) of the survey data revealed seven main components of the 39 factors. The authors' interpretation of these main components as well as their most instrumental factors are:

- **Faulty thinking:** uncritical use of old solutions in new designs; unawareness of the social and environmental factors in designing
- **Organisation structure and leadership:** problems with organisational structures and managerial practices; organisational change
- **Motivation and commitment:** poor commitment of the participants on a project; unawareness of the goal of a project; lack of motivation
- **Competence:** poor mathematical skills; poor training; problems with tools
- **Distribution of information:** outdated information; problems with getting right information; problems with the communication with a client
- **Occupational stress:** rush at work; several simultaneous projects; stress
- **Intention related factors:** misinterpretation of others' actions; unawareness of the needs of a client; unawareness of others' methods and skills

As pointed out, error in design poses risks. McMahon and Busby [2005], stating the complexity of design processes (cf. 6.2.1) and human limitations (cf. 6.3) as causes, identify the following (non-mutually exclusive) risks in design:

- **Technical risk:** the risk that the product will not perform as intended.
- **Project risk:** the risk that a project will fail or miss cost or time targets.
- **Risk to life and limb:** the risk that the personal safety of stakeholders will be jeopardised when using (or even abusing) the product.
- **Risk to the environment, or to future generations:** e.g. pollution or depletion of scarce resources.

Pahl and Beitz [1996], focusing on mainly on technical risk, state that engineering design is always prone to incomplete information and uncertainties and that good designers should be aware of that (cf. 6.2.3). They also point out, however, that a design which would be devoid of any technical risk would at the same time probably be unmarketable as the necessary measures would render the product too expensive, too heavy, etc. Thus, a reasonable trade-off between technical and economic risk must be found.

6.4.2 Design Failure in the Generic Model of Design-Related Product Quality

In literature, the term *failure*, in context with design, is often used synonymously with the terms *error*, *fault*, *mistake* and even *flaw*. In this thesis, however, a design failure is regarded as a failure to meet specific success criteria (see 6.1) as a result of design error (see 6.4.1). Alternatively to not meeting specific success criteria, failing to avert design risk would also qualify as design failure. A design error as such, having no major consequences whatsoever (like most design errors observed in [Busby 2001]) is not seen as a failure here.

In the beginning of this chapter, it was shown that the achievement of product quality is a strong criterion of design success, quality in this thesis being defined as the degree to which perceived product attributes match with expected attributes (see 4.2). Thus, failing to meet this success criterion qualifies as a design failure. The question to be answered in this section is: how can the emergence of this particular design failure be explained?

Surely, design error plays an important role. Errors eventually leading to design flaws (cf. definition in 4.2) can relate to almost any design activity, aspect of communication and piece of design related information [McMahon et al. 1997]. They can occur in any managerial and technical activity [Busby 2001] and can be caused by faulty thinking, occupational stress and a lack of competence [Saariluoma et al. 2006].

Using the generic model of design-related product quality proposed in this thesis, design failure resulting in design flaws can be described on a level of detail that does not have to focus on specific design errors. Instead, four major “failure modes” can be identified. These failure modes, which can be seen as “deal breakers” in terms of product quality, can comprise all sorts of design error (see 6.4.1). Within the model, these errors can occur in the Designer-Stakeholder domain (modes 1 and 2) as well as the Designer-Product domain (modes 3 and 4). The four failure modes are:

Mode 1: Misinterpreting the expectations of stakeholders

It is widely accepted that no design project is likely to be successful if based on incomplete or wrong requirements. However, care must be taken that the requirements ultimately reflect the expectations of the various stakeholders in the product [Schmidt-Kretschmer et al. 2006].

Mode 2: Poorly communicating product-related information to stakeholders

The example of the rental bicycle (see Figure 4-4) illustrates this failure. In addition to the aspects already discussed in 4.1.3, it is worthwhile to note that a manufacturer’s failure to provide useful instructions or adequate warnings for its product can violate e.g. German Product Liability Law [Bauer et al. 1994] or US laws [American Law Institute 1998 in Hales & Gooch 2004].

Mode 3: Not understanding the product (as the stakeholders would)

In the terms of Wheelwright and Clark [1992] this failure often occurs when designers focus too much on “design parameters” (or requirements for that matter) instead of “customer attributes”. As mentioned in 4.1.3, what makes a “correct” perception of a product’s attributes difficult is the fact that a) the product is not finished (if anything like a prototype or test sample is available at some point of the development process at all) and b) the (likely) conditions under which specific stakeholders would perceive the attributes can rarely be recreated.

Mode 4: Failing to implement the product attributes as intended

Finally, this failure mode takes into account that even without the above situations applying, designers might not be able to arrive at the design they aimed at – e.g. because of lacking knowledge or sometimes even plain blunders. This might be due to the organisational realities that industrial design projects are subject to. In order to meet budget aims, schedules and sometimes (sadly enough) requirements (see the example 2.4), trade-offs with a direct impact on design often cannot be avoided [cf. Gericke & Blessing 2006].

6.5 Discussion

In this chapter, the relationship between design flaws and design failure has been established. It has been shown that various authors regard product quality as a measure for design success, whereby a design flaw, i.e. "a design-related product attribute that impairs product quality" (see 4.2) is a token of design failure. By assuming a perspective that focuses on the designer rather than the design process, some major factors were addressed which make the design context complex, dynamic and intransparent. Consequently, important human factors determining how well individuals cope with such an environment were reviewed. It has been pointed out that design error and design risk are fundamental to design failure, showing that design failure is based on design error, but that a design error not necessarily results in design failure. With regard to product quality as described by the generic model presented in 4.1, four major failure modes have been proposed.

A review of current research reveals that there is often no clear distinction between errors, slips, (structural[20]) failures, faults and flaws. In many contributions these terms are used interchangeably. Generally, the issue of (human) error in design seems somewhat elusive. This finding is reflected by the existing efforts to classify design errors. It is e.g. unclear whether an incorrectly read dimension qualifies as a "slip that occurs in carrying out an activity" or a "decoding error"; also the border between choosing an "inappropriate technique" and a "method error" is blurry (see Table 6-5). The identification of 57 different fundamental causes for 86 errors implies that each fundamental cause explains on average 1.5 errors. One could as well conclude that in design, each error has its individual cause. The study of Saariluoma et al. [2006], while contributing to a better understanding of the importance of factors like e.g. stress, poor training and lack of motivation, suffers from the problem that the identified main components are actually difficult to interpret – a general problem with results obtained from a factor analysis.

It is for this elusiveness of design errors (cause) that in this thesis, design failure (effect), inasmuch as leading to a design flaw (symptom), is explained by the set of failure modes proposed in 6.4.2.

[20] cf. [James 2004 in Clarkson & Eckert 2005, p. 25]

Ultimately, the question why design flaws happen, is closely related to the question why individuals err. Identifying the reasons for which would be out of the scope of this thesis (refer to e.g. [Reason 1990] or [Dörner 2005]). Besides, it is reasonable to assume that designers will always make errors – unless design becomes less complex, less dynamic and less intransparent in the future (which is rather unlikely). Even Busby [2001] admits: “The origins of error in the basic structure of the design task, and in unpredictable conjunctions of events, make it hard to find definitive remedies.”.

The studies reviewed in 6.3 show that a common characteristic of successful designers is experience. Experience is defined as “practical knowledge, skill, or practice derived from direct observation of or participation in events or in a particular activity” [Merriam-Webster 2006] and therefore closely related to learning – of which feedback is an essential element (see chapter 5).

It is interesting to note how “Design for Minimum Risk” [Pahl & Beitz 1996] in fact draws on the concepts of experience, learning and feedback: Consciously marketing a product which is subject to a certain amount of acceptable technical risk, gathering feedback about its behaviour in reality and learning about its performance limits in order to implement an already identified alternative design solution if necessary is an approach that must be, of course, “[…] coupled with a systematic follow-up of the practical experiences gained through it.”

7 Design Flaws as Seen By Designers: An Exploratory Study

7.1 General

In chapter 2, some examples of design flaws were studied, showing that they can occur in a wide range of products (reaching from medical devices to cars), that they can pose minor annoyances as well as major threats to life and limb and that they can affect users, manufacturers, retailers and repair staff alike. The generic model proposed in chapter 4 describes design-related product quality as an interaction between designers, product attributes and stakeholders, and design flaws as the result of a disturbance of this interaction.

The interaction between the stakeholders in a product and its designers in the form of design feedback has been addressed in chapter 5, showing that feedback is an important element of design processes in general and of design flaws in particular. Various potential sources from which designers might obtain more or less useful feedback about design flaws have been identified in- and outside their companies as well as during and after product development.

Chapter 6 focused on the individual and process-related issues in designing contributing to design failure, i.e. designers failing to implement specific product attributes such that a sufficient level of quality is achieved. The importance of design experience was pointed out in terms of being one of the most important human factors in avoiding design failure as well as in the context of coping with design risk whose minimisation, according to [Pahl & Beitz 1996], is a long-term, iterative process of approaching a technical limit.

All these findings, however, only partially answer the research questions formulated in 1.2. As far as the first question ("What is the nature of design flaws?") is concerned, it is – on a general level – unknown e.g.

- how design flaws manifest themselves,
- what the technological causes of design flaws are, or
- how severe and how likely they are.

Concerning the second research question ("What is the nature of feedback about design flaws?"), the sources consulted so far offer no information – again, on a general level – as to e.g.

- who gives feedback, i.e. how design flaws are usually detected,
- how this feedback relates to the manifestation of design flaws, or
- what role product testing plays.

The final research question ("What influences the ability of designers to correct design flaws?") is based on the certainty that, as discussed in chapter 6, design will be always be prone to failure. Consequently, a question of the like "How can design flaws be prevented?" would be equivalent to a question like "How can design be improved?" and therefore hardly be expedient. However, investigating the factors which enable designers to succeed in finding and implementing a solution for a design flaw offers an insight into the aspect of learning from design flaws. To achieve this, it is necessary to find out how

- design flaws,
- the feedback about design flaws and
- the design context (e.g. the design problem or organisational structures)

influence the chances of designers to succeed in the above sense.

7.2 Study Design

In 7.1, the most important questions found to be left open by current research were summarised. These questions show that the phenomenon of design flaws, their feedback and their correction – as a whole – seems to be a problem on which relatively little information exists and which lacks any commonly accepted models or concepts. Therefore, the study described in this chapter is *exploratory* in nature.

As the word suggests, exploratory studies are often conducted when a problem could not be clearly defined yet, or its real scope is still indistinct [Yin 2003]. An exploratory study allows for an initial insight into the phenomenon to be studied. Instead of testing hypotheses, it may generate hypotheses (possibly to be tested in a follow-up study). Therefore, an exploratory study is theory-building and not theory-based [Stebbins 2001]. Building a theory is usually achieved by collecting and analysing a large body of data, finding structures not known before [Adler & Clark 2003].

For the study described in this chapter, such an exploratory approach implied the need to investigate a wide range of companies and products. To accomplish this aim, a mail survey was chosen as method. Before addressing the issues of questionnaire construction (7.2.2), survey implementation (7.2.3) and data evaluation (7.2.4), the following section shall very briefly discuss some fundamental considerations concerning the study methodology.

7.2.1 Considerations

Design is a complex activity that involves products, processes and probably first of all: people. Their activities require methods to capture, analyse and describe human behaviour – which is a traditional domain of social sciences. The application of methods from social sciences in design research has been discussed e.g. in [Bender et al. 2002], with a special focus on mail surveys e.g. in [Gries & Blessing 2005].

Atteslander [1995] identifies the following four main categories of empirical research methods in social sciences:

- **Content analysis:** methods falling under this category play a somewhat special role since their unit of analysis is the outcome of human activity rather than human behaviour itself[21].
- **Experiment:** the objective of methods belonging to this category is to study human behaviour in a controlled situation in which the subjects (people and where required artefacts) become part of an artificially created, controlled and reproducible process.
- **Observation:** this approach is based on the systematic recording and interpretation of observable behaviour in natural situations at the time of its occurrence. Observational studies are determined by the parameters structure, openness and participation. Unstructured studies do not rely on a predefined observation pattern and can therefore only be used in an exploratory setting. Unlike in an open observation, the participants of a covert study are unaware that it takes place. Finally, the researcher can decide whether or not to participate in the activities of its subjects.
- **Survey:** methods based on a survey approach also aim at gaining an understanding of human behaviour in natural situations – but not necessarily at the time of its occurrence. They always require some kind of deliberate communication between the subject(s) and the researcher which implies that the participants need to reflect on their own behaviour (or the behaviour of others) and/or to recall facts. Apart from questionnaire-based surveys, the socio-scientific understanding of a survey also includes interviews.

Regardless of the method(s) used, the quality of an empirical study is defined by the following criteria [Bortz & Döring 2002; Lienert & Raatz 1998 in Bender 2004]:

- **Objectivity:** the degree to which the uninterpreted results are independent from the individual who obtained them.
- **Reliability:** the level of precision and reproducibility that can be achieved in measuring specific attributes.
- **Validity:** the extent to which a study can actually measure what it intends to measure.
- **Empirical relevance (or external validity):** the transferability of results to reality.
- **Efficiency:** the cost-benefit ratio of a study.

According to these criteria, a mail survey – which can be defined as an empirical study in which subjects answer a questionnaire without the supervision of an interviewer – generally offers the best efficiency in achieving a high level of empirical relevance. Also, objectivity should be of no concern as the evaluation of questionnaires usually leaves little room for individual interpretation (especially when avoiding open-ended questions). The only drawback might the reliability of the results due to the lack of control over the test subjects. Usually, it cannot even be verified that the questionnaire has been completed by the addressee

[21] The results obtained in [Hales 2003; 2005], for example, were based on a "Forensic Analysis of the Design Process" focusing on the design documents or the disputed products themselves.

and not by some other individual. However, this problem can be (at least to a certain degree) attenuated by a sufficiently large sample.

These general advantages alone, however, were not decisive in choosing a mail survey approach for the study described in this chapter. It is rather the nature of the phenomenon investigated in this thesis – design flaws, their feedback and their correction – which ultimately determined the method.

Following a content analysis approach, e.g. by examining flawed products, might have provided some insight into the nature of design flaws (research question 1), but would neither have revealed any deeper technological causes nor the nature of feedback about these design flaws (research question 2). It would have been also difficult to draw conclusions as to the influences on the ability of designers to correct design flaws (research question 3).

An experimental approach, was not considered for two reasons. Firstly, it seemed unsuited to study the nature of design flaws and their feedback (research questions 1 and 2). Secondly, any "artificially created, controlled and reproducible process" (see above) would only have allowed for a very limited insight into the influences on the ability of designers to correct design flaws (research question 3).

The main problem with an observational approach (e.g. in a similar setting as in [Badke-Schaub & Frankenberger 2004]) is that the emergence of design flaws cannot be predicted. Given the questionable efficiency in terms of covering a broad range of products an observational study was discarded.

7.2.2 Questionnaire Construction

Based on the questions in 7.1, a questionnaire was designed in which 28 exploratory questions were arranged in three sections (see Appendix B: Questionnaire).

In section I, the participants were asked to give some general information about their company (number of employees, annual sales, etc.) and to define an activity profile of its designers.

Section II was titled "Questions about the product and its development". In the beginning of this section, the participants were instructed to refer all following questions to a single product which was the result of the development process that they were most familiar with and which was already available on the market (subsequently referred to in the questionnaire as PRODUCT).

In section III, the participants were asked questions about the most severe design flaw of the PRODUCT which was defined as "an unwanted behaviour of the PRODUCT which is for the most part caused by its design". The subjects were advised that the study was based on the concept that according to this definition, any product is flawed to a certain extent (be it, that it leaves room for optimisation). Again, the participants were instructed to refer all subsequent questions to one and the same flaw (referred to as DESIGN FLAW).

By default, the questions were asked in a “check all that applies” format. Questions that required the participants to choose only one option were clearly marked as such. Quantitative information was to be given by entering a value instead of selecting a category (i.e. 1-50, 51-100, etc.). Open questions were avoided altogether. Whenever possible, an answer option like “Other (please state):” was offered.

Following common practice [Dillman 2000], an early draft of the questionnaire was tested on five representatives from industry in order to identify questions that could be misinterpreted and/or felt difficult to answer, questions to which the participants were inclined to refuse an answer (a particularly interesting point, given the rather delicate topic of the study) and to pick up suggestions for further questions. In addition, the average time for completing the questionnaire was taken, which was about 12 minutes and felt tolerable by all test persons.

In addition to the paper version of the final questionnaire (which was printed on light green paper in form of a twelve-page A5 booklet), an online version was implemented on an Internet server.

7.2.3 Survey Implementation

The survey population encompassed all German companies whose economic activities can be described with NACE codes [Eurostat 1996] ranging from 28.6 (et seqq.) to 37, which include the manufacture of:

- machinery and equipment (29 et seqq.),
- office machinery and computers (30 et seqq.),
- medical, precision and optical instruments (33 et seqq.),
- motor vehicles (34.1 et seqq.) as well as
- aircraft and spacecraft (35.3 et seqq.).

The sample frame was defined by all firms fitting into the above category range listed in the 2003 editions of the “Hoppenstedt” company databases for small and medium [Hoppenstedt 2003b] as well as large companies [Hoppenstedt 2003a]. From this list of 18,196 companies, a random sample of 1,000 firms was drawn.

By referring to the information from the database and subsequent research on the Internet, 794 recipients of the questionnaire could be identified by name. Since only a small minority could doubtlessly be recognised as designers (the survey’s target group), most of the addressees were owner-managers, CTOs and similar members of upper management. Consequently, the cover letters contained a passage in which the recipients were asked to forward the enclosed questionnaire to “a person in a leading position who is most familiar with a specific product and its development”. The letter also contained the URL and a password for the online version of the questionnaire.

The addressees were assured strict confidentiality and anonymity. They were informed of the fact that the questionnaires could not be traced back to any company or individual.

In addition to the hand-signed cover letter (and the questionnaire of course), the mailing included a franked return envelope and a ball pen as a small incentive. Two weeks after mailing, reminder letters with an enclosed replacement questionnaire were sent to all companies from the sample.

After 50 working days, the survey was brought to an end. In total, 171 responses were received, 16 of which online. Ten companies refused to take part in the study and six had ceased to exist, resulting in a response rate of 17.1%.

7.2.4 Data Analysis

For the analysis of the data obtained from the mail survey, appropriate statistical methods were necessary. Since normal distribution could not be assumed, only non-parametric tests were used. These shall only be discussed briefly here. Details on all statistical methods used in this study can be found in e.g. [Bortz 1999; Bortz & Lienert 2003; SPSS 2003].

The confidence level of the study was set to $\alpha = 0.05$, which means that any found difference or correlation is only statistically significant for $p \leq \alpha$ where p is the probability that the observation occurred by chance. For findings with $\alpha < p \leq 0.1$, a statistical tendency is assumed.

The χ^2-test of independence was applied whenever the null-hypothesis had to be tested that two nominal variables are stochastically independent. In cases where two nominal variables could only assume two values, resulting in a 2×2 contingency table, Fisher's exact test was preferred as this test (unlike the χ^2-test independence) still delivers valid results for contingency tables containing frequencies lower than 5. In cases where the null hypothesis had to be tested that an observed frequency distribution of a nominal variable corresponds to an expected frequency distribution, Pearson's χ^2-test of goodness of fit was applied.

Apart from the above tests suitable for nominal data, the following three non-parametric tests applicable to ordinal and metric data were used: the median test, the Mann-Whitney-U test and the Kruskal-Wallis-H test. The median test is basically a special case of the χ^2-test of independence. For n sub-samples to be compared, a $n \times 2$ contingency table is generated which for each sub-sample contains the number of cases with a value higher and the number of cases with a value lower than the sample median. The resulting χ^2-value indicates whether the n subsamples significantly differ in terms of the ordinal or metric variable analysed. Both Mann-Whitney-U and Kruskal-Wallis-H tests are rank-based, the latter being an extension of the Mann-Whitney-U test for more than two sub-samples.

For testing correlations between two ordinal variables, Kendall's τ method was used. It has lower demands on the data than Spearman's ρ which requires ordinal values to be equidistant in order to deliver valid results.

The exploratory nature of this study is reflected by the extensive use of clustering algorithms to identify patterns in the data. A cluster analysis seeks to identify homogeneous sub-samples within an overall sample. In other words: it seeks to identify a set of groups, i.e. clusters, with minimum in-group variation and maximum between-group variation. Two types of clustering algorithms are distinguished: partitional and hierarchical. With partitional algorithms, the number of clusters must be predefined, whereas hierarchical algorithms are able to automatically determine the number of clusters. Hierarchical algorithms can furthermore be agglomerative ("bottom-up") or divisive ("top-down"). Bottom-up algorithms start with each single element as a separate cluster which are successively merged into larger clusters. Conversely, "top-down" algorithms begin with the whole sample and successively divide it into smaller clusters. For hierarchical algorithms, the distance measure is important. In agglomerative algorithms, it determines how "close" two clusters are and therefore if they can be merged. A common distance measure is e.g. the euclidean distance or binary similarity.

The SPSS TwoStep clustering algorithm [SPSS 2001], which was used in the data analysis, is an hierarchical and agglomerative algorithm which is very efficient on large data sets (n > 100) by pre-clustering it using specific clustering criteria (Schwarz's Bayesian Information Criterion or Akaike Information Criterion). The following settings were used:

- Log-likelihood distance measure
- Schwarz's Bayesian information criterion
- Automatically determined number of clusters (maximum: 5)

7.3 Product Characteristics

Early in the study, the participants were asked to describe various characteristics of the product (see 7.2.2). Among other things, it had to be assigned to one the following main categories:

- Consumer good
- Investment good
- Vendor part

The reason why these categories were offered was that each category might have different implications on the questions investigated in this study. Consumer goods are simply defined as products which are used by consumers (e.g. a tennis racket or a vacuum cleaner) [Gabler 1992, p. 1902]. Investment goods, on the other hand, are defined as products which are used by non-consumers to produce other goods or services (e.g. a machine tool or a roller coaster) [Gabler 1992, p. 1715]. Vendor parts are intended to be built into other products. Unlike their name suggests, they are not necessarily single parts (e.g. a screw or a washer disc). An aircraft engine, for instance, is also a vendor part.

Investment goods and vendor parts are designed, manufactured and marketed in a business-to-business (B2B) environment, whereas the economic value creation of consumer goods usually takes places in a more typical business-to-consumer (B2C) fashion. In a B2B environment, businesses interact directly. The manufacturing process of vendor parts, for instance, is usually closely integrated into the supply chain of the customer. Often, vendor parts are designed to the specifications of the OEM (see 6.2.1). In a B2C setting, there are additional stakeholders, e.g. distribution and retail. It can also be assumed that a consumer, at the very end of the value chain, has quite different expectations in and perceptions of different product attributes than e.g. a procurement manager who has to decide which machine tool to buy or the worker who has to use it.

The frequency and percentage distribution of consumer goods, investment goods and vendor parts is shown in Figure 7-1.

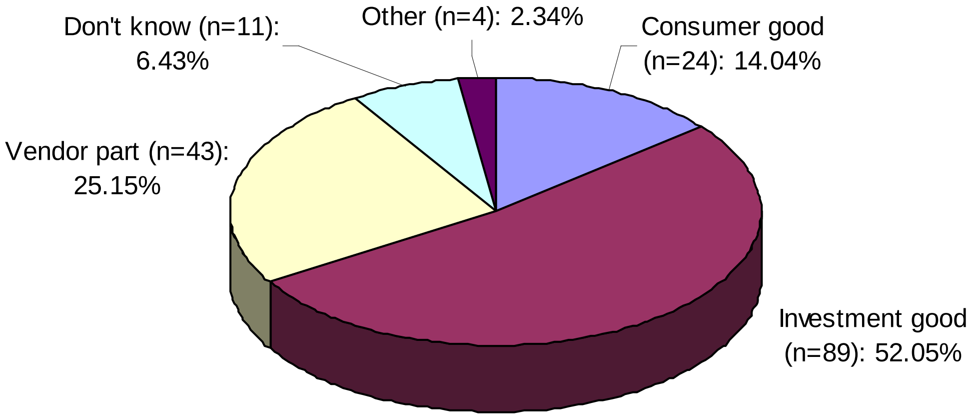

Figure 7-1 Frequencies and percentages of product categories[22] (n=171)

Apart from the product category, three more product characteristics seemed interesting in the context of design flaws, their feedback and the success designers have in correcting them:

- production volume
- life span
- complexity

The production volume of a product might be an interesting characteristic as it directly influences the absolute number of flawed product on the market and in use. The success companies have in correcting design flaws could depend on this parameter as opportunities for receiving feedback are multiplied. At the same time, the pressure to succeed increases. High production volumes also indicate a stronger role that manufacturing plays as a quality stakeholder. The life span of a product constitutes the maximum amount of time in which companies can receive feedback about its design flaws. This parameter therefore has a similar multiplier function as the production volume. The complexity of the products in this study is approximated by their number of different parts. The success designers have in correcting the design flaw of a product might depend on this parameter.

Consumer goods, investment goods and vendor parts have been found to differ significantly in production volume, life span and complexity. Products from these categories distinguish each other as illustrated by the symbols in Table 7-1. In summary, they can be characterised as follows:

- The most prominent feature of consumer goods is a comparatively short life span.
- Products that qualify as investment goods are more complex and produced in lower volumes than products from other categories.
- Vendor parts are characterised by their high production volumes.

[22] Question II.1: "Please assign the product to one of the following categories"

Table 7-1 Comparison of product categories (median values)

Product category \ Variable	Production volume [a] ($p < 0.001$)		Life span [b] ($p = 0.021$)		Complexity [c] ($p < 0.001$)	
	Units/year	Rating	Years	Rating	# of parts	Rating
Consumer goods (n=24)	20,000	➔	5 ½	➘	33	➔
Investment goods (n=89)	275	➘	10	➔	300	➚
Vendor parts (n=43)	100,000	➚	10	➔	20	➔
Sample (n=171)	2,000	n/a	10	n/a	80	n/a

p-values based on median test. Key to symbols: ➚: high; ➔: medium; ➘ low

[a] Question II.2 [b] Question II.3 [c] Question II.5

7.4 Characteristics of Design Flaws

7.4.1 Manifestations

In the first question of section III, participants were asked how the design flaw manifests itself, i.e. what problem it causes. The given answer options were in order of a typical life cycle of a product, the problems reaching from manufacturing and assembly to disassembly and recycling. Figure 7-2 shows the percentage distribution of answers in descending order. It reveals that "Problems with manufacturing and assembly" is the most often stated manifestation followed by "Failure of parts" and "Poor function fulfilment".

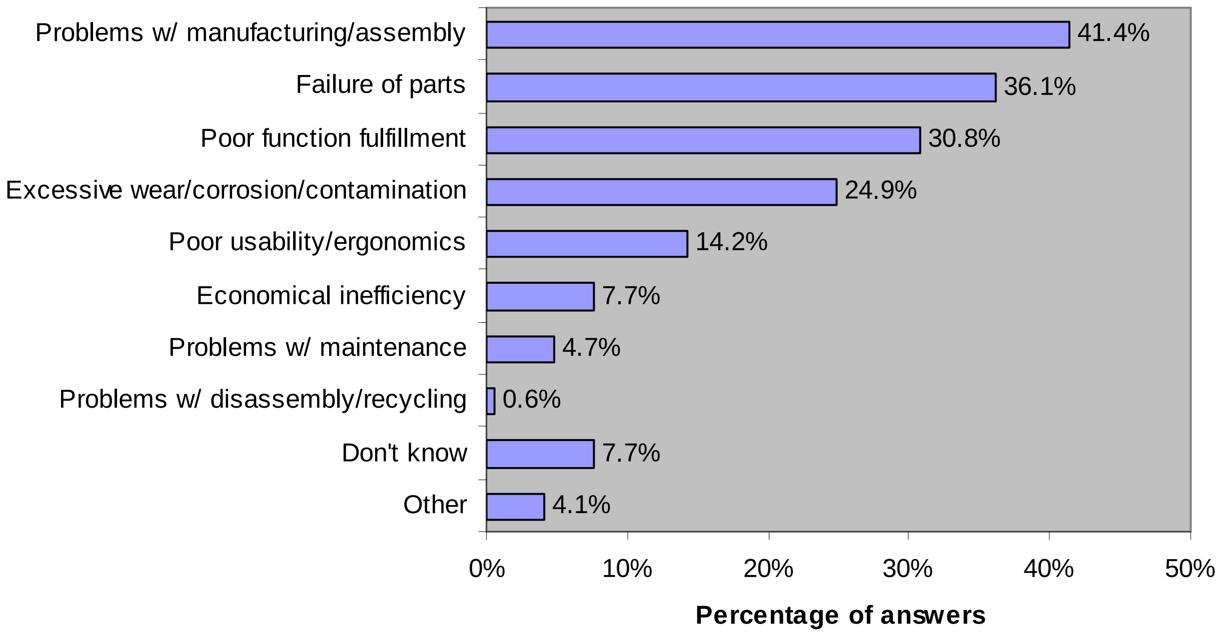

Figure 7-2 Manifestations of design flaws[23] (n = 169, multiple answers possible)

[23] Question III.1: "How does the design flaw manifest itself?"

To identify any answer patterns within this data, a cluster analysis was performed (see section 7.2.4). For this purpose, the 13 cases in which the answer option "Don't know" was selected were excluded. Figure 7-3 shows the percentage distributions of answers for each of the four clusters that were identified.

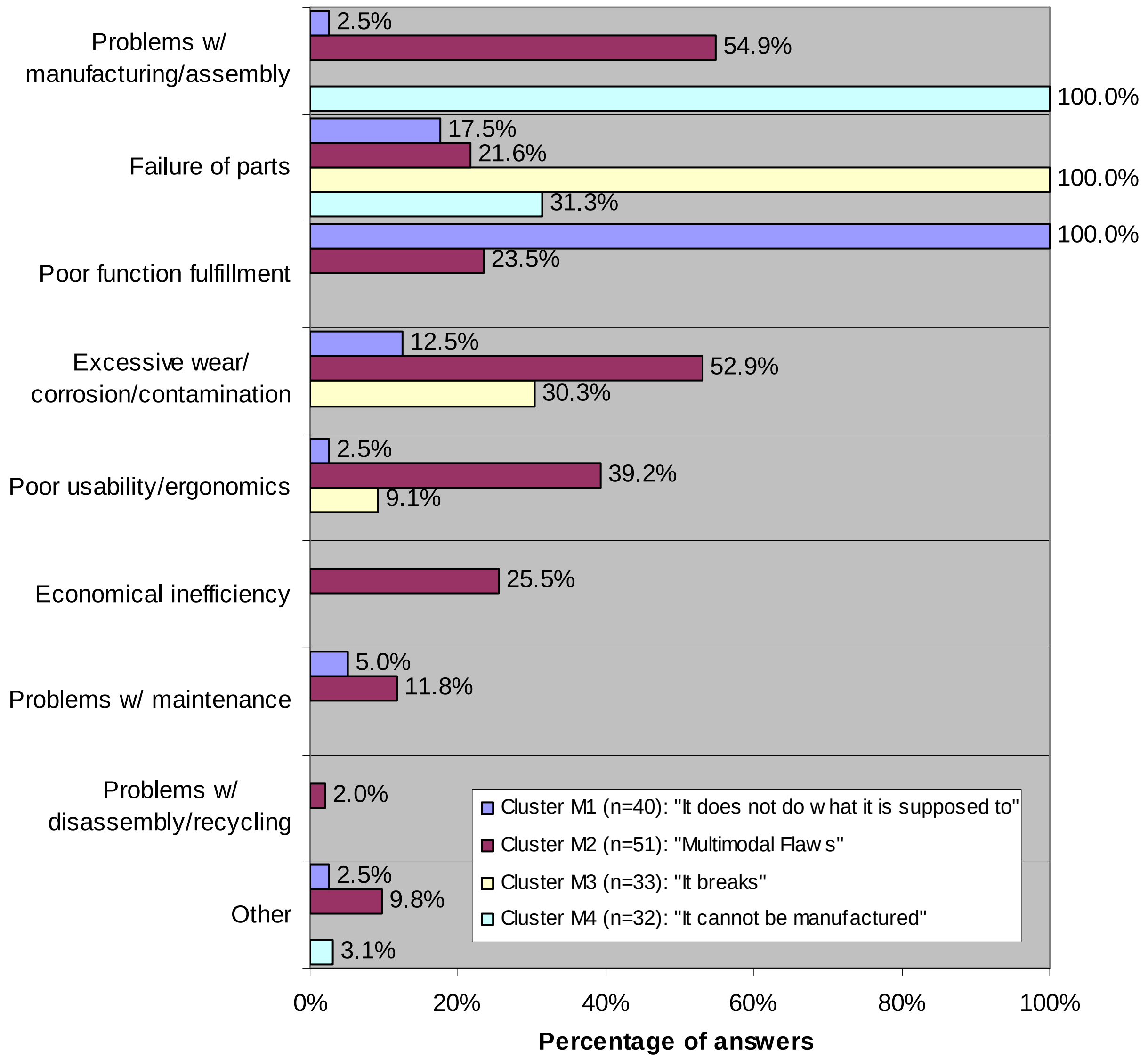

Figure 7-3 Manifestations of design flaws by cluster

Table 7-2 shows the results of Pearson χ^2-tests comparing the distributions of values of individual variables within each individual cluster with the distribution of the sample. The χ^2-value is crucial for interpreting the data as it is a measure of the importance of a cluster's variables, assuming that variables whose distribution of values does not differ significantly from the overall distribution were not important for the formation of the cluster [SPSS 2003].

As for k variables k independent hypotheses are tested on the same set of data, a *Bonferroni adjustment* needs to be applied [Abdi 2007]: it states that a local level of significance α' needs to be defined which equals α/k. Variables whose distribution of values not only differs significantly from the sample but whose observed frequencies are lower than the expected frequencies can be interpreted as being important for the formation of a cluster in terms of being uncharacteristic for its cases. They are underlined in Table 7-2.

The variable "Failure of parts", for instance, while being the second most often stated manifestation in cluster M1, is stated significantly less often than in the overall sample. The most often stated option "Poor function fulfilment" is still the most important variable with $\chi^2 = 80$.

The most often stated manifestation in M2, "Problems with manufacturing/assembly", is in fact unimportant for the formation of this cluster. "Excessive wear", the second most often stated option, is significant but has the lowest χ^2-value in comparison with "Economical inefficiency" and "Poor usability/ergonomics", the latter variable in fact turning out to be the most important one in the formation of cluster M2.

The lack of any participants stating that the design flaw resulted in "Problems with manufacturing/assembly" or "Poor function fulfilment" has been important for the formation of cluster M3, although the highest χ^2-value belongs to the variable "Failure of parts".

Cluster M4, characterised by all of its participants stating that the design flaw causes "Problems with manufacturing/assembly", also features significantly low frequencies of answers to the options "Poor function fulfilment" and "Excessive wear/corrosion/ contamination"

Based on the data in Table 7-2, it also follows that "Problems with maintenance", "Problems with disassembly/recycling" and "Other" manifestations played no role in the formation of any cluster.

Table 7-2 p- and χ^2-values expressing the importance of individual variables for the formation of each cluster describing the manifestation of design flaws

Variable \ Cluster	M1		M2		M3		M4	
	p	χ^2	p	χ^2	p	χ^2	p	χ^2
Problems with manufacturing/assembly	0.0115	6.39	0.1498	2.01	**<u>0.0000</u>**	**<u>26.86</u>**	**0.0000**	**39.31**
Failure of parts	**<u>0.0051</u>**	**<u>7.84</u>**	0.0103	6.59	**0.0000**	**51.39**	0.3627	0.83
Poor function fulfilment	**0.0000**	**80.00**	0.1375	2.21	**<u>0.0000</u>**	**<u>16.50</u>**	**<u>0.0001</u>**	**<u>16.00</u>**
Excessive wear/corrosion/contamination	0.0397	4.23	**0.0000**	**17.55**	0.6616	0.19	**<u>0.0006</u>**	**<u>11.79</u>**
Poor usability/ergonomics	0.0239	5.10	**0.0000**	**22.25**	0.3163	1.00	0.0159	5.82
Economical inefficiency	0.0565	3.64	**0.0000**	**19.65**	0.0833	3.00	0.0881	2.91
Problems with maintenance	0.9707	0.00	0.0317	4.62	0.1817	1.78	0.1884	1.73
Problems with disassembly/recycling	0.6115	0.26	0.2376	1.40	0.6445	0.21	0.6496	0.21
Other	0.5438	0.37	0.0666	3.36	0.2131	1.55	0.7097	0.14

Significant values in boldface. Underlined if observed frequencies lower that expected frequencies. Bonferroni adjustment applied ($\alpha' = 0.0056$).

Based on the frequencies and importance of their variables (see Figure 7-3 and Table 7-2), the four identified clusters can be characterised as follows:

- **Cluster M1 ("It does not do what it is supposed to"):** cases in which the design flaw impairs the product's ability to fulfil some or all of its intended purposes, usually not due to parts of the product simply breaking but maybe due to conceptual flaws.
- **Cluster M2 ("Multimodal flaws"):** cases in which the design flaw manifests itself in a multitude of ways but essentially in modes that affect the end-user.
- **Cluster M3 ("It breaks"):** cases in which the design flaw causes (parts of) the product to break, fail, crack, melt, etc.
- **Cluster M4 ("It cannot be manufactured"):** cases of design flaws that lead to problems with manufacturing and/or assembly.

The lack of any participants stating that the design flaw lead to "Poor function fulfilment" in cluster M3 is not conclusive. One interpretation would be that the parts failure did not impair the product's overall functionality. On the other hand, "Failure of parts" could have simply excelled "Poor function fulfilment" as an answer option. This issue will be investigated later.

Figure 7-4 shows how the clusters are distributed within the categories consumer goods, investment goods and vendor parts (see 7.3). The corresponding frequencies reveal a highly significant association between product category and cluster affiliation[24].

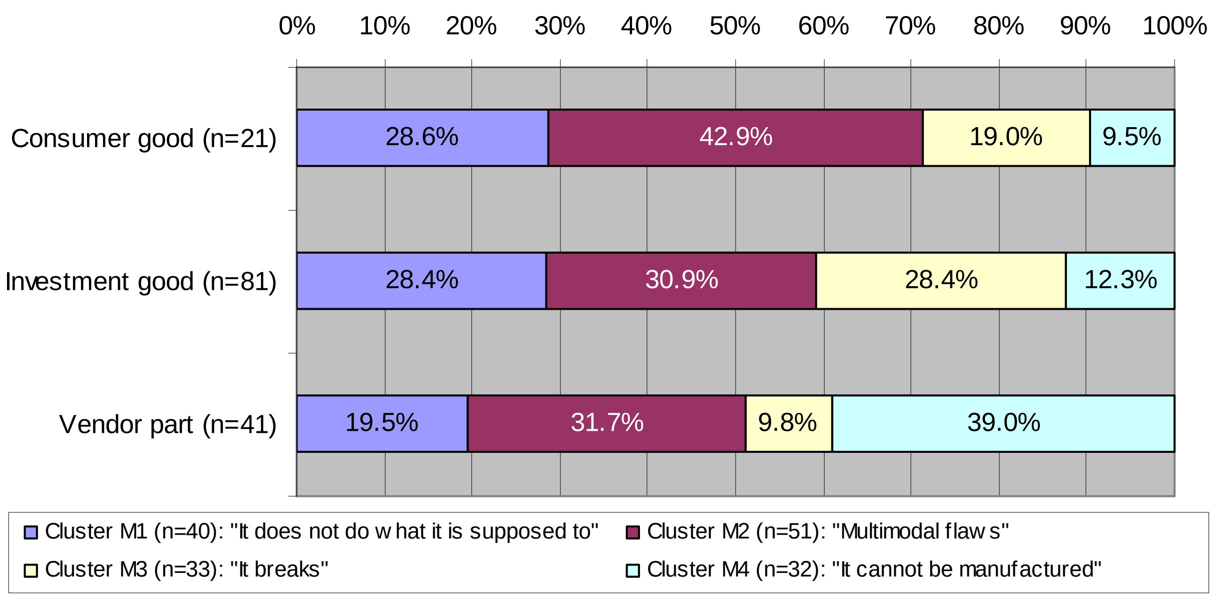

Figure 7-4 Percentage distributions of clusters describing the manifestation of design flaws in different product categories

While the percentage of cases belonging to cluster M1 ("It does not do what it is supposed to") is practically equal among consumer and investment goods, it is noticeably lower among vendor parts. This might be due to the fact that vendor parts are supposed to be built into other products for which other manifestation patterns are more likely.

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[24] $p = 0.008$ (χ^2-test of independence)

Among investment goods and vendor parts, there is virtually the same percentage of cases belonging to cluster of multimodal flaws (M2). However, M2 is the most frequent cluster among consumer goods. This observation matches the finding that the most important manifestation of design flaws within this cluster, i.e. "Poor usability/ergonomics" (Table 7-2), is probably most critical for the typical consumer.

The distribution of the three percentage values of cluster M3 ("It breaks") among product categories is almost linear, the lowest value to be found among vendor parts and the highest one among investment goods. This distribution somewhat mirrors the different complexities of products from these categories (Table 7-1). However, the observation that vendor parts are of relatively low complexity might not be the main reason for the lowest percentage of cases where parts just break. Products from this category usually have to be well-specified, well-tested and sometimes even standardised (see 7.3). The fact that investment goods feature a higher percentage of cases where parts break could be explained by the finding that these products generally consist of more parts than consumer goods and vendor parts (Table 7-1).

The high percentage of cases belonging to cluster M4 ("It cannot be manufactured") within the group of vendor parts probably needs to be seen in context with the comparatively high production volumes in this product category (Table 7-1). It can be assumed that the design of these products is quite manufacturing-driven – also because the manufacturing of vendor parts is often integrated into the supply chain of the OEM. Therefore, it must be taken into account that designers of vendor parts might have stated that the design flaw causes problems with manufacturing by referring to the manufacturing process of the OEM.

7.4.2 Technological Domains

In question III.2, the participants were asked to state the technological domain that caused the design flaw. In consideration of the industries that defined the sample frame of the study, the offered answer options were supposed to cover the most likely spectrum of technological domains of the products to be encountered. However, the answer option "Materials" was added afterwards as 6 cases where participants originally stated this domain as "Other" made this step seem justified.

The percentage distribution of answers is given in Figure 7-5. Not surprisingly, the most frequently stated option is mechanics: 94 designers identified this domain as the cause of the design flaw, slightly more than the next most frequent answers "Electronics" (n = 37), "Software" (n = 33) and "Electrics" (n = 23) combined. Remarkably, there is a rather high frequency (n = 15) of cases where the answer option "Don't know" was given.

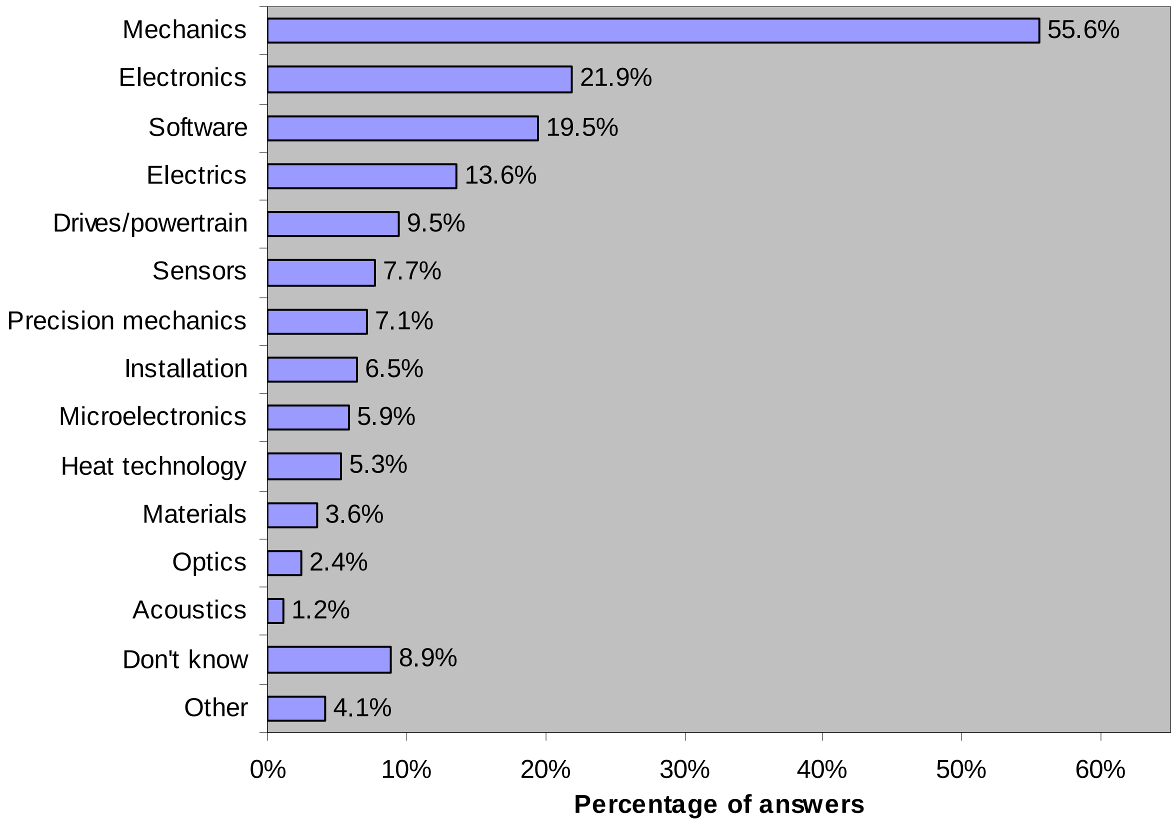

Figure 7-5 Technological domains of design flaws[25] (n = 169)

Again, to identify any answer patterns in this data set – characterised by many variables with similar and low frequencies – a cluster analysis was applied. However, unlike with the manifestations of the design flaw, the cases where the answer option “Don’t know” was given were included. The percentage distributions of answers for the three identified clusters are shown in Figure 7-6.

Cluster T1 is dominated by 59 cases where participants stated that the cause of the design flaw was in the mechanical domain. It also features the highest relative frequency of the answer option “Electrics”. The most frequent statements in cluster T2 are “Mechanics” (n = 35), “Electronics” (n = 34) and “Software” (n = 31). Cluster T3 includes all cases from the overall sample where the answer options “Don’t know” but also “Materials” and “Optics” were given.

[25] Question III.2: “Please state the domain that caused the design flaw” (several answers possible)

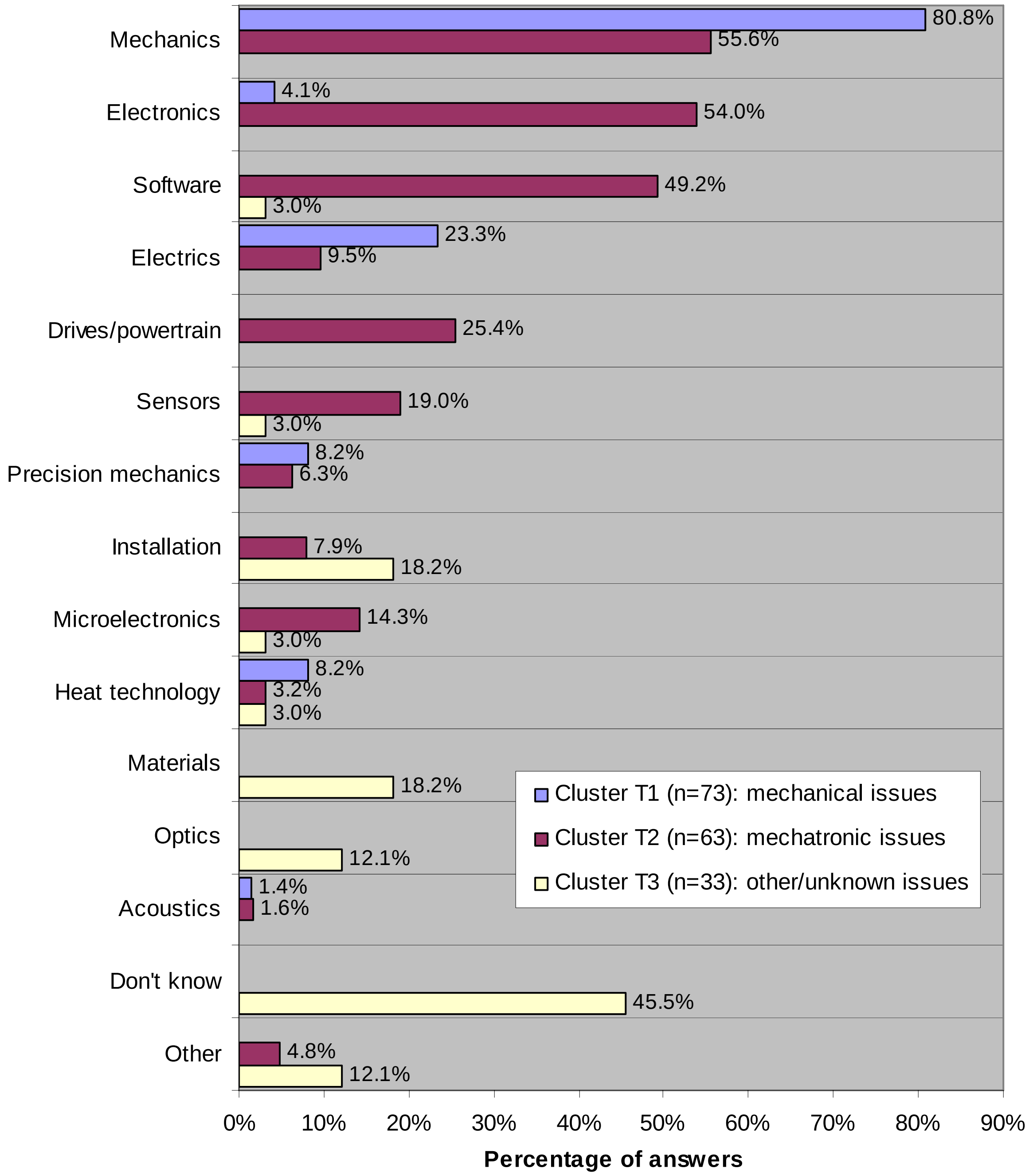

Figure 7-6 Technological domains of design flaws by cluster

The p and χ^2-values in Table 7-3 reveal that for forming cluster T1, not only the high frequency of the answer option “Mechanics” has been relevant but also the low frequency of “Electronics” and “Software” (3 and 0 statements respectively).

“Mechanics”, while being the most often stated option in cluster T2, is in fact almost completely irrelevant as a variable as its near-zero χ^2-value shows. The two most important variables are “Electronics” and “Software” with almost identical values for χ^2, followed by “Drives/powertrain” and “Sensors”.

Table 7-3: p- and χ^2-values expressing the importance of individual variables for the formation of each cluster describing the technological domain of design flaws

Technological domain \ Cluster	T1		T2		T3	
	p	χ^2	p	χ^2	p	χ^2
Mechanics	**0.0000**	**18.78**	0.9916	0.00	**<u>0.0000</u>**	**<u>41.36</u>**
Electronics	**<u>0.0002</u>**	**<u>13.50</u>**	**0.0000**	**37.90**	**<u>0.0024</u>**	**<u>9.25</u>**
Software	**<u>0.0000</u>**	**<u>17.05</u>**	**0.0000**	**37.61**	0.0197	5.44
Electrics	0.0159	5.82	0.3443	0.87	0.0226	5.20
Drives/powertrain	0.0057	7.63	**0.0000**	**18.65**	0.0632	3.45
Sensors	0.0136	6.08	**0.0007**	**11.44**	0.3149	1.01
Precision mechanics	0.4045	0.70	0.8844	0.02	0.1437	2.08
Installation	0.0242	5.08	0.6460	0.21	0.0066	7.39
Microelectronics	0.0321	4.59	0.0049	7.93	0.4821	0.49
Heat technology	0.2709	1.21	0.4471	0.58	0.5571	0.35
Materials	0.1012	2.69	0.1278	2.32	**0.0000**	**20.63**
Optics	0.1834	1.77	0.2165	1.53	**0.0002**	**13.59**
Acoustics	0.8829	0.02	0.7669	0.09	0.5296	0.40
Unknown	0.0077	7.11	0.0132	6.14	**0.0000**	**54.59**
Other	0.0757	3.15	0.8050	0.06	0.0214	5.29

Significant values in boldface. Underlined if observed frequencies lower that expected frequencies. Bonferroni adjustment applied ($\alpha' = 0.0033$)

What sets apart cluster T3 from the overall sample is its higher than expected observed distributions of frequencies of the answers “Unknown”, “Materials” and “Optics” (as said, all cases where these answers were given are concentrated here) next to its lower than expected observed frequency distributions of the answers “Mechanics” and “Electronics”.

Based on this analysis of the overall data, “Electrics”, “Precision mechanics”, “Installation”, “Microelectronics”, “Heat technology”, “Acoustics” and “Other” technological domains of design flaws played no significant role in identifying the three basic answer patterns that clusters T1, T2 and T3 represent and which could be described like this:

- **Cluster T1 (“Mechanical issues”):** cases where the design flaw belongs to the domain of classical mechanical engineering.
- **Cluster T2 (“Mechatronic issues”):** cases in which the design flaw stems from technological domains which correspond to those in mechatronics.
- **Cluster T3 (“other/unknown issues”):** cases where the technological domain of the design flaw is non-mechanical but mainly unknown.

Figure 7-7 shows the percentage distributions of clusters within each product category, revealing that the distributions within consumer goods and vendor parts are virtually identical with cases belonging to cluster T1 accounting for more than half of the cases each. The absolute majority of cases among investment goods, however, belongs to the cluster of mechatronic issues. The observed frequencies corresponding to Figure 7-7 indicate a highly significant association between product category and technological domain[26].

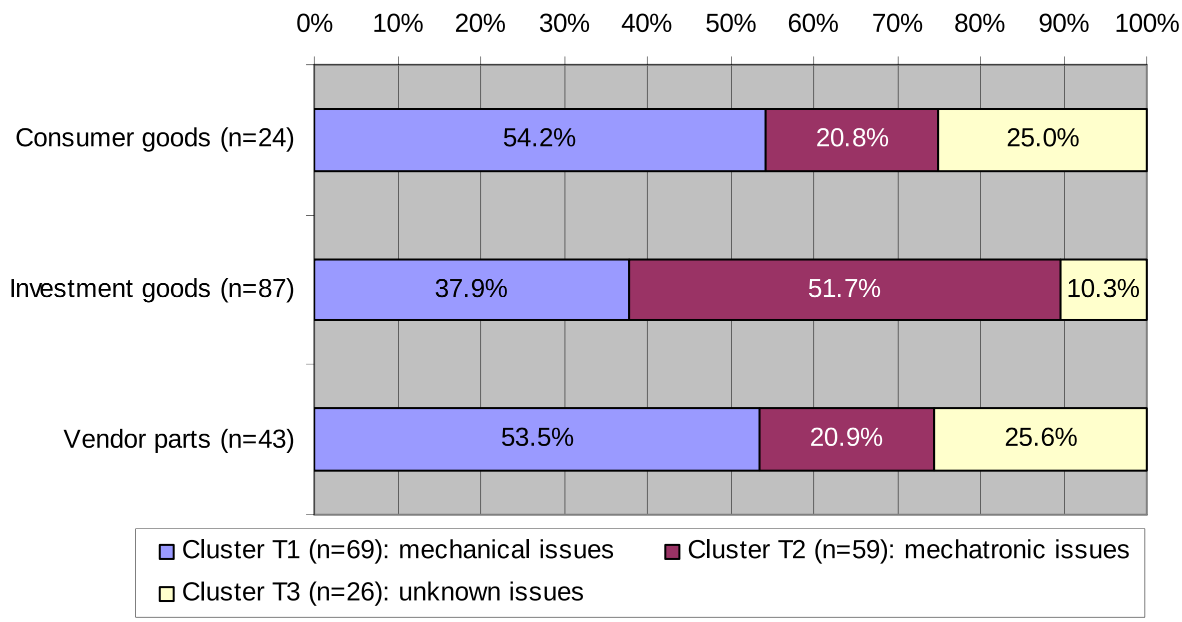

Figure 7-7 Percentage distributions of clusters T1 through T3 within different product categories (n = 154)

[26] $p = 0.002$ (χ^2-test of independence)

The association of cases to clusters T1 through T3 and M1 though M4 is visualised in Figure 7-8 by showing the percentage distribution of cases belonging to the clusters describing the technological domain of the design flaw within each cluster representing a different manifestation. The observed frequencies constitute a highly significant association between technological domain and manifestation of a design flaw[27].

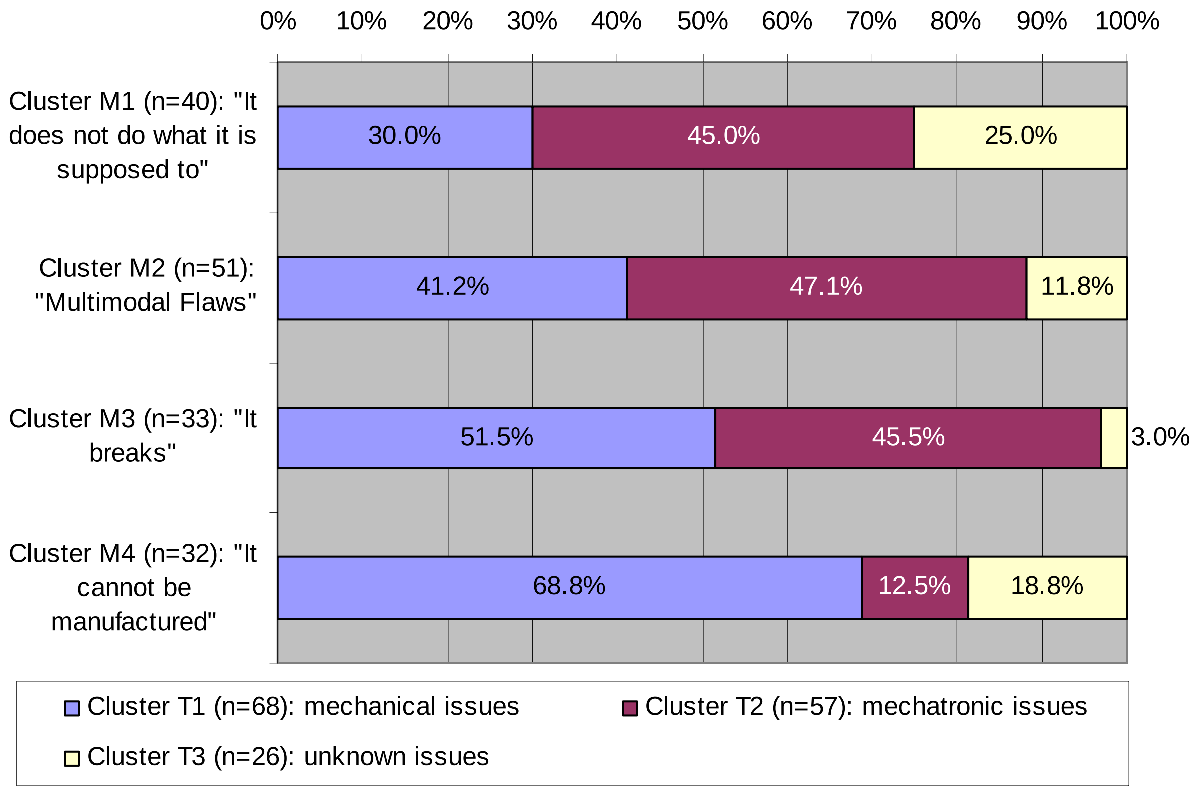

Figure 7-8 Percentage distributions of clusters T1 through T3 within clusters M1 through M4 (n = 156)

Among all manifestations of a design flaw, mechanical issues seem to matter least in cases where it impairs a product's ability to fulfil its purpose if this condition is not due to something breaking and failing[28]: only 12 cases belong to cluster M1 and T1. The relative frequency of cases belonging to the same cluster in cases where the design flaw manifests itself as to cause problems with manufacturing is more than twice as high. Out of the 32 cases belonging to cluster M4, 22 also belong to T1.

While the percentage of cases belonging to cluster T2 is fairly equal throughout clusters M1 to M3, cases in which the design flaw is related to problems with manufacturing relatively rarely seem to have their cause associated with "Mechatronic issues".

The technological domain of the design flaw being unknown applies to only 1 out of the 33 cases belonging to cluster M3 which is characterised by the design flaw resulting in parts to fail – quite in contrast to the 1 out of 4 cases within cluster M1 where the design flaw leads to functional deficiencies.

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[27] $p = 0.003$ (χ^2-test of independence)
[28] Note the importance of the variable "Failure of parts" for the formation of cluster M1 (see Table 7-2)

7.4.3 Magnitude

The participants were asked to assess the severity of the design flaw on the scale level shown in Table 7-4.

Table 7-4 Description of severity levels[29]

Scale level	Description
1	User does not notice
2	Negligible reduction of the product's utility
3	Noticeable reduction of the product's utility
4	Considerable reduction of the product's utility
5	Failure of the product or system [a)] with no or insubstantial damage
6	Failure of the product or system with damage requiring repair
7	Failure of the product or system with substantial but repairable damage
8	Destruction of the product or system
9	Direct danger to the user under certain (operating) conditions
10	Direct danger to the user in unforeseeable conditions

[a)] The term "system" refers to the overall technical object in which the product might be embedded.

Likewise, a value between 1 (occurrence practically impossible) and 10 (occurrence certain) should be assigned to the likelihood of the design flaw.[30] Figure 7-9 shows the frequency distribution of answers regarding severity and likelihood. Both variables do not correlate which means that e.g. less severe design flaws are not more likely to occur (and vice versa).[31]

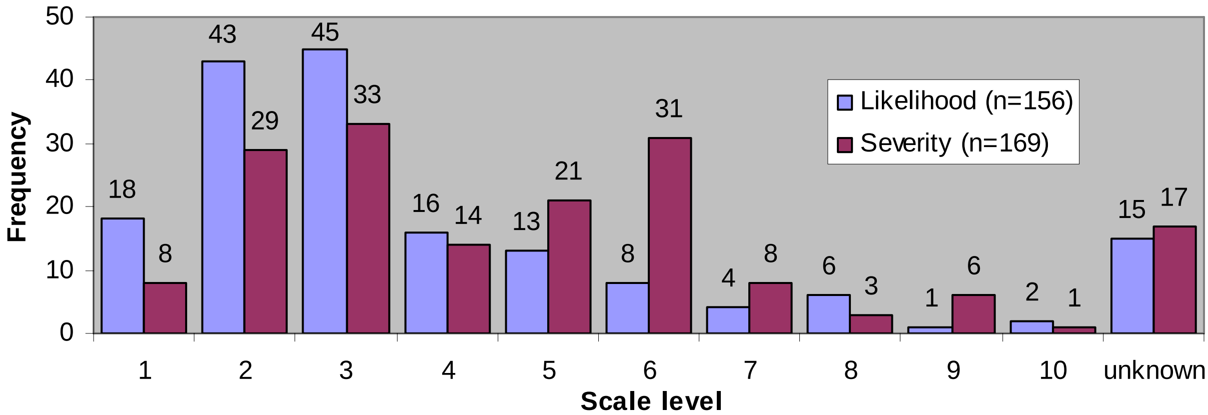

Figure 7-9 Frequency distributions of likelihood and severity of design flaws

[29] Question III.4: "Please assess the severity of the design flaw at the time of its occurrence"
[30] Question III.5: "Please assess the likelihood of the design flaw"
[31] $\tau = 0.036$, $p = 0.577$ (Kendall's τ method)

It is therefore feasible to define a new a variable *magnitude* as the product of severity and likelihood, similar to the risk number (RN) in the FMEA method (see 3.4.2) but assuming values between 1 and 100.

Table 7-5 contains the key statistical figures regarding the magnitude of design flaws in this study and Figure 7-10 shows the frequency distribution of magnitude levels which is observably right-skewed.

Table 7-5 Key statistical figures related to the magnitude of design flaws

n	Minimum	Maximum	Mean value	Standard deviation	25. Percentile	75. Percentile	Median
147	1	70	14.796	12.250	6	18	12

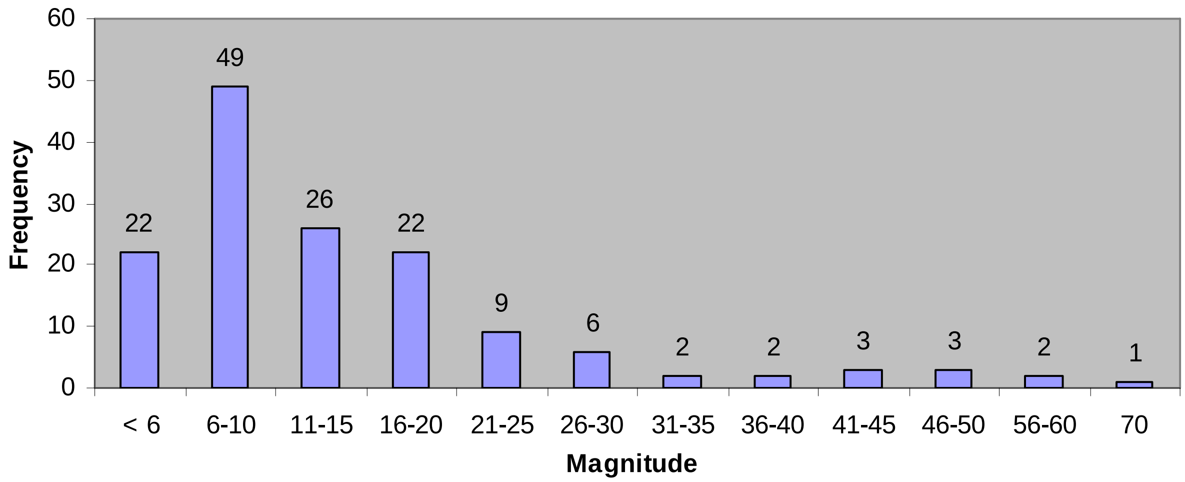

Figure 7-10 Frequency distribution of magnitude levels (n=147)

Table 7-6 compares the magnitudes of consumer goods, investment goods and vendor parts (see 7.3). Although the design flaws of investment goods feature a slightly above-mean magnitude – whereas the mean magnitudes of consumer goods and vendor parts are fairly similar – products from these three categories do not significantly differ in terms of this variable.[32]

Table 7-6 Magnitudes of design flaws by product category

Magnitude / Product category	Minimum	Maximum	Mean value
Consumer good (n = 24)	4	40	14.21
Investment good (n = 87)	1	70	16.22
Vendor part (n = 43)	1	56	13.58

[32] p = 0.588 (Kruskal-Wallis-H test)

In contrast, the differences of magnitudes between clusters describing the manifestation of design flaws (see 7.4.1) are highly significant[33]. As Table 7-7 shows, cases in which design flaws impair the functionality of a product (M1) or cause problems with manufacturing (M4) feature the lowest, almost equal mean magnitude. Cases with multimodal design flaws (M2) exhibit a magnitude whose mean value is well above the mean value of the sample. Design flaws causing parts failure of any kind (M3) reveal the highest mean magnitude.

Table 7-7 Magnitudes of design flaws by their manifestation pattern

Cluster \ Magnitude	Minimum	Maximum	Mean value
M1 (n = 37): "It does not do what it is supposed to"	4	28	11.26
M2 (n = 47): "Multimodal Flaws"	1	48	17.00
M3 (n = 31): "It breaks"	6	70	19.23
M4 (n = 28): "It cannot be manufactured"	1	56	11.69

At this point, the issue of no one of the participants in M3 stating that the design flaw lead to "Poor function fulfilment" shall be revisited (see 7.4.1). Assuming that the product's function has not been impaired by parts failure (which is characteristic for this cluster), only severity levels up to 4 should be observed (see Table 7-4). However, only 12 out of 33 cases in this cluster meet this criterion. In fact, of the remaining cases, 14 feature a severity level of 6 ("Failure of the product or system with damage requiring repair"). Therefore, most participants in M3 probably have ranked "Failure of parts" higher than "Poor function fulfilment", thus seeing no need to select the latter answer option too. In conclusion, the design flaws in M3 lead to physical damage, which in most cases results in the failure of the product. This explains the highest magnitude of all manifestation patterns.

Table 7-8 compares the magnitudes of design flaws by grouping the cases according to the technological domains of the design flaws (see 7.4.2). While "mechatronic" design flaws have a slightly higher mean magnitude than design flaws from the other two clusters, the observed differences are not significant[34].

Table 7-8 Magnitudes of design flaws by their technological domain

Cluster \ Magnitude	Minimum	Maximum	Mean value
T1 (n = 69): "Mechanical issues"	1	60	14.72
T2 (n = 59): "Mechatronic issues"	2	70	15.91
T3 (n = 26): "other/unknown issues"	2	50	14.63

[33] $p = 0.002$ (Kruskal-Wallis-H test)
[34] $p = 0.424$ (Kruskal-Wallis-H test)

7.5 Characteristics of Design Feedback

7.5.1 Modes of Feedback

Figure 7-11 shows how designers responded to the question as to the occasion on which the design flaw became known. Similarly to question III.1 (regarding the manifestation of the flaw), the answer options were given in order of a typical product life cycle, reaching from “During design” to “During disassembly/recycling”.

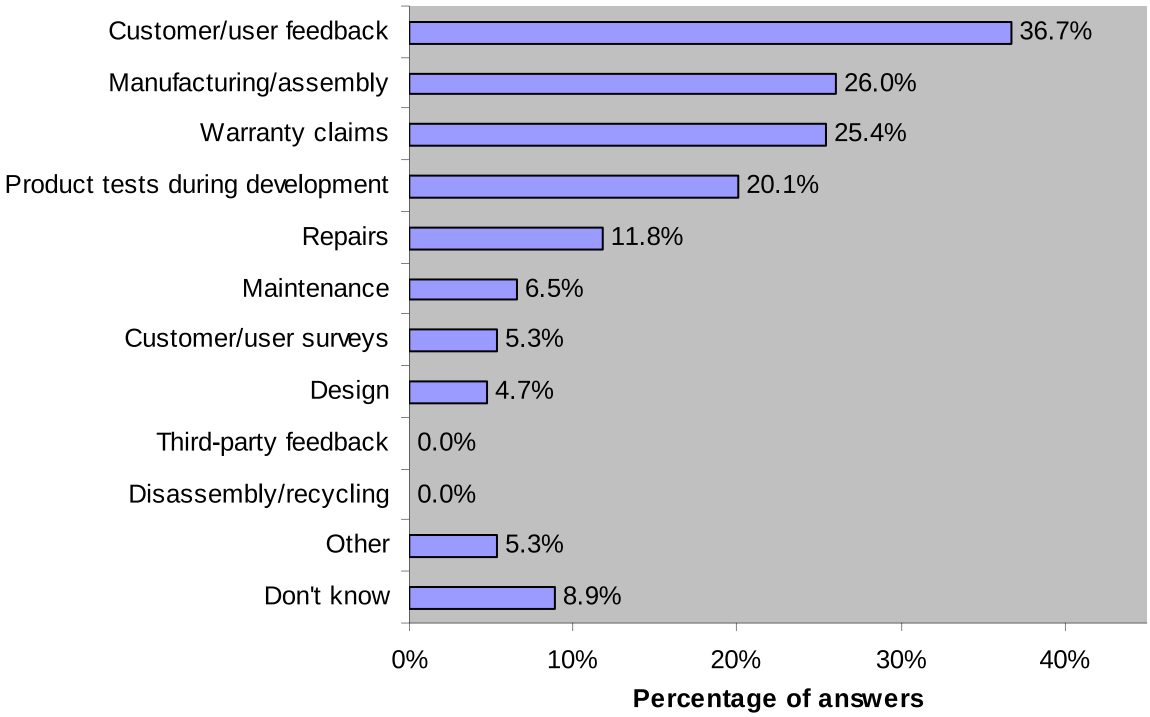

Figure 7-11 Sources of feedback about design flaws[35] (n = 169, multiple answers possible)

The most frequently chosen answer option “Unsolicited feedback by direct users/customers” has been selected by 62 participants, followed by an almost equal number of designers stating “Feedback from manufacturing/assembly” and “While processing warranty claims” (44 and 43 cases respectively) as the source of feedback about the design flaw. In 34 cases, the answer option “Product tests during development” was selected.

Neither answer option “Third-party feedback or feedback from media (e.g. Stiftung Warentest)” nor “During disassembly/recycling” was selected in a single instance, implying that these “miscellaneous” sources of design feedback (see 5.3) play little or no role in practice.

[35] Question III.6: “On which occasion did the design flaw become known?”

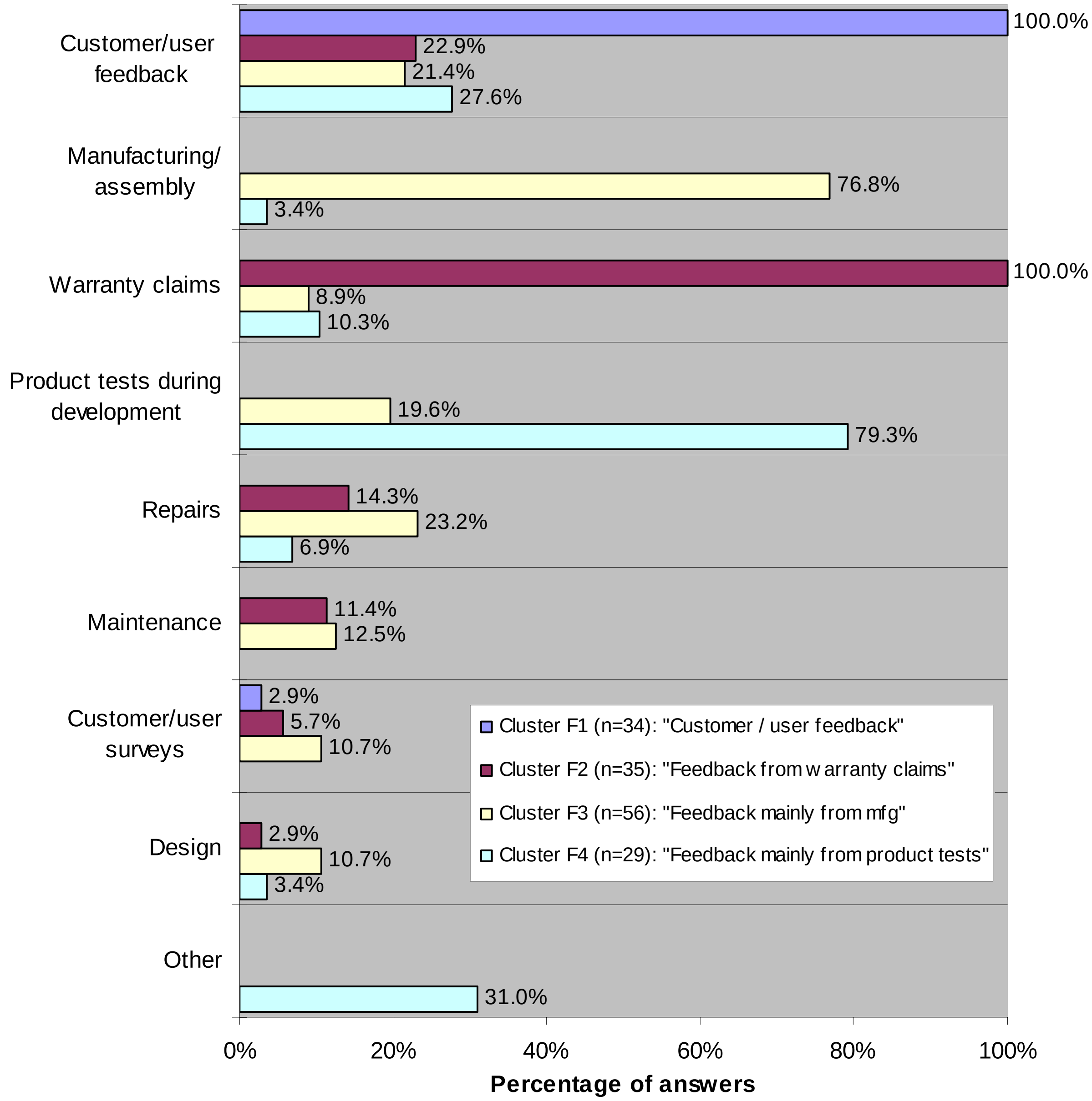

Figure 7-12 Sources of feedback about design flaws by cluster

Like with questions III.1 and III.2, a two-step cluster analysis was carried out on the data to recognise any patterns in the answers. Figure 7-12 above shows the result, i.e. the percentages of answer options for each of the 4 clusters that were identified by the algorithm.

Cluster F1 is easily described: in all of its 34 cases, "Unsolicited feedback by direct users/customers" was stated as source of feedback about the design flaw, in 33 cases of which exclusively (one participant additionally stated "customer/user surveys").

In all 35 cases belonging to cluster F2, designers stated that the design flaw became known while handling warranty claims. Apart from a similar percentage of cases in which "Customer/user feedback" lead to the discovery of the flaw as in clusters F3 and F4, there are also a few cases where other sources of feedback were stated (e.g. "Repairs" and "Maintenance").

In cluster F3, the majority of participants (43 out of 56) stated that they learned from manufacturing or assembly that the design flaw existed. In a fairly equal number cases, the feedback came from repair, direct customers or users, and product tests, being the next most frequent statements (13, 12 and 11 cases respectively).

23 out of 29 designers in cluster F4 reported that the design flaw was revealed in product tests during development (a similar proportion of the most frequent answer as in F3). Also, all cases from the overall sample where the answer option "Other" was chosen are found here.

Table 7-9: p- and χ^2-values expressing the importance of individual variables for the formation of each cluster describing the feedback about design flaws

Cluster / Feedback source	F1		F2		F3		F4	
	p	χ^2	p	χ^2	p	χ^2	p	χ^2
Customer/user feedback	**0.0000**	**50.45**	0.0358	4.41	**0.0041**	**8.26**	0.1640	1.94
Manufacturing/assembly	**0.0002**	**13.60**	**0.0002**	**14.00**	**0.0000**	**63.79**	**0.0027**	**8.97**
Warranty claims	**0.0003**	**13.17**	**0.0000**	**90.35**	**0.0015**	**10.04**	0.0349	4.45
Product tests during development	**0.0019**	**9.63**	**0.0016**	**9.92**	0.6604	0.19	**0.0000**	**55.22**
Repairs	0.0243	5.08	0.8192	0.05	0.0228	5.18	0.3292	0.95
Maintenance	0.1058	2.62	0.3249	0.97	0.1196	2.42	0.1353	2.23
Customer/user surveys	0.4705	0.52	0.9739	0.00	0.1203	2.41	0.1797	1.80
Design	0.1723	1.86	0.5332	0.39	0.0627	3.46	0.6717	0.18
Other	0.1463	2.11	0.1405	2.17	0.0623	3.48	**0.0000**	**33.44**

Significant values in boldface. Values underlined if observed frequencies lower that expected frequencies.
Bonferroni adjustment applied ($\alpha' = 0.0056$).

Table 7-9 shows the relevance of individual variables for the formation of each cluster, revealing no great surprises when comparing the data with Figure 7-12. Therefore, the following descriptions of answer patterns regarding the feedback about the design flaw can be given:

- **Cluster F1 ("Customer/user feedback"):** cases where the design flaw was revealed by unsolicited feedback from customers or direct users.
- **Cluster F2 ("Feedback from warranty claims"):** cases in which warranty claims were the source of feedback about the design flaw.
- **Cluster F3 ("Feedback mainly from manufacturing"):** cases in which the design flaw was detected during manufacturing or assembly.
- **Cluster F4 ("Feedback mainly from product tests"):** cases in which designers learned from product tests during development or from sources not otherwise mentioned that there is a design flaw.

In the following sections, the relationships of these clusters to other findings obtained so far shall be dealt with in more detail.

7.5.2 Customer/User Feedback

Figure 7-13 shows how the clusters describing the manifestation of design flaws (M1–M4; see 7.4.1) are distributed within the cluster of cases in which customer and user feedback lead to the detection of the design flaw. This allows for an analysis of how the manifestation of a design flaw is related to this particular answer pattern of feedback about a design flaw.

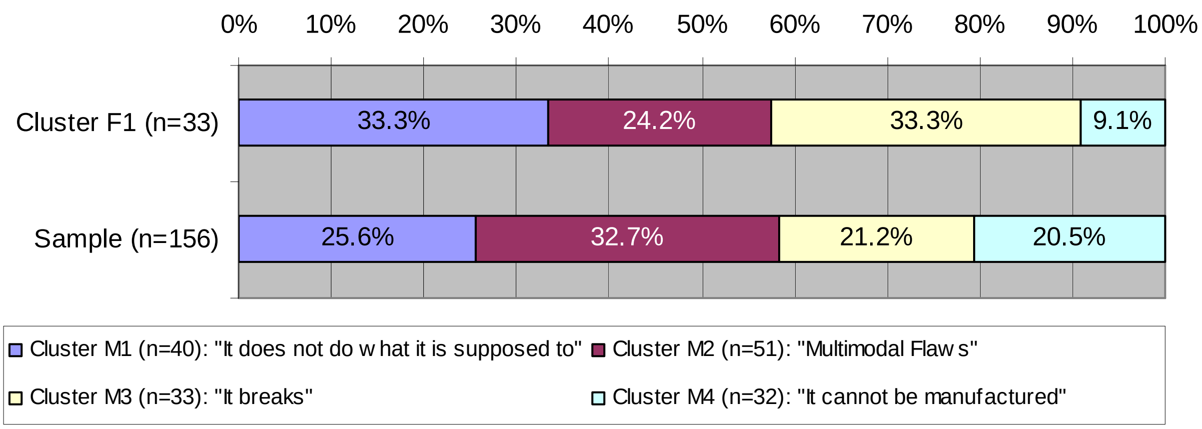

Figure 7-13 Distribution of manifestation clusters in cluster F1 (“Customer/user feedback”) compared to the sample

As can be seen, design flaws impairing the functionality of the product (M1) as well as design flaws leading to physical damage of the product (M3) play a more important role for cases characterised by feedback from customers and users (F1) than for all cases. Although multimodal flaws and flaws causing problems with manufacturing are less instrumental for F1, the observed distribution does not differ significantly from the sample[36].

Figure 7-14 compares the distributions of product categories (see 7.3) within the cluster “customer/user feedback” (F1) and the sample. In F1, there is a slightly higher percentage of investment goods whereas the percentages of consumer goods and vendor parts are lower. However, both distributions do not differ significantly[37].

[36] $p = 0.117$ (Pearson χ^2-test)
[37] $p = 0.581$ (Pearson χ^2-test)

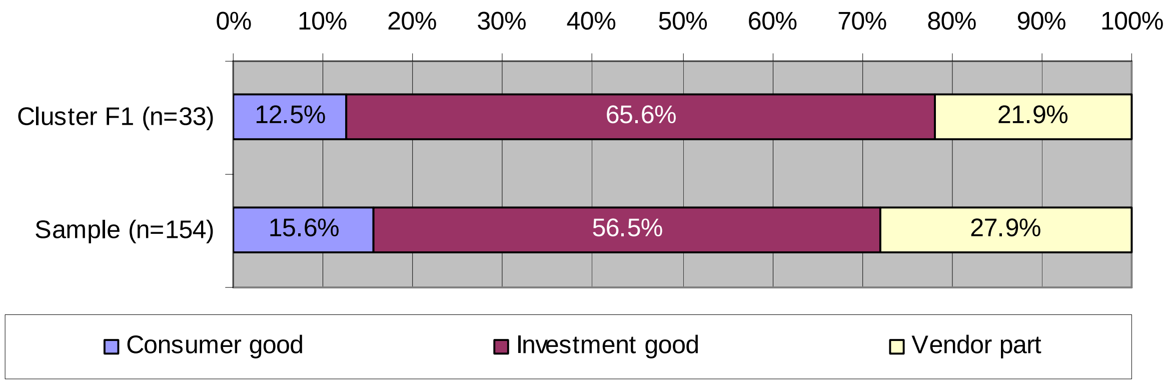

Figure 7-14 Distribution of product categories in cluster F1 ("Customer/user feedback") compared to the sample

As Table 7-10 shows, the mean magnitude (see 7.4.3) of design flaws reported by customer and user feedback is significantly higher than the mean magnitude of all other design flaws.

Table 7-10 Mean magnitude of design flaws

Mean value of magnitude		**p-value (Mann-Whitney-U test)**
Cluster F1 (n = 33) [a)]	Rest of sample (n = 138)	
17.06	14.17	0.043

[a)] Cases in which feedback mainly came from customer/user feedback

7.5.3 Feedback from Warranty Claims

Figure 7-15 shows that in cases where the design flaw was detected by a warranty claim (F2), there is a much lower percentage of cases in which the design flaw caused problems with manufacturing (M4). As with cases of customer/user feedback (F1; see above), there is a higher percentage of breaking (M3) than in the sample, although the relative difference is not as distinct. Functional (M1) and "multimodal" flaws (M3) exhibit a slightly higher percentage. However, the distribution of manifestation patterns (M1–M4) among cases characterised by feedback from warranty claims (F2) does not differ significantly from the distribution in the sample[38].

[38] $p = 0.322$ (Pearson χ^2-test)

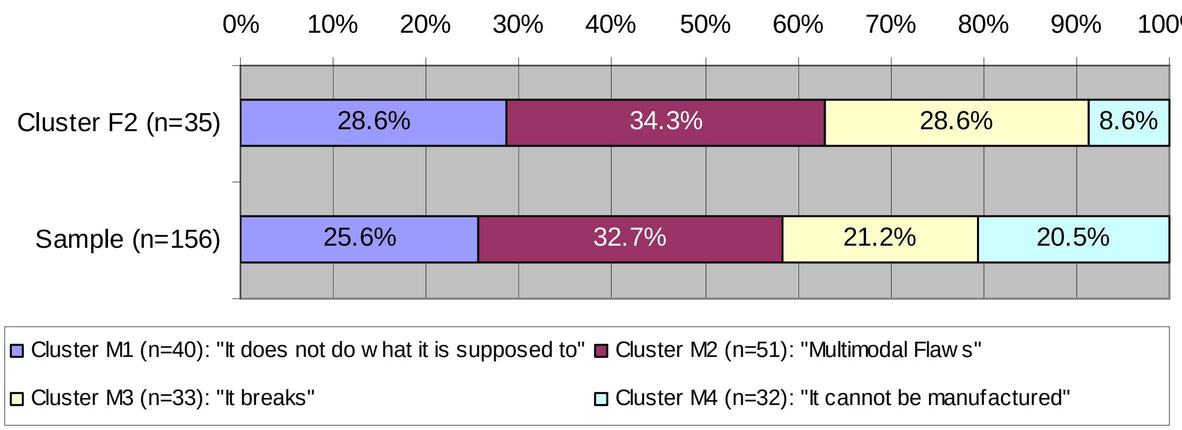

Figure 7-15 Distribution of manifestation clusters in cluster F2 ("Feedback from warranty claims") compared to the sample

While among cases of feedback from warranty claims (F2) a higher percentage of consumer goods and a lower percentage of vendor parts can be observed (Figure 7-16), the overall distribution of product categories is not significantly different from the sample[39].

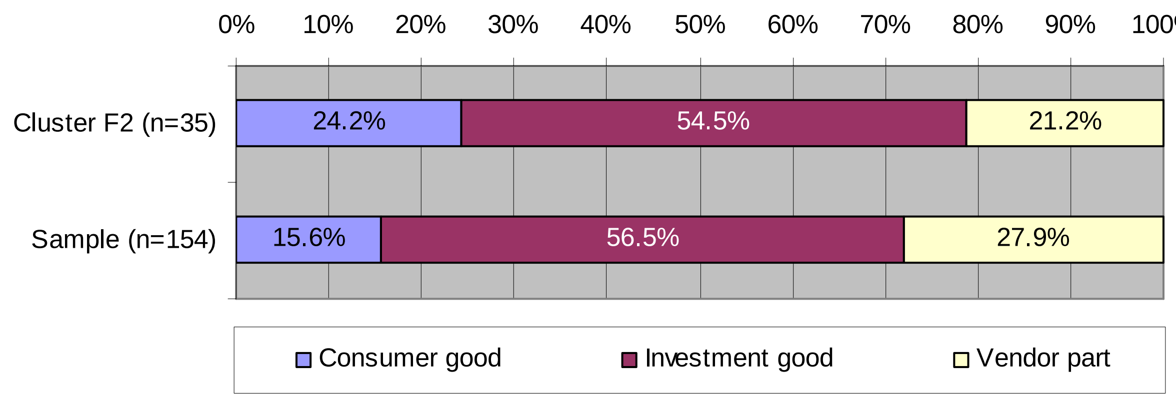

Figure 7-16 Distribution of product categories in cluster F2 ("Feedback from warranty claims") compared to the sample

Although the mean magnitude of design flaws in cluster F2 ("Feedback from warranty claims") is almost as high as the as the mean magnitude of design flaws reported by customer and user feedback (cluster F1; see Table 7-10), the difference to the rest of the sample is only likely significant.

Table 7-11 Mean magnitude of design flaws

Mean value of magnitude		**p-value (Mann-Whitney-U test)**
Cluster F2 (n = 35) [a)]	Rest of sample (n = 131)	
16.67	14.25	0.061

[a)] Cases in which feedback mainly came from warranty claims

[39] p = 0.343 (Pearson χ^2-test)

7.5.4 Feedback from Manufacturing

The distribution of manifestation patterns among cases for which feedback from manufacturing is typical (F3) differs with high significance from the distribution in the sample[40]. In relation to the size of cluster F3 ("Feedback from manufacturing"), there are more than twice as many cases for which design flaws causing problems with manufacturing (M4) are typical than in the sample (Figure 7-17). The high percentage of "multimodal" flaws (cluster M2) can be explained by the high percentage of "Problems with manufacturing" in this cluster (see Figure 7-3).

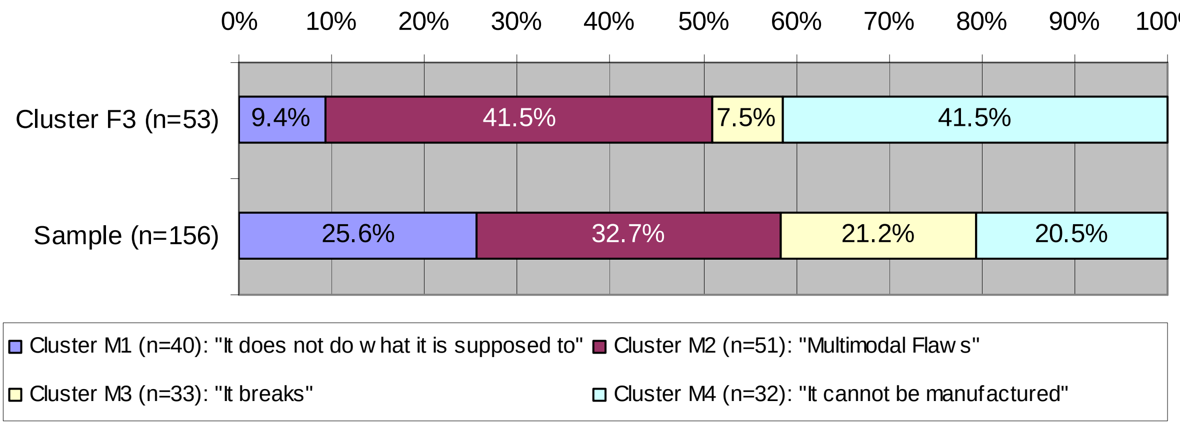

Figure 7-17 Distribution of manifestation clusters in cluster F3 ("Feedback from manufacturing") compared to the sample

As Figure 7-18 shows, the distribution of product categories among cases characterised by feedback from manufacturing (F3) exhibits a clear shift towards vendor parts. As a whole, however, the differences between the distribution in F3 ("Feedback from manufacturing") and the sample is only likely significant[41].

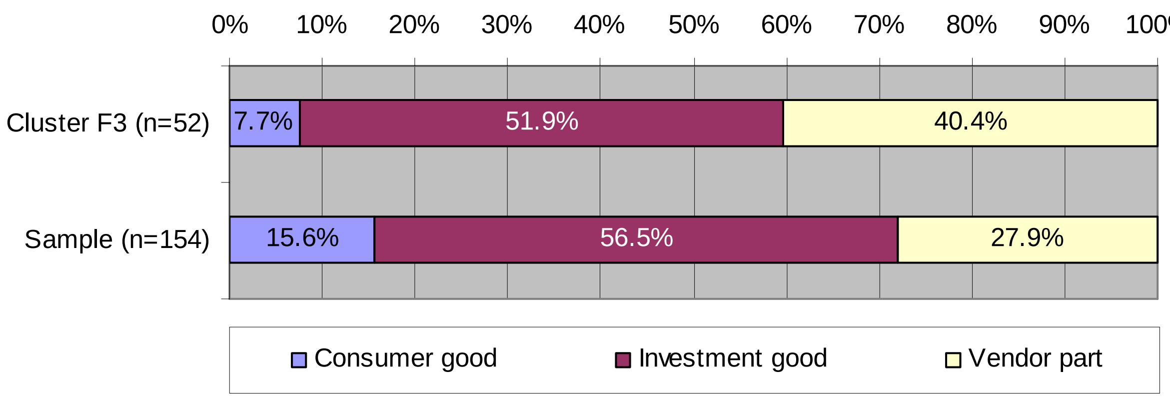

Figure 7-18 Distribution of product categories in cluster F3 ("Feedback from manufacturing") compared to the sample

[40] $p < 0.001$ (Pearson χ^2-test)
[41] $p = 0.076$ (Pearson χ^2-test)

Unlike design flaws which have reached the market, triggering unsolicited feedback by customers and users (F1) or even warranty claims (F2), design flaws reported by manufacturing (F3) – which may not have left the company – have a significantly lower mean magnitude (Table 7-2).

Table 7-12 Mean magnitudes of design flaws

Mean value of magnitude		p-value (Mann-Whitney-U test)
Cluster F3 (n = 56) [a]	Rest of sample (n = 115)	
13.04	15.76	0.022

[a] Cases in which feedback mainly came from manufacturing

Many of the findings presented so far show that manufacturing-related issues seem to play an important role for the manifestation of as well as the feedback about design flaws, in summary:

- Problems with manufacturing and assembly is the most often stated manifestation of design flaws (Figure 7-2), representing a distinct answer pattern (cluster M4; Figure 7-3).
- In cluster M4 (“It cannot be manufactured”), the only other manifestation identified is “Failure of parts” (Figure 7-3) which might be noticeable during manufacturing.
- Cases belonging to that answer pattern feature the largest percentage of a single technological cause of the flaw (mechanical issues; Figure 7-8).
- Manufacturing is the second most important source of feedback about design flaws (Figure 7-11), again being characteristic for a distinct answer pattern (cluster F3; Figure 7-12).

It therefore seems worthwhile to examine the relationship between manufacturing-related design flaws and their revelation in more detail. While clustering the survey data on how feedback about design flaws is received was expedient in order to obtain a better understanding of this topic as such, for the following closer examination of feedback about manufacturing-related design flaws, the unclustered data is used.

Even though 40.5% of designers in the study stated problems with manufacturing and assembly as a manifestation of the design flaw, making it the most frequently selected answer option (Figure 7-2), the percentage of participants stating that they received feedback from that source is notably lower: 26.0% (Figure 7-11). If a certain likelihood is assumed that feedback about a design flaw is most likely received from the stakeholders affected by its manifestation, there is a (theoretical) gap of up to 24.5 percentage points.

Figure 7-19 specifically shows that in cases where the design flaw lead to problems with manufacturing or assembly (M_{mfg}) only 55.7% of designers stated they also learned about it from this source. While this association between manifestation and feedback is statistically significant[42], it is far from being as strong as it could be. Interestingly, the higher relative frequency of cases where the design flaw was known during design is significant as well[43].

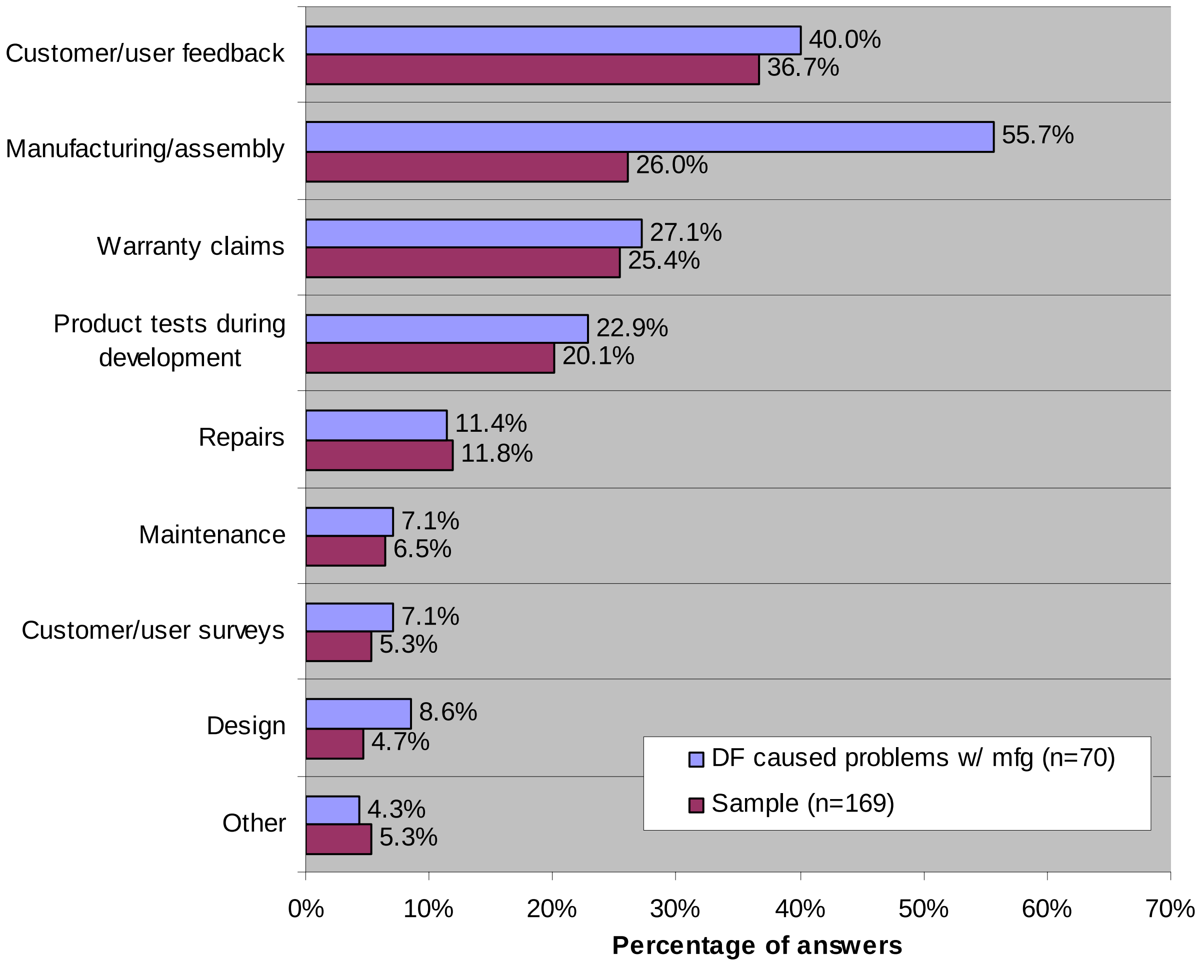

Figure 7-19 Sources of feedback in cases where the design flaw caused "Problems with manufacturing/assembly" compared to the sample[44]

In Figure 7-20, the 70 cases in which the participants have stated that the design flaw manifests itself as to cause problems with manufacturing or assembly have been split into two subsamples by separating the 22 cases where problems with manufacturing and assembly were the only manifestation of the design flaw ($M_{mfg\ only}$) from the 48 cases in which also other manifestations were stated ($M_{mfg\ +\ other}$).

[42] $p < 0.001$ (χ^2-test of independence)
[43] $p = 0.048$ (χ^2-test of independence)

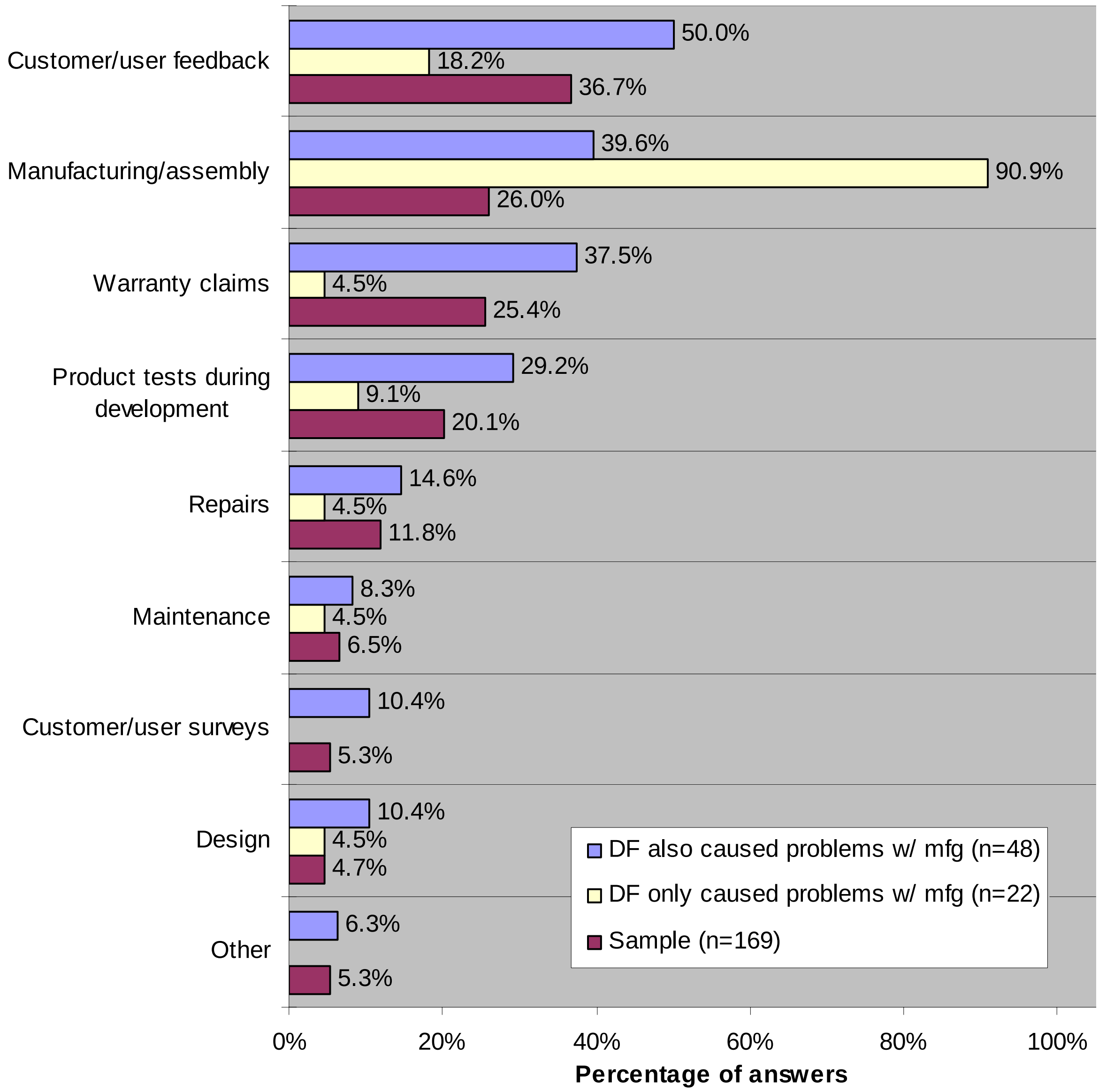

Figure 7-20 Sources of feedback in cases where the design flaw only/also caused "Problems with manufacturing/assembly" compared to the sample[44]

Among the cases in which the design flaw caused problems with manufacturing only ($M_{mfg\ only}$), the percentage of cases in which feedback from manufacturing or assembly was received is considerably higher than in cases where the design flaw also caused problems with manufacturing ($M_{mfg\ +\ other}$). The two cases in $M_{mfg\ only}$ in which still no feedback was received from manufacturing received feedback from customers/users instead.

Figure 7-21 compares the percentage distributions of cases in which the design flaw caused problems with manufacturing only ($M_{mfg\ only}$), of cases in which the design flaw also caused problems with manufacturing ($M_{mfg\ +\ other}$) and the remaining manifestations for the different product categories and the sample. This comparison delivers a more detailed insight into the relationship between manufacturing-related design flaws and which product categories they affect than Figure 7-4 (see 7.4.1) does, showing that compared to the distribution of

[44] Answer options "Third-party feedback", "Disassembly/Recycling", and "Don't know" not shown

frequencies in the overall sample, the observed distribution among vendor parts differs with high significance[45], whereas the distributions among consumer and investment goods do not[46].

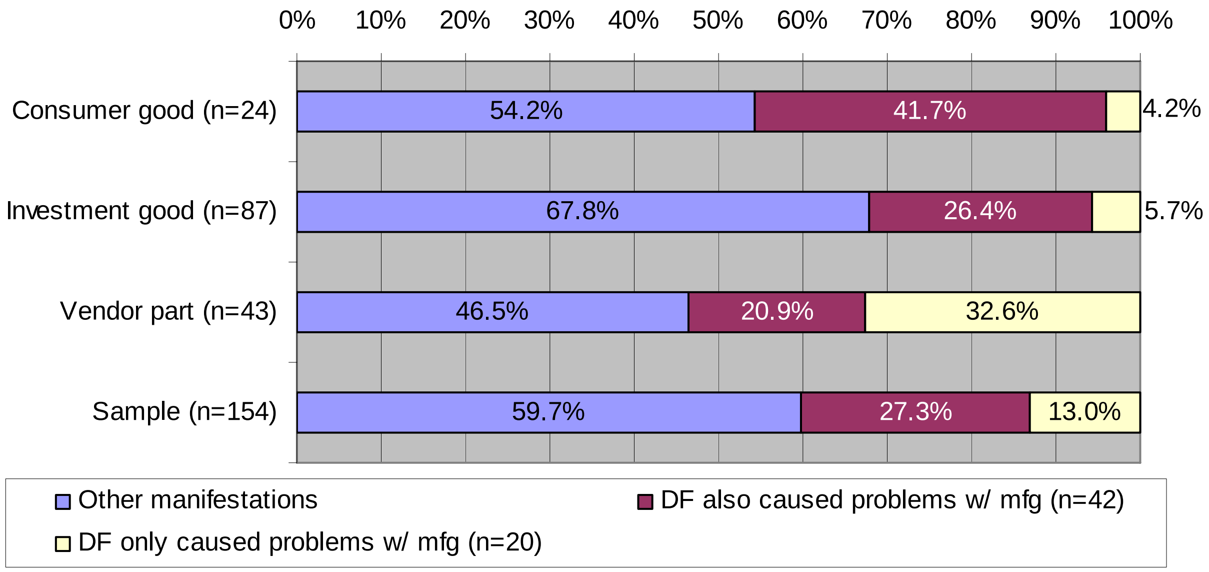

Figure 7-21 Percentage distribution of manifestation patterns of design flaws for different product categories and the overall sample

Therefore, it can be concluded that vendor parts feature the highest percentage of cases where the design flaw affects manufacturing only, for which the (much less ambivalent and more plausible) feedback pattern as described in Figure 7-20 applies. This finding is probably another symptom of the importance of manufacturing-related issues that designers of vendor parts face, indicated by the high production volumes of this product category (see Table 7-1). Also, as those who buy vendor parts usually build them into their own products, feedback from customers can very well be equivalent to feedback from manufacturing (though not the own one).

As far as cases in which the design flaw also caused problems with manufacturing ($M_{mfg + other}$) are concerned (for which customer/user feedback is the most often stated way of learning from a design flaw), there is of course the possibility that in contemplating question III.1 ("How does the design flaw manifest itself?") participants merely *assumed* that problems with manufacturing or assembly would (also) be a potential manifestation. Another explanation would be that the initial feedback came from other sources and that the designers, in the course of events realised themselves that the design flaw indeed had also caused problems with manufacturing.

7.5.5 Feedback from Product Tests During Development

Figure 7-22 shows the distribution of manifestation clusters (M1–M4) among cases characterised by feedback from product tests (F4). Unlike in the sample, design flaws

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[45] $p < 0.001$ (Pearson χ^2-test)
[46] $p = 0.184$ and $p = 0.106$ respectively (Pearson χ^2-test)

impairing the functionality of the product (M1) dominate, followed by design flaws leading to physical damage (M3) and “multimodal” design flaws (M2). Also, design flaws leading to problems with manufacturing play a much lesser role. However, cluster F4 is too small (n=28) for the observed distribution to be significantly different from the sample[47].

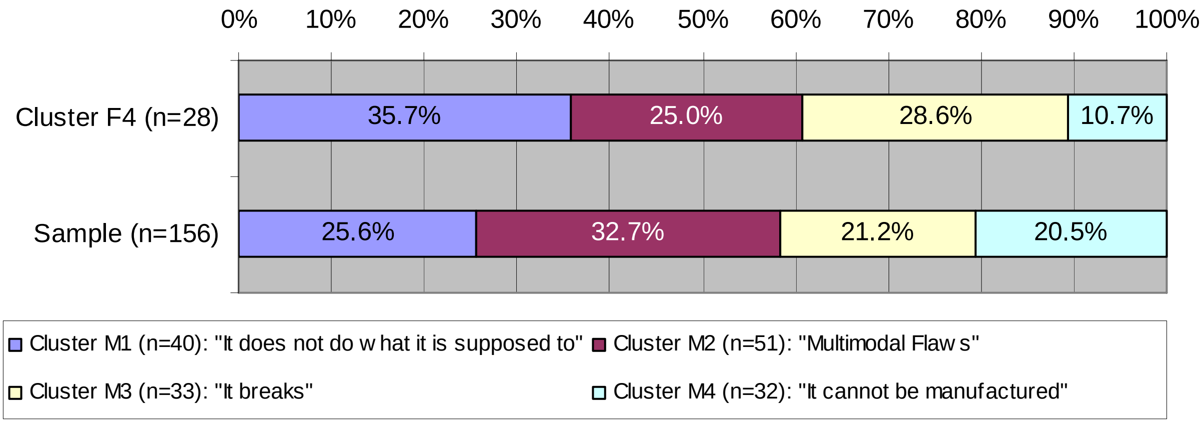

Figure 7-22 Distribution of manifestation clusters in cluster F4 (“Feedback mainly from product tests”) compared to the sample

Figure 7-23 reveals that the distribution of product categories among cases in which feedback was mainly received from product tests (F4) is shifted towards a larger percentage of consumer goods and a lower percentage of vendor parts compared to the sample. The direction of this shift is opposite to the one observed with cases characterised by feedback from manufacturing and assembly (F3; see Figure 7-18). Still, the distributions of product categories in cluster F2 and the sample do not differ significantly[48].

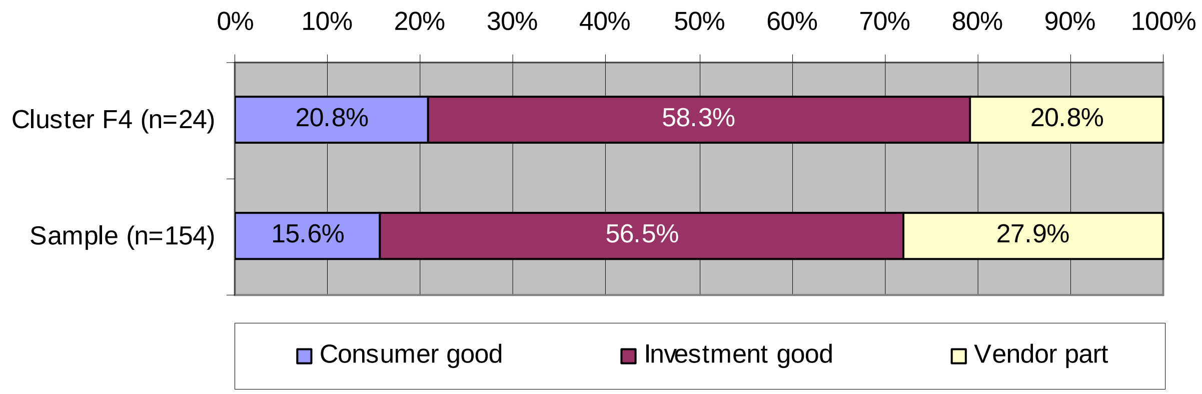

Figure 7-23 Distribution of product categories in cluster F4 (“Feedback mainly from product tests”) compared to the sample

As with those design flaws detected during manufacturing (F3), design flaws that are fed back by testing the product still have the chance of being corrected or at least attenuated before they may affect an external stakeholder. In cluster F4, there were still 27.6% of participants

[47] $p = 0.301$ (Pearson χ^2-test)
[48] $p = 0.647$ (Pearson χ^2-test)

stating that they received “Unsolicited feedback from customers/users” – despite the majority of cases of feedback from “Product tests during development”. While the mean magnitude of design flaws in cluster F4 is indeed lower than in all other cases, the difference is not significant (Table 7-13).

Table 7-13 Mean magnitudes of design flaws

Mean value of magnitude		**p-value (Mann-Whitney-U test)**
Cluster F4 (n = 29) [a)]	Rest of sample (n = 142)	
13.32	15.14	0.148

[a)] Cases in which feedback mainly came from product tests

As discussed in 5.2, testing in all its forms is an important element of product development as it is one of the earliest sources of feedback about the physical (or at least actual) properties of the future product. It is also one of the first occasions on which non-designers get in contact with the product. In the following, the role of testing as a source of feedback about design flaws shall be analysed in more detail. Again, for this analysis the unclustered data is used.

To understand the role that product testing plays, participants were asked to specify how the product was tested during its development. The answer options were given roughly in order of concretisation of the product, reaching from “Testing of individual parts” to “Product trials by selected customers/users (lead user testing)”. The percentages of answers are shown in Figure 7-24.

Not surprisingly, the most frequent answer is “Testing of prototypes/preproduction units” as it is almost certain that during the development of a product, at some point there is some physical object that more or less resembles the products that the later customers will use. However, cases where testing a prototype is not possible would be where a one-off or customised product has been developed. Still, testing individual assemblies, the second most frequent answer, should be feasible regardless of a product’s batch size and can be considered common practice especially with complex products. Quite unexpectedly, lead user testing ranks third. If the answer option was not completely misunderstood, however, this result might show that user integration – at least in late phases of product development – seems to be taken rather seriously by companies.

Figure 7-24 also shows the percentages of applied testing methods for the subsample of those participants who also stated that the design flaw was fed back by “Product tests during development” (see Figure 7-11 in 7.5.1). This comparison allows for an estimation as to how effective the different ways of testing the product have been. Even though the percentages of answer options in Figure 7-24 are generally higher in case where the design flaw was revealed by testing ($F_{testing}$), based on the observed frequencies only the higher percentages of “Testing of individual parts”, “Testing of individual assemblies” and “Mandatory tests” constitute significant results[49].

[49] $p = 0.043$, $p = 0.034$, and $p = 0.014$ respectively (χ^2-test of independence)

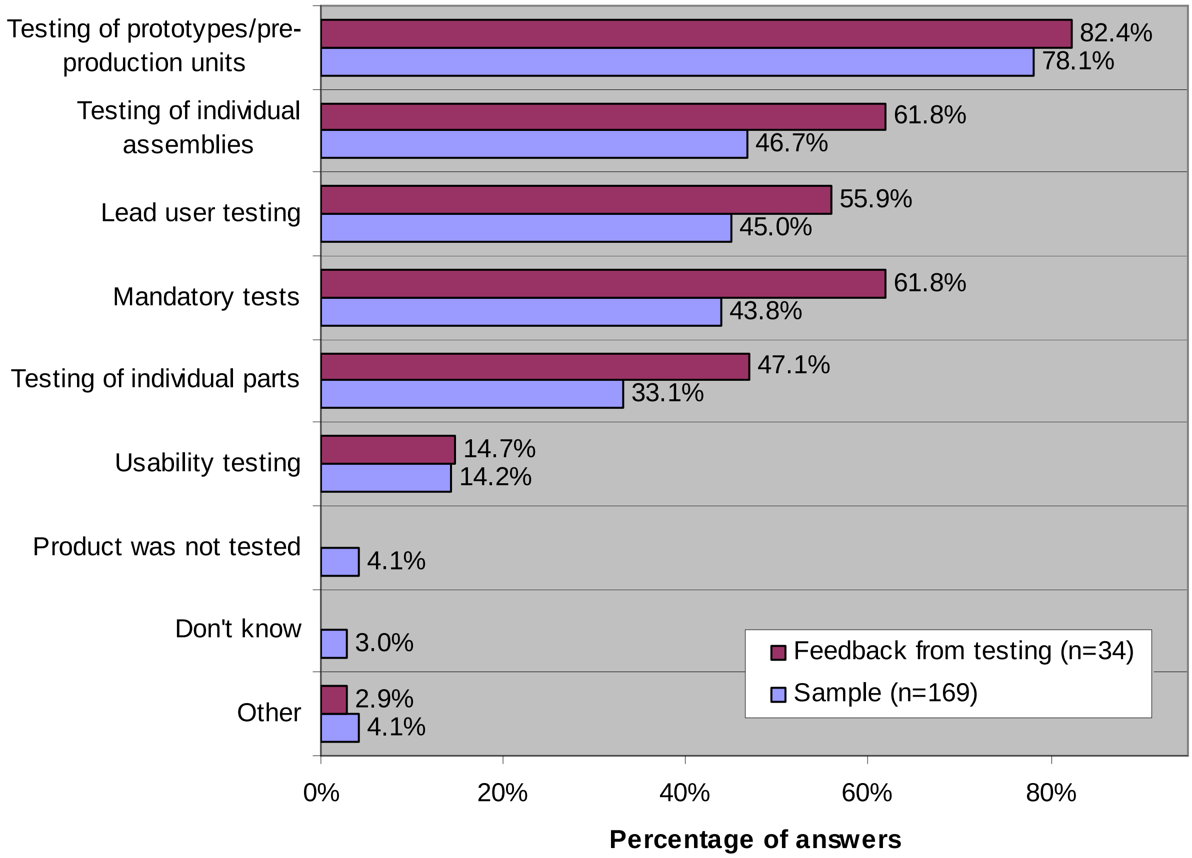

Figure 7-24 Testing methods used in cases where the design flaw was revealed by testing ($F_{testing}$) and the sample[50] (multiple answers possible)

An explanation for that finding could be that the outcome of these testing methods give a comparatively clear "go/no-go signal". Such a signal can be especially obtained from mandatory tests which are often required for a type approval of a new product. For these tests, there are usually clearly defined guidelines not only as to the requirements to specific product properties but also as to how to test them (e.g. the regulations pertaining to the CE-mark).

When a design flaw is detected while the product is still being developed, it should be assumed that companies take all appropriate effort to prevent this flaw from affecting other stakeholders, especially the end-user. As mentioned in 7.2.2, the participants in the study were instructed to refer all questions to a product that was already on the market. The relatively high percentage of cases in which the design flaw was detected in product tests during development (see Figure 7-11) is inasmuch interesting as, should the above assumption hold true and the company has indeed succeeded in preventing the flaw from affecting other stakeholders, there should be no feedback from these sources.

To identify the cases in which design flaws detected during development might not have been prevented from affecting other stakeholders, the cases in which the design flaw was revealed by product tests ($F_{testing}$) were analysed for other sources of feedback.

[50] Question II.9: "How was the product tested during its development?"

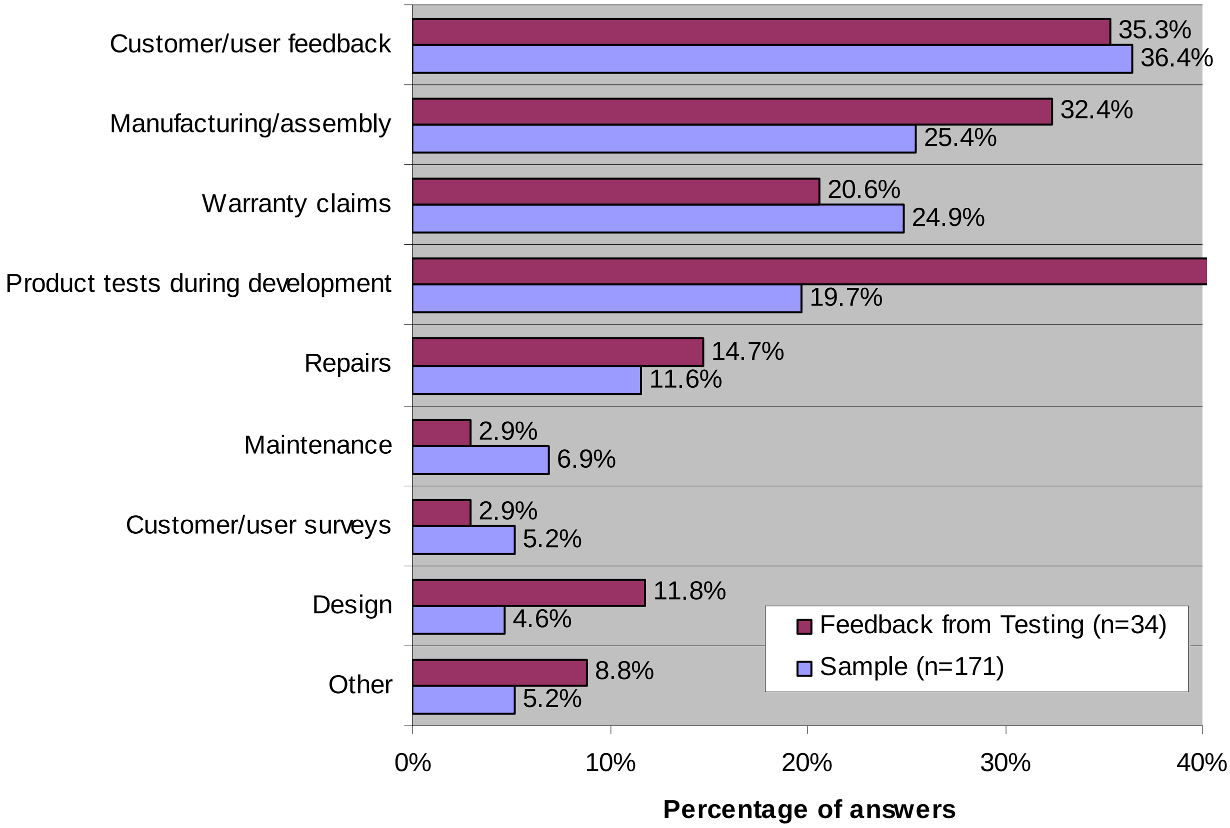

Figure 7-25 Sources of feedback about design flaws in cases where the answer option "Feedback from Testing" ($F_{testing}$) was selected and in the sample

As can be seen in Figure 7-25, even in cases where the design flaw was detected by testing ($F_{testing}$) – and therefore should have been known already during development – the relative answer frequencies regarding other sources of feedback do not differ significantly from the sample (the only example being, quite interestingly, "Design", which is likely significant[51]). The percentages given in Figure 7-25 are based on all 34 cases of ($F_{testing}$). However, by leaving out the 14 cases in $F_{testing}$ where "Product tests during development" was the only selected answer option, there are still 20 cases in which the design flaw must have "slipped through" ($F_{testing + other}$).

Considering the product example of the Ford Pinto (see 2.4), where a quite severe design flaw was discovered by a mandatory crash test but the car was still brought on the market without implementing necessary design changes, it is worthwhile to mention that the mean magnitude of design flaws (see 7.4.3) in $F_{testing + other}$ is significantly[52] lower than in the overall sample (Table 7-14).

[51] $p = 0.053$ (Fisher exact test)
[52] $p = 0.006$ (Mann-Whitney-U test)

Table 7-14 Magnitudes of design flaws in cases where the design flaw "slipped through" compared to the rest of the sample

Product category \ Magnitude	Minimum	Maximum	Mean value
$F_{testing + other}$ (n=19) [a)]	2	15	8.21
Rest of the sample (n=128)	1	70	15.77

a) cases in which the design flaw "slipped through"

Furthermore, the maximum observed severity (see Table 7-4) in $F_{testing + other}$ amounts to a value of 7 which means that the personal safety of individuals was probably not put at risk.

7.6 Determinants of Successfully Correcting Design Flaws

As pointed out in 1.2, an important objective of this thesis is to identify the factors that increase the likelihood of designers successfully correcting design flaws. As discussed earlier, this requires a definition of success that does not only reflect the "true spirit" of what it means to correct (and possibly learn from) a design flaw but which is also measurable in some meaningful way. In this study, this measurement was taken by letting the participant select from one of the answer options shown in Table 7-15.

Table 7-15 Success in dealing with design flaws[53] (n = 171)

	Answer option	Frequency	Percentage
A	The design flaw has not been dealt with. [a)]	13	7.60
B	Attempts were made to develop a solution for the design flaw. [a)]	13	7.60
C	A solution for the design flaw was developed which, however, was not or will not be implemented in the product. [a)]	10	5.85
D	The design flaw was corrected and the solution has been or is currently being implemented in the product. [b)]	135	78.95

a) "unsuccessful" cases

b) "successful" cases

As can be seen, the answer distribution is extremely skewed with almost 80% of participants having selected the answer option that reflects the highest level of success of correcting the design flaw. Therefore, instead of dividing the overall sample into four sub-samples (each corresponding to the level of success as expressed by the selected answer option), the sample was split. In so doing, successful cases are defined as those in which the participants selected the answer option corresponding to D in Table 7-15, whereas unsuccessful ones are those in which designers opted for statements A, B, or C.

53 Question III.8: "Which of the following statements applies most?"

Furthermore, the 135 successful cases were split into cases where the feedback about the design flaw was received from internal stakeholders and cases where this feedback was received from external stakeholders. To form the sub-sample of successful cases in which feedback was received from internal stakeholders, all successful cases belonging to the cluster "Feedback from manufacturing" (F3) were merged with all successful cases from the cluster "Feedback from product tests" (F4). Similarly, the sub-sample of successful cases where the feedback came from external stakeholders was created by combining the clusters "Customer/user feedback" (F1) and "Feedback from warranty claims" (F2). Figure 7-26 illustrates the distribution of successful and unsuccessful cases.

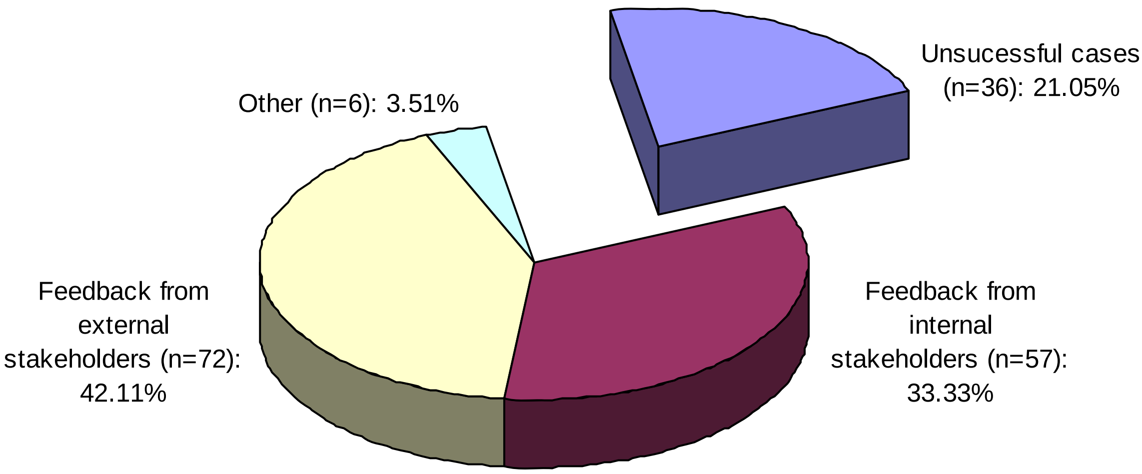

Figure 7-26 Distribution of successful and unsuccessful cases (separated) (n = 171)

Splitting the successful cases into those that received feedback about the design flaw from internal stakeholders and those who learned about it from external stakeholders allows for a more accurate description of success. Companies that managed to correct the design flaws of their products after they were detected on the market are certainly less successful than those that were able to "intercept" design flaws in product testing or manufacturing. Also, it could be alleged that the companies which received (unsolicited) feedback from customers and/or warranty claims were successful in correcting design flaws for a large part because they *had to be*. These issues will dealt with in more detail in the rest of this section.

In the following, the term "determinant" is used in the sense of "[…] an element that identifies or determines the nature of something or that fixes or conditions an outcome" [Merriam-Webster 2006]. In that sense, the previous findings will be analysed as to how they determine the success of designers in correcting design flaws.

7.6.1 Company-related determinants

Table 7-16 compares some company-related data of successful and unsuccessful cases, showing that the successful companies are significantly larger in staff-related terms (i.e. number of employees and number of designers) but do not differ significantly from their unsuccessful counterparts in terms of annual revenue.

Table 7-16 Comparison of successful and unsuccessful cases

Group \ Variable	Number of employees [a] (p = 0.048)			Number of designers [b] (p = 0.005)			Annual revenue [c) d)] (p = 0.206)		
	min	max	median	min	max	median	min	max	median
Successful cases	7	40,000	100	0	6,000	6	0.025	3,000	16.5
Unsuccessful cases	2	6,000	56	0	120	3	0.4	280	8.5
Sample	2	40,000	90	0	6,000	5	0.025	3,000	15.0

p-values based on median test

[a)] Question I.1 [b)] Question I.2 [c)] Question I.3 [d)] in million €

Table 7-17 contains the same data for all successful cases, comparing the cases in which feedback about the design flaw was received from internal stakeholders with cases of feedback from external stakeholders. Both groups do not differ significantly in any of the tested variables.

Table 7-17 Comparison of successful internal and successful external feedback

Group \ Variable	Number of employees [a] (p = 0.426)			Number of designers [b] (p = 0.317)			Annual revenue [c) d)] (p = 0.688)		
	min	max	median	min	max	median	min	max	median
Internal feedback	7	40,000	104	0	6,000	7	0.025	3,000	20.0
External feedback	14	15.000	95	0	800	5	0.055	3,000	15.0
All successful cases	7	40,000	100	0	6,000	6	0.025	3,000	16.5

p-values based on median test

[a)] Question I.1 [b)] Question I.2 [c)] Question I.3 [d)] in million €

7.6.2 Product-related determinants

Figure 7-27 shows the different distributions of product categories (see 7.3) among unsuccessful and successful cases. Among the latter, the distribution of consumer goods, investment goods and vendor parts is also shown for the sub-sample in which feedback was received from internal stakeholders and the sub-sample of cases in which external stakeholders reported the design flaw. Although among all successful cases, a higher percentage of investment goods can be observed, there is no significant relationship between product category and general success[54]. Looking at the successful cases only, it turns out that there is a large difference in the percentages of investment goods and vendor parts between cases of external and internal feedback. In cases of successful external feedback there is a higher than average percentage of investment goods while cases in which manufacturing or product testing revealed the design flaw a higher percentage of vendor parts can be observed.

[54] $p = 0.176$ (χ^2-test of independence)

Still, the relationship between product category and the origin of feedback in successful cases is only likely significant[55].

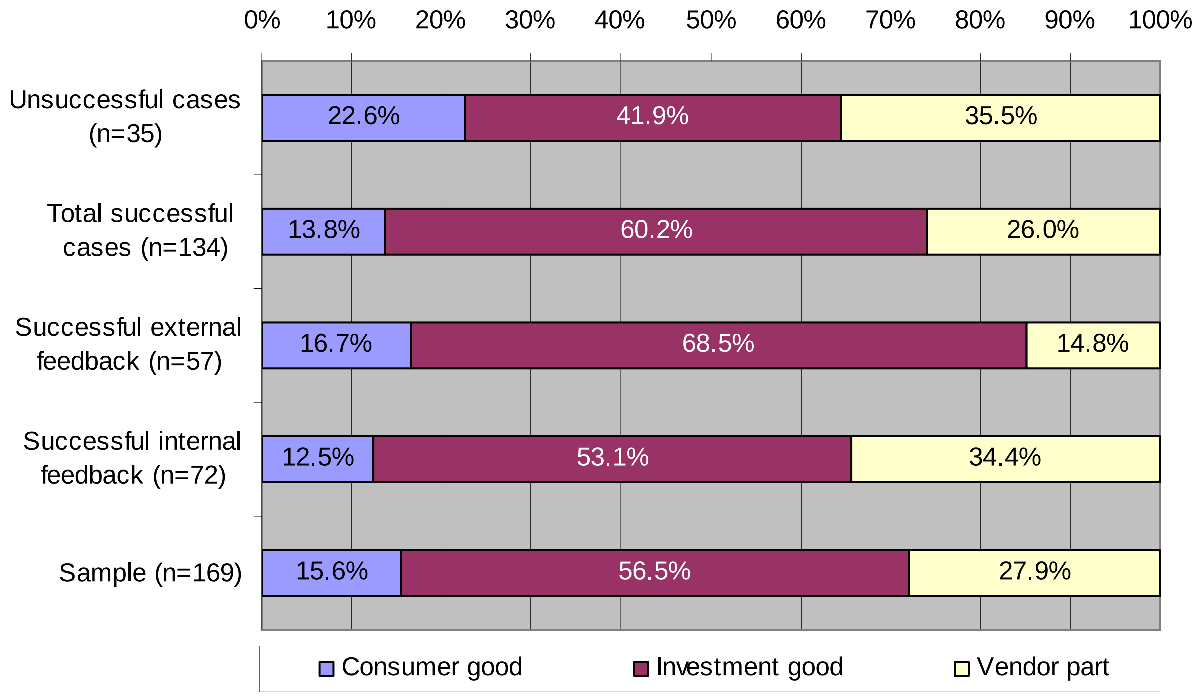

Figure 7-27 Percentage distributions of product categories

Significance aside, a possible explanation for the observation that when design flaws are corrected successfully (according to the definition in Table 7-15) internal feedback is more likely to occur with vendor parts, could again be that products from this category a) are produced in larger quantities than other products which strengthens the role of manufacturing as a stakeholder and b) the fact that vendor parts are usually well specified and well tested (see 7.3 and 7.5.4). The higher percentage of investment goods in successful cases of external feedback could be explained by their low production volume and high complexity (see Table 7-1 in 7.3). Both factors could make "intercepting" design flaws during product development difficult. Therefore, companies might be better prepared for correcting design flaws that are revealed in the field.

Figure 7-28 illustrates how clusters M1–M4 (describing the manifestation of design flaws; see 7.4.1) are distributed among successful and unsuccessful cases. The distribution of manifestations among unsuccessful cases is not much different from the distribution in the rest of the sample. In fact, no significant relationship between general success and manifestation could be observed[56]. The successful sub-sample, however, delivers a quite different picture: among cases in which feedback was received from internal sources, there is a much higher percentage of cases in which the design flaw caused problems with manufacturing (cluster M4) than in cases of successfully correcting design flaws upon external feedback. Likewise, there is a lower percentage of breaking (M3) and loss of

[55] $p = 0.052$ (χ^2-test of independence)
[56] $p = 0.921$ (χ^2-test of independence)

functionality (M1). The observed frequencies represent a highly significant relationship between manifestation of a design flaw and the origin of its feedback in successful cases[57].

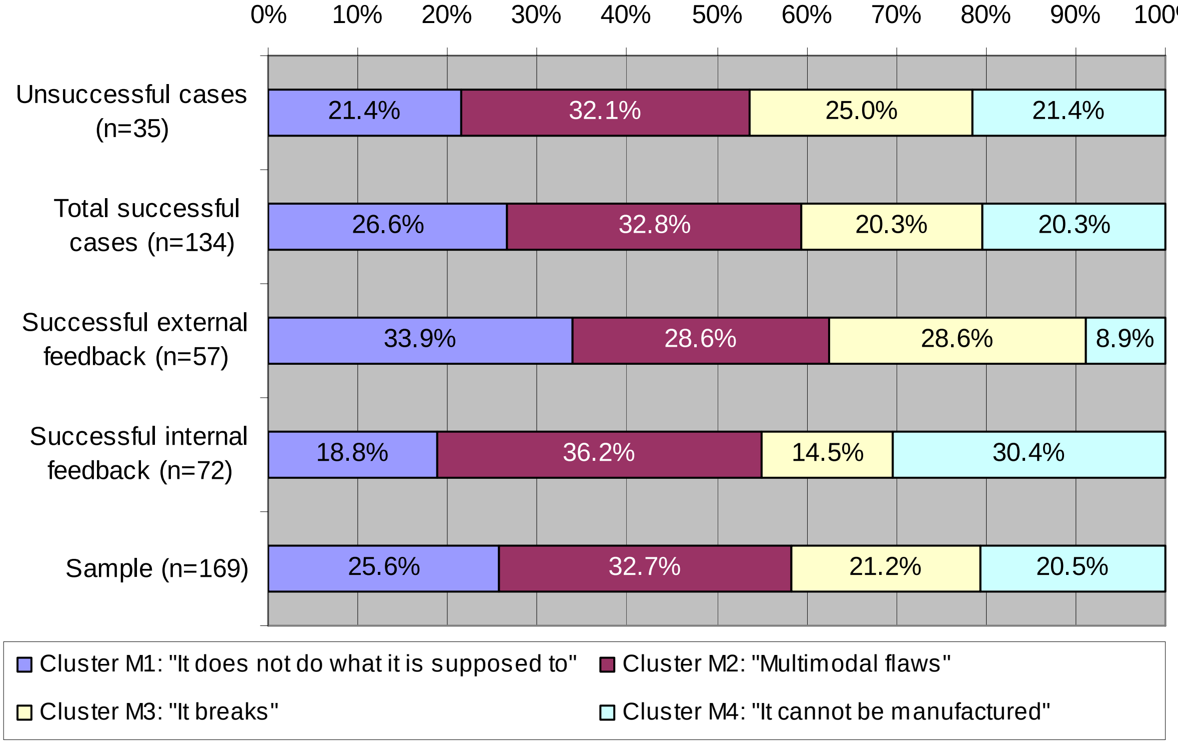

Figure 7-28 Percentage distributions of manifestations of design flaws

This observation might reflect the finding in Figure 7-27 that among successful cases, the group in which internal feedback was received features a higher percentage of vendor parts compared to the group that reacted to external feedback. Vendor parts, as discussed earlier, are much more manufacturing-driven, for which the high percentage of cases characterised by problems with manufacturing (M4) is explainable.

As pointed out in 7.4.2, three major patterns of technological causes of design flaws exist, represented by clusters T1 through T3. Figure 7-29 shows how these clusters are distributed among successful and unsuccessful cases. Observably, cases characterised by predominantly mechanical causes of the design flaw (T1) virtually have the same percentage in all sub-samples as in the overall sample. Among all successful cases, there is a much higher percentage of "mechatronic" causes (T2) and a much lower percentage of "other/unknown" causes (T3) compared to the unsuccessful cases. The observed frequencies constitute a highly significant association between the cause of the design flaw and the general success of its correction[58]. Looking at the successful sub-sample only, in cases where the design flaw was detected by external feedback there is a higher percentage of "mechatronic" causes (T2) than in cases of internal feedback.

[57] $p = 0.004$ (χ^2-test of independence)
[58] $p = 0.003$ (χ^2-test of independence)

Still, there is no significant association between the origin of feedback and the technological cause of the design flaw in cases of successfully correcting it[59].

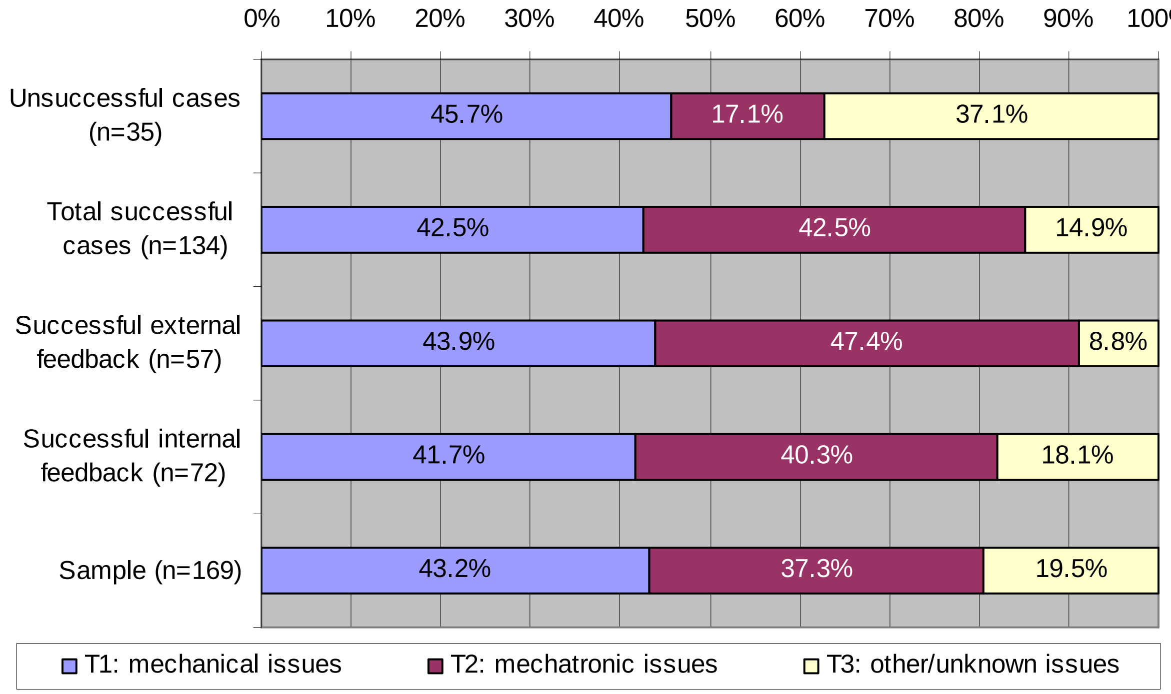

Figure 7-29 Percentage distributions of technological causes of design flaws

A possible explanation for the higher general success rate in cases of "mechatronic" design flaws is the relatively high percentage of cases in which software contributed to the flaw (see Figure 7-6). While software has become ever more pervasive in more and more different products and consequently an increasingly important area of design flaws, the above result also shows that such problems might be solved rather easily – e.g. by means of a software/firmware update (like the example of the mobile phone in 2.6 illustrates). Another interpretation of the data in Figure 7-29 comes at no great surprise: not knowing what causes a design flaw obviously lowers the chance of correcting it.

The relationship between the magnitude of a design flaw (see 7.4.3) and general success in correcting it is shown in Table 7-18. It follows that in successful cases design flaws had a significantly lower magnitude.

Table 7-18 Mean magnitudes of design flaws in successful and unsuccessful cases

Mean value of magnitude			**p-value (Mann-Whitney-U test)**
Successful cases (n=135)	Unsuccessful cases (n=36)	Overall sample [a)] (n=171)	
13.36	22.17	15.77	0.003

[a)] only for comparison

[59] p = 0.306 (χ^2-test of independence)

When the mean magnitudes of design flaws in successful cases only are compared – again according to whether internal or external feedback was received – a yet higher significance is observed (Table 7-19). The finding that design flaws detected by external stakeholders exhibit a significantly higher magnitude than those which are fed back by internal stakeholders supports the consideration from the beginning of this section that a design flaw which has entered the market and is reported from customers puts a much higher pressure on companies to successfully find a solution.

Table 7-19 Mean magnitudes of design flaws in cases of internal and external feedback

Mean value of magnitude			**p-value (Mann-Whitney-U test)**
Internal feedback (n=57)	External feedback (n=72)	Successful cases [a)] (n=135)	
11.49	15.65	13.36	< 0.001

[a)] only for comparison

7.6.3 Feedback-related determinants

To investigate the question whether there is a relationship between internal and external feedback in general, the relative frequencies of successful and unsuccessful cases were compared for the whole sample. Table 7-20 shows that the percentages differ little, indicating no significant relationship between the origin of feedback and the success in correcting the reported design flaw.

Table 7-20 Frequencies and percentages of successful and unsuccessful cases for internal and external feedback

	Successful cases		**Unsuccessful cases**		
	n	%	n	%	Σ
Internal feedback	72	84.71	13	15.29	85
External feedback	57	82.61	12	17.39	69
Σ	129	83.77	25	16.23	154

p = 0.446 (Fisher's exact test); percentages of row values

To better understand how feedback relates to success, the unclustered data about the various sources of feedback (see Figure 7-11 in 7.5.1) is used in the following. Table 7-21 compares the percentages of each source of feedback in successful and unsuccessful cases. It turns out that only product tests and warranty claims are significant determinants of the two sub-samples – both a more often observed in successful cases.

Table 7-21 Sources of feedback about the design flaw in successful and unsuccessful cases (n = 169, multiple answers possible)[60]

Source of feedback	Percentages of answers		p-value (Fisher exact test)
	Successful cases	Unsuccessful cases	
Design	5.2	2.8	1
Product tests during development	**23.7**	**5.6**	**0.017**
Manufacturing/assembly	28.1	16.7	0.202
Warranty claims	**28.9**	**11.1**	**0.048**
Maintenance	7.4	5.6	0.463
Repair	11.9	11.1	1
Unsolicited customer/user feedback	38.5	30.6	0.557
Customer/user feedback	4.4	8.3	0.395
Other	5.2	5.6	1

Significant values in boldface

This finding could explain why in terms of success it is not relevant whether feedback was received from internal or external stakeholders as both significant individual sources of feedback are mutually exclusive to the groups of internal and external feedback. Apart from that, the findings are explainable. Assuring that the product meets its requirements is the reason why product tests are undertaken during development. Finding design flaws is therefore to some extent anticipated. When it turns out by warranty claims that there is a design flaw, companies, should they decide to work out a solution, have to be successful.

Table 7-22 shows the relative frequencies of statements about *how* the products were tested in successful and unsuccessful cases. Not surprisingly, it turns out that in unsuccessful cases, products are significantly more often *not* tested. What makes the finding that successful cases feature a significantly higher percentage of cases in which the products underwent usability tests remarkable is that in 7.5.5 this method of testing has previously been found to contribute least to the detection of design flaws (see Figure 7-24).

Among the successful cases, there is no significant relationship between any testing method and the origin of the feedback (internal or external stakeholders).

[60] Question III.6: “On which occasion did the design flaw become known?”

Table 7-22 Applied testing in successful and unsuccessful cases (n = 169, multiple answers possible)[61]

Variable	Percentages of answers		p-value (Fisher exact test)
	Successful cases	Unsuccessful cases	
No testing	**2.2**	**11.1**	**0.034**
Tests of individual assemblies	48.9	33.3	0.085
Tests of individual parts	35.0	22.2	0.225
Tests with finished prototypes	78.8	66.7	0.113
Mandatory tests	44.5	36.1	0.449
Usability tests	**16.8**	**2.8**	**0.049**
Lead user trials / beta testing	45.3	38.9	0.446
Other	5.1	0.0	0.276

Significant values in boldface

Regardless of the test method as such, feedback from product tests during development being a significant determinant of successfully correcting design flaws is also quite interesting in consideration of the observed phenomenon of design flaws "slipping though", i.e. design flaws affecting other stakeholders despite the fact that they could possibly have been known since the product was tested during development (see 7.5.5).

Table 7-23 shows that of the 20 cases in which the design flaw slipped through ($F_{testing + other}$) there is only one unsuccessful case. Together with the frequencies of all remaining cases, there is a statistically significant relationship between already knowing from earlier testing that the design flaw exists and the subsequent success in correcting it.

Table 7-23 Frequencies and percentages of successful and unsuccessful cases in cases where the design flaw "slipped through" and the rest of the sample

	Successful cases		Unsuccessful cases		
	n	%	n	%	Σ
$F_{testing + other}$ [a)]	19	95.00	1	5.00	20
Rest of sample	115	77.18	34	22.82	149
Σ	134	79.29	35	20.71	169

p = 0.0495 (Fisher's exact test); percentages of row values

[a)] Cases in which the design flaw "slipped through"

As Table 7-24 reveals, not a single case of design flaws "slipping through" in which this design flaw has been corrected successfully was reported by an external stakeholder.

[61] Question II.9: "How was the product tested during development?"

Table 7-24 Internal and external feedback in successful cases of design flaws "slipping through" and the rest of the sample

	Internal feedback		**External feedback**		
	n	%	n	%	Σ
$F_{testing + other}$ [a)]	19	100.00	0	0.00	19
Rest of sample	53	48.18	57	51.82	110
Σ	72	55.19	57	44.81	129

$p < 0.001$ (Fisher's exact test); percentages of row values

[a)] Cases in which the design flaw "slipped through"

7.6.4 Activity-related determinants

In order to identify the task profile of the company's designers, participants were given a list of activities whose order roughly corresponds to the phases of product development, manufacturing and (after) sales. For each activity, the participants should choose from one of the following options:

A. Designers involved or responsible

B. Designers not involved or task outsourced

C. Task generally not undertaken by company

Figure 7-30 shows the results, illustrating that (with the exception of product support) designers are stronger involved in early phases of the product life.

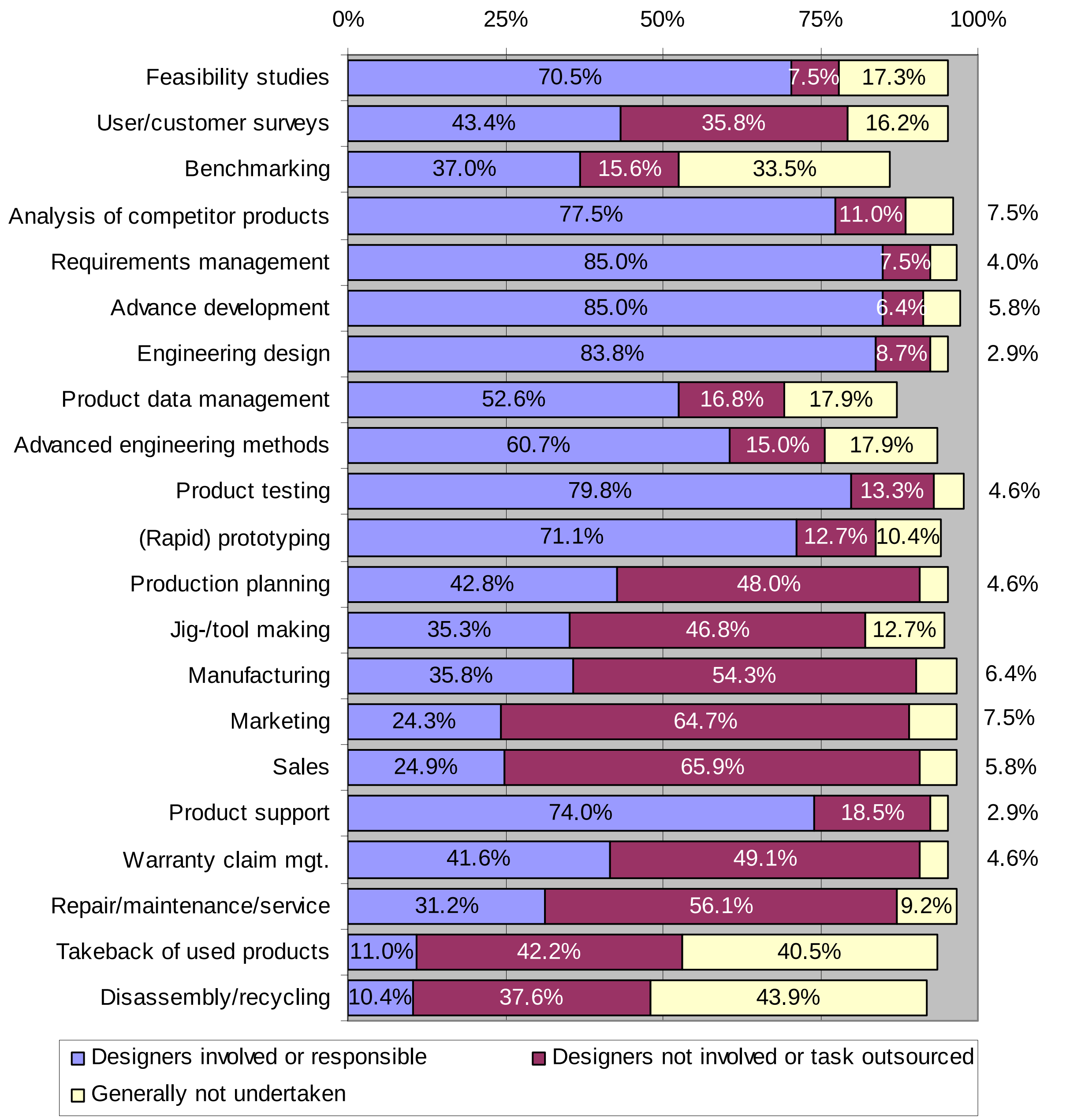

Figure 7-30 Activity profile of designers [62] (n = 171, answer option "Don't know" not shown)

To test whether the activity profiles differ in successful and unsuccessful cases, each answer option was assigned to a value {A, B, C} → {3, 2, 1}, defining an ordinal scale that reflects how close designers are involved in a specific activity.

[62] Question I.4: "In which of the following activities is your company – and especially its designers – involved?"

Table 7-25 Activities with answer profiles that differ significantly in successful and unsuccessful cases

Variable	Percentages of answers [a]						p-value [b] (Mann-Whitney-U test)
	Successful cases			Unsuccessful cases			
	A	B	C	A	B	C	
Feasibility studies	75.4	7.5	14.9	51.4	8.6	25.7	0.047
Customer/user surveys	49.3	32.8	14.9	20.0	48.6	20.0	0.010
Benchmarking	41.8	13.4	33.6	17.1	22.9	34.4	(0.096)
Requirements management	89.6	6.7	2.2	68.6	11.4	8.6	0.031
Product data management (PDM)	56.7	17.2	14.9	37.1	17.1	25.7	(0.059)
Advanced engineering tools	65.7	16.4	14.2	42.9	11.4	28.6	0.043
Product support	79.1	15.7	2.2	57.1	25.7	5.7	0.036
Take-back of used products	12.7	44.8	38.1	5.7	31.4	48.6	(0.082)

Difference to 100%: “Don’t know”.

[a] Option key: A: designers involved or responsible; B: designers not involved or task outsourced; C: generally not undertaken.

[b] Likely significant values in brackets

Table 7-25 contains the activities for which a significant or likely significant difference in the level of involvement was found when comparing the successful with the unsuccessful cases. Note that the percentage values are given for informational purposes only as the abovementioned scale values were used as input for the applied Mann-Whitney-U test. Since this test is rank-based, any scale values $\{s_1, \ldots, s_i\}$ for which an order $s_1 > s_2 > \ldots > s_i$ or $s_1 < s_2 < \ldots < s_i$ exists, delivers the same result.

Most activities in which designers of successful companies are more closely involved seem to be traditionally design-related, including product support, which, in German companies, is a task not untypical for design engineers[63].

Feasibility studies, customer/user surveys and (possibly) benchmarking being significant determinants of success might show that closer involvement in (early) analytical activities, aiming at gaining a better understanding of technical, market and competitive constraints, play an important role in enabling designers to successfully react to design flaws of their products.

Conversely, there is no indication that – in general (see below) – closer involvement in any task outside the scope of what can be considered the core activities of designers is typical for cases in which the design flaw has been successfully corrected. Taking manufacturing as an example, there is no reason to conclude from the data that designers being more closely involved in this activity is a significant determinant of success – despite the importance of

[63] The term “Produktpflege” used in the German questionnaire has a strong connotation implying (continuous) product improvement.

manufacturing regarding manifestation and feedback of design flaws as pointed out in 7.4 and 7.5.

Regarding the successful cases only and comparing the cases of internal feedback with those of external feedback in the same manner as in Table 7-25 reveals no activity which differs significantly in terms of involvement.

However, when comparing the successful cases of internal feedback (see Figure 7-26) with the rest of the sample, the results in Table 7-26 are obtained.

Table 7-26 Activities with answer profiles that differ significantly in successful cases of internal feedback and the rest of the sample

Variable	Percentages of answers a)						p-value b) (Mann-Whitney-U test)
	Successful internal feedback			Rest of sample			
	A	B	C	A	B	C	
Feasibility studies	77.8	9.7	11.1	64.6	6.1	22.2	0.030
Customer/user surveys	55.6	27.8	12.5	34.3	41.4	19.2	0.013
Benchmarking	50.0	11.1	26.4	27.3	18.2	39.4	0.015
Requirements management	90.3	5.6	2.8	80.8	9.1	5.1	(0.082)
Advanced engineering tools	66.7	18.1	12.5	56.6	13.1	21.2	(0.072)
Marketing	31.9	58.3	8.3	19.2	68.7	7.1	(0.076)

Difference to 100%: “Don’t know”.

a) Option key: A: designers involved or responsible; B: designers not involved or task outsourced; C: generally not undertaken.

b) Likely significant values in brackets.

It turns out that out of the six activities identified as being a (likely) significant determinant of successful cases in which feedback was obtained from internal stakeholders, all except “Marketing” are also found among the activities in which successful designers are more closely involved in general (see Table 7-25). The data also indicates that the designers from the analysed sub-sample show an even closer involvement in all activities they share with successful designers in general. While all of these activities belong to the early phase of the product life cycle, it shows that in cases of successfully correcting design flaws upon receiving feedback from internal stakeholders designers are with likely significance more closely involved in an activity not traditionally associated with engineering design: marketing.

Similar to the above, successful cases of receiving feedback from external stakeholders were compared with all other cases. As Table 7-27 shows, there are quite few activities that differ significantly in terms of involvement. The only activity outside the typical task spectrum of product developers is “Repair/maintenance/service”.

However, this observation is probably explained by the high percentage of investment goods in this group (see Figure 7-27). Compared to products from other categories, investment goods typically need to be repaired and serviced more often and – in a B2B environment (see

7.3) – often by the companies who also designed them. This explanation is supported by the fact that the cases not belonging to the sub-sample of successful external feedback exhibit a comparatively high percentage of answer option C ("generally not undertaken"), which also contributed to the significance of the observed differences. When only comparing the percentage ratios of options A and B, there is virtually the same ratio in successful cases of external feedback and in the rest of the sample (1:1.8 vs. 1:1.82).

Table 7-27 Activities with answer profiles that differ significantly in successful cases of external feedback and the rest of the sample

Variable	Percentages of answers a)						p-value b) (Mann-Whitney-U test)
	Successful external feedback			Rest of sample			
	A	B	C	A	B	C	
Advance development	93.0	5.3	1.8	80.7	7.0	7.9	0.028
Product testing	87.7	10.5	1.8	75.4	14.9	6.1	0.047
Product support	82.5	12.3	1.8	69.3	21.9	3.5	(0.071)
Repair/maintenance/service	35.1	63.2	1.8	28.9	52.6	13.2	0.043

Difference to 100%: "Don't know".

a) Option key: A: designers involved or responsible; B: designers not involved or task outsourced; C: generally not undertaken.

b) Likely significant values in brackets.

Interestingly, designers in cases characterised by successfully correcting design flaws upon receiving feedback from external stakeholders (including warranty claims) are also significantly closer involved in product testing – which would rather be expected in cases of successfully correcting design flaws revealed by internal feedback (for which feedback from product testing has been found to be characteristic; see 7.6)

In 6.2, it was pointed out that the design process, and therefore the activities of the designers, strongly depends on the design problem. An important dimension of which is its novelty. Hence, participants were asked to chose from the statements in Table 7-28 the one that best describes the development process of the product. The wordings of these options are each equivalent to the definitions of original (A), adaptive (B) and variant design processes (C) as defined in [Pahl & Beitz 1996].

Table 7-28 Answer options describing original, adaptive and variant designs[64] (n = 171)

	Answer option	Frequency	Percentage
A	“Development of new solution principles for a substantially new problem or task and/or entering a new technological territory”	31	18.31
B	“Adaptation of an existing design to new boundary conditions using well-tried solution principles; task not basically new”	111	64.94
C	“Adaptation to new boundary conditions by variation of existing parts/assemblies as part of processing an order”	18	10.53
D	Don’t know	11	6.43

Figure 7-31 shows how original, adaptive and variant designs are distributed in the sample as well as in unsuccessful and successful cases of correcting design flaws. For the overall sample, the percentage distribution of original, adaptive and variant designs is in accordance with literature, e.g. [Pahl & Beitz 1996] or [Hundal 1997].

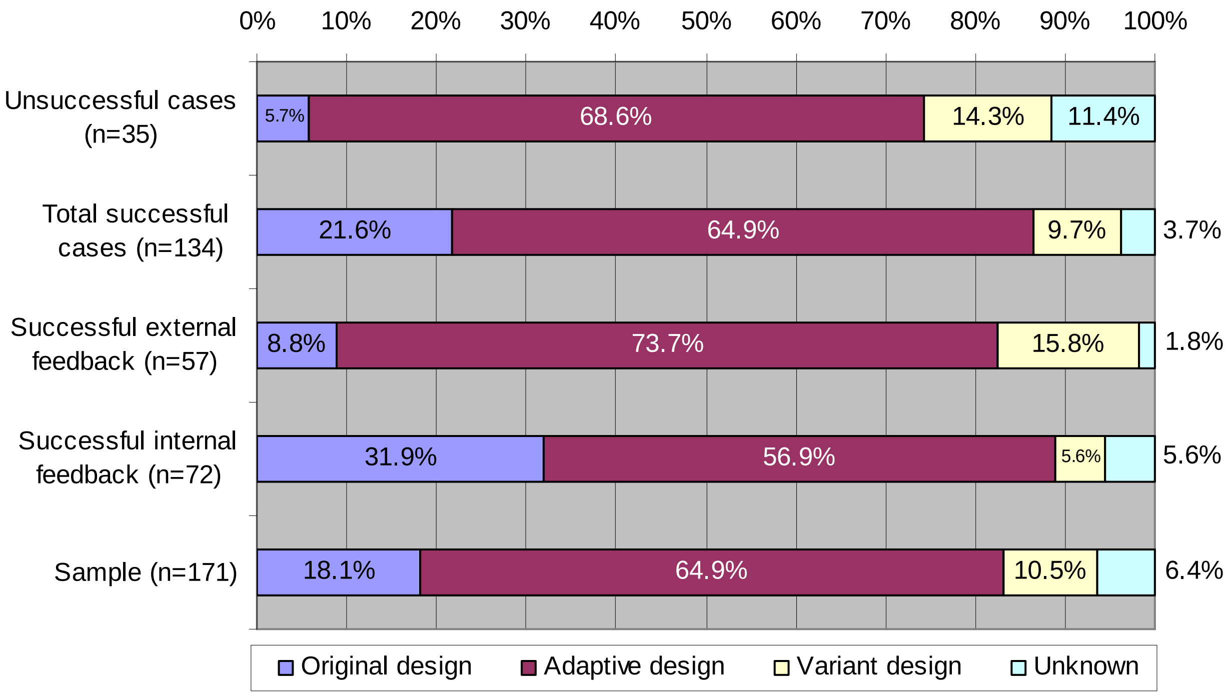

Figure 7-31 Percentage distributions of original, adaptive and variant designs

When comparing the total of successful with the unsuccessful cases, however, it strikes that among the latter there is a higher percentage of adaptive designs, variant designs and cases in which the participants opted “Don’t know” as an answer, whereas the relative frequency of original designs is noticeably lower.

The same is observed in cases of successful external feedback when this group is compared to the cases of successful internal feedback, the offset being even bigger.

[64] Question II.8: “Which of the following statements applies most?”

Table 7-29 reveals how significantly the groups shown in Figure 7-31 differ. A χ^2-test of independence was used to find out whether there is a significant relationship between the regarded sub-sample and the design type. It turns out that there is just a likely significant relationship between design type and general success in correcting design flaws. When design flaws are corrected successfully, however, there is a highly significant relationship between the origin of feedback (i.e. from internal or external stakeholders) and the observed frequencies of original, adaptive and variant designs.

Table 7-29 p-values of different tests comparing successful and unsuccessful cases for different variables

Test \ Sub-samples	Unsuccessful vs. total successful cases	Successful internal vs. successful external feedback
χ^2-test of independence	0.057	**0.003**
Mann-Whitney-U test [a)]	**0.042**	**< 0.001**

Significant p-values in boldface

[a)] cases in which "Don't know" was stated excluded

When interpreting original, adaptive and variant design using an ordinal scale representing the novelty of the designed product, a Mann-Whitney-U test can be applied (in a similar fashion as in the above analyses of the activity profiles). Table 7-29 shows that according to the observed frequencies, the products in the total of successful cases are significantly more "novel" than the products in the unsuccessful cases. Products whose design flaws have been successfully corrected upon receiving feedback from internal stakeholders are even highly significantly more "novel" than products whose design flaws were successfully correcting in reacting to external feedback.

7.7 Discussion

7.7.1 Summary of the Findings

The findings in this chapter establish an empirical relationship between the characteristics of products, the characteristics of and the feedback about their design flaws and, most importantly, the success designers had in correcting them. Due to the exploratory nature of the study, special data analysis methods were required, allowing to identify patterns and filter out irrelevant factors. Using a two-step clustering algorithm, this objective was achieved very well. While the results of clustering algorithms can never be said to be "right" or "wrong", all of the identified patterns passed the test of "common-sense". Also, all cluster-based comparisons showed significant differences (except for one instance).

The categorisation of consumer goods, investment goods and vendor parts allowed for a differentiated view of products of provably different complexities, life spans and production volumes (see 7.3).

As far as the design flaws of these products are concerned, it has been shown that problems with manufacturing, failure of parts and poor function fulfilment are the most important manifestations both in terms of being the three most often stated problems, but also as characteristic variables of according clusters (see 7.4.1).

As a technological cause, mechanical issues are stated in more than half of the cases, clearly dominating the picture. Among these cases, however, purely mechanical and “mechatronic” causes can be clearly distinguished, the latter cause pattern being most typical for investment goods (see 7.4.2).

Manufacturing remains an important factor also for the feedback of design flaws, surpassed only by direct, unsolicited feedback from users or customers (see 7.5.1). Considering the nature of vendor parts, however, it can be assumed that a certain percentage of answers indicating the latter source of feedback may also relate to manufacturing (to that of the OEM, that is). Nonetheless, feedback coming mainly from manufacturing is characteristic of the largest cluster that was identified among the data on the sources of feedback (F3), next to feedback from warranty claims (F2), unsolicited feedback by customers or users (F1) and feedback from product tests (F4).

Regarding the feedback of manufacturing-related design flaws, a clear communication gap between manufacturing and design was identified as in only 55.7% of cases in which a design flaw caused problems with manufacturing, feedback was received from that source (see 7.5.4). This phenomenon is particularly observed among consumer and investment goods.

A deeper analysis of product tests as a source of feedback about design flaws reveals that not all testing methods are equally effective in terms of detecting design flaws (see 7.5.5). However, the most important finding related to testing as a source of design feedback is that in some cases, products with design flaws must have entered the market despite the fact, that their flaws were known from product tests already.

According to the data obtained in this study, companies are quite successful in correcting design flaws. Almost 80% of cases were “success stories” of designers having found a solution and implementing that solution into their products (see 7.6). To allow for a more accurate description of success, these generally successful cases were split into two groups according to whether feedback was received from internal or external stakeholders.

Firms belonging to the generally successful group have been found to be significantly larger in terms of employees and designers, a finding that is unsupportive of the view that smaller companies with their flatter hierarchies and more flexible structures might be more likely to succeed in correcting design flaws (see 7.6.1). A product-related determinant of success has been found in the technological cause of the design flaw as “mechatronic” design flaws were significantly more often corrected successfully (see 7.6.2).

The relation between feedback about design flaws and the success in correcting them is such that design flaws revealed by product tests and warranty claims are significantly more often found among successful cases. Also, the previously identified group of cases in which products were brought on the market despite the companies knowing from product tests that they suffer from a design flaw has been found to contain significantly more successful cases than the rest of the sample (see 7.6.3).

Regarding the activities of designers, it was found that generally, closer involvement in “traditional” tasks are a determinant of success. However, in successful cases of receiving feedback from internal stakeholders (see above), a likely significantly closer involvement in marketing is observed. In cases of successfully correcting design flaws upon receiving feedback from internal stakeholders, designers seem to be significantly more closely involved in repair, maintenance and service.

Perhaps the most interesting finding of the study is that among successful cases, there are significantly more products which are the outcome of an original design process after [Pahl & Beitz 1996]. This difference is even more distinct when successful cases of receiving external feedback are compared with successful cases of receiving internal feedback, the latter group featuring a significantly higher percentage of original designs and a significantly lower percentage of adaptive and variant designs (see Table 7-29). Obviously, if adaptive and variant designs benefit from any know-how or experiences from the past, it is not leveraged in terms of successfully correcting any flaws.

7.7.2 Alternative Explanations

While possible alternative explanations for the findings were discussed specifically in the particular sections, there are more general issues which shall be addressed here.

The first issue concerns the clustering that was used to group similar cases. While the identification of these patterns follows strict algorithms, their interpretation (and labelling) is necessarily subjective. Especially with cluster-based comparisons, it is important to realise that it is not the cluster labels that are being evaluated but a group of cases in which (some) variables have similar values.

Another issue deals with what could be called a possible “manufacturing bias” of the obtained answers, observable particularly in the response to question III.1 (“How does the design flaw manifest itself?”; Figure 7-2) and III.6 (“On which occasion did the design flaw become known?”; Figure 7-11). This phenomenon probably needs to be seen in context with the organisational realities of companies. In the typical product development cycle, manufacturing is the closest neighbour to design and manufacturing-related issues relatively close to the spheres of influence and experience of designers.

As a final issue, considering that among the successful cases we find in summary more original, more sophisticated products designed by professionals being more closely involved in activities like PDM and advanced engineering methods while being part of a comparatively large workforce, the question is to what extent the results, as a whole, simply reflect large, capable companies outperforming smaller “backyard-businesses”.

7.7.3 Limitations of the Study

Whereas at the beginning of this chapter (see 7.2.1), general considerations regarding the study design have been addressed and possible alternative interpretations of the findings as such were discussed above, this section shall reflect on the limitations of the study that probably result from its survey methodology, i.e. the way how the data was acquired.

The anonymity of the study, i.e. the fact that the questionnaires could not be traced back to the respondents made it impracticable to verify if the sample represented the survey population. However, in view of the sample size and – more importantly – the sampling method used, representativity (being a concept which is, by the way, scientifically controversial[65]) was probably not an issue in this study.

Even though similar surveys of designing organisations have yielded higher response rates [Gries & Blessing 2005], the achieved value of 17.1% (see 7.2.4) can still be considered quite respectable when compared to the literature value for business surveys of around 10% [Dillman 2000], especially if the rather delicate topic is taken into account.

The high percentage of cases in which "The design flaw was corrected and the solution has been or is being implemented in the product" (almost 80%; see Table 7-15) might be an indicator that the survey suffered, perhaps not quite unexpectedly, from considerable nonresponse error. It seems likely that designers who felt they had dealt successfully with the issue probably had a higher motivation for participating in the study. As a result of the imbalance of successful and unsuccessful cases (135 vs. 36), significant findings were more difficult to identify, but are, however, not less valid.

As far as the questionnaire is concerned, there is reason to assume that it was too comprehensive, probably overwhelming many participants (even though the pilot study suggesting otherwise; see 7.2.2). The final questions (III.9 – III.13) were not analysed due to obvious and considerable inconsistencies in the data. Apart from that, while avoiding open questions might have benefited response rates and therefore the *quantity* of data, the *quality* of data might have suffered as the answer options might have been too coarse. When presenting question in a "check all that applies"-format, there is always the risk of offering too few and/or inappropriate answer options. Adding a box like "Other (please state)" only serves as the proverbial fig leaf as participants rarely tick it (and if so rarely care to give a description). Also, even if meticulous care is taken in providing clear instructions for filling out the survey form, there can be no guarantee that they are followed. As a central concept of the questionnaire used in this study was to let participants refer all questions to one specific design flaw of one specific product, that error source needs to be allowed for in particular.

Another question that remains is to what extent success in *correcting* a design flaw (the measure used to split the sample into a successful and unsuccessful group) can serve as an indicator for the success of *learning* from design flaws – contributing to which being an aim of this work (see 1.2). Certainly, participants belonging to the successful group do have the best premises of having learned something as they (unlike the rest) have found a design solution considered worthy of implementing, having the chance of "seeing it in action". Per se, however, the "unsuccessful" designers cannot be denied the possibility of having learned their lesson either. Given the possibilities and the scope of a study like this (bearing in mind that, as mentioned above, the questionnaire was probably too comprehensive anyway) this possibly weak indicator of successfully learning from design flaws could be seen as another, yet inevitable limitation.

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[65] see e.g. [von der Lippe & Kladobra 2002]

One big limitation of the study is that it does not tell much about products and their design flaws as such – only about their characteristics. Including open questions about these issues, however, would probably have had negative effects on response rates, not only for reasons of survey methodology but especially with regard to issues of confidentiality.

After all, the exploratory nature of the study needs to be considered. Since it was intended to be *theory-building* and not *theory-based*, any conclusions (see next section) are subject to verification by suitable follow-up studies.

7.7.4 Conclusions

7.7.4.1 Post-Project Communication Between Manufacturing and Design Is Inadequate

The findings in 7.5.4 show obvious deficiencies in the communication between manufacturing – a key stakeholder in terms of product quality – and design. These deficiencies show that while cross-functional integration might have been effective *during* the product development, *after* development projects are completed, metaphorically speaking, the walls in Figure 6-5 are back again.

From the data, it can be assumed that the design projects studied were completed for two reasons. Firstly, the participants were instructed to refer all answers to a product for which this condition is true. Secondly, in cases where the design flaw manifested itself as to cause problems with manufacturing, feedback was also received from sources where the according stakeholders normally do not participate in product development, e.g. warranty claims (see Figure 7-20).

As already addressed in 7.5.4, there are two likely explanations for the finding that on average, in about 4 out of 10 cases no feedback is received from manufacturing where it should have been. The first explanation would be that as a manifestation of the design flaw participants stated "Problems with manufacturing or assembly" in assuming that next to the actual manifestations, manufacturing could also be problematic. The second explanation, however, is more disturbing: that designers, after having received feedback about the design flaw from other sources, had to confront manufacturing with the problem, eventually realising that the design flaw also manifested itself there while no feedback was ever received from that source.

7.7.4.2 Under Certain Conditions, Flawed Products Enter the Market Knowingly

Even allowing for a certain degree of survey error, it can be concluded from the study that in around 12% of cases, design flaws of products available on the market are known to their designers (see 7.5.5). Designers are significantly more successful in correcting these design flaws that have "slipped through" (see Table 7-23).

It would be fatal, however, to conclude that allowing design flaws to reach the customers makes it easier to correct them – perhaps after waiting to see if it is necessary at all. While it might be that this has been indeed the reasoning in some cases observed, it seems more appropriate to assume that in fact designers have failed in two respects: not only in achieving quality but also in keeping with the development project schedule.

This failure (see chapter 6) could follow this pattern: a design flaw is revealed by testing. However, the design team realises that it is too late to do the necessary redesigns as e.g. moulds are already being tooled, parts have been ordered or the production line is already being prepared. The foreseeable costs and, even worse, market entry delays resulting from a design change at this point are not acceptable. Therefore, the decision is made to manufacture the product as planned.

A factor that certainly plays a role in this decision is the estimated magnitude of the discovered design flaw, i.e. its severity and its likelihood (see 7.4.3). The study shows that this magnitude is significantly lower for design flaws that "slipped through" than on average (see 7.5.5). A false estimation, however, can have serious economic (and sometimes legal) consequences – not only when it is too optimistic as in the example of the Ford Pinto (see 2.4)[66]. The costly product recall of the mobile phone described in 2.6 is probably an account of a decision that was wrong because too pessimistic assumptions where made about the magnitude of the design flaw.

There might be two reasons why designers in cases where the design flaw "slipped through" are more successful in correcting it than in other cases. The first (likely) reason is that the necessary design changes as such were not very complex but triggered processes in downstream functions or at suppliers which took time – which was bought by the decision to market the product anyway. The second reason is: the designers had to be successful. That might sound trivial but once a decision is made to market a (however) flawed product while still working on a solution, it can be assumed that – given the risks of such a strategy – there is a certain level of commitment to succeed.

7.7.4.3 Innovating Implies Successfully Correcting Design Flaws

The finding that among successful cases of correcting design flaws, there is a significantly higher percentage of original designs (especially when feedback from internal stakeholders is received; see 7.6.4), is clearly in conflict with the possibility that adaptive and variant designs benefit from any experience designers might have gained from previous design projects.

A possible explanation for this finding might be that when companies decide to develop a product which involves new solution principles for a substantially new problem, possibly entering new technological territory, they are more aware of the risks that are involved. As a result of that, problems are anticipated to a certain degree and there is a higher commitment to testing and correcting them.

The finding that the highest percentage of products based on an original design is found among cases of successfully reacting to feedback from internal stakeholders (see Figure 7-31) further supports this explanation.

Also, when an entirely new product is developed, there is a higher likelihood that its designers are still there to cope with any problems that might occur after launch. It can be assumed that these individuals have a better understanding of the product and its design issues than designers who face a problem with a product that they might not have designed themselves.

[66] assuming no wilful blindness here

The latter situation seems far more likely when an existing – possibly successful product – had to be adapted. When a design flaw with such a product occurs, designers might be less successful in correcting it because they were not involved in the original design which could explain why there is a higher percentage of unsuccessful cases among adaptive and variant designs (see Figure 7-31).

This assumption is again endorsed by the distribution of original, adaptive and variant designs among successful cases of internal and external feedback. For cases in which design flaws have successfully been corrected which were reported by external stakeholders (i.e. through unsolicited customer/user feedback or warranty claims), longer feedback loops (cf. 5.2.2) can be assumed than for those cases in which design flaws were still "intercepted" in product testing and manufacturing. As has been shown, the former group features a significantly higher percentage of adaptive designs and a significantly lower percentage of original designs.

Among successful cases, there is a significantly higher percentage of designers who have stated that the feedback about the design flaw came from product testing (see Table 7-21 in 7.6.3). Assuming that during the development of a product which is based on an original design, more testing is required than with a product based on an adaptive or variant design, the conclusion outlined in 7.7.4.2 agreeably complements the above explanations why chances of correcting a design flaw are highest when designers work on original designs. Given that with adaptive or variant designs testing might be more often deemed unnecessary at all, the finding that among unsuccessful cases there is a significantly higher percentage of designers stating that the flawed product has *not* been tested also makes sense (see Table 7-22).

The role that original designs play in the results of the study support the view of Petroski [2000] who states that repeated success in design can lead to the belief that chosen design strategies were correct, even if they were not. Now it seems that this belief, or mindset, might also hamper designers' ability to correct (and possibly learn from) design flaws of products based on adaptive and variant designs which, in the truest sense of the word, *succeed* a more or less long line of previous designs when tracing them back to their original design.

7.7.4.4 Successfully Handling Design Flaws Takes a Whole Company

The activity profile of the designers working in the companies which participated in the study gives an insight into how closely this group of professionals is involved in various processes along the product life cycle (see Figure 7-30). It has been revealed that the level of involvement of designers in some activities is significantly different in successful and unsuccessful cases. While there is the general tendency that designers in the successful group are more closely involved in almost any activity (and be it slightly), significantly closer involvement is only observed with, by and large, traditional tasks of designers (see Table 7-25).

With regard to general success, many post-design functions (e.g. manufacturing, sales or repair/maintenance/service) exhibit differences in the level of involvement which are hardly noticeable, let alone significant. The only function with a significantly higher involvement among successful cases, where designers deal with the physical outcome of design rather that design itself, is product support. This activity, however, still belongs to the classical area of responsibility of designers.

The finding that generally successful designers work in companies that are significantly larger in terms of staff (see Table 7-16) supports the above findings inasmuch as larger companies have a more distinct division of labour than smaller ones. As Busby [1998] points out, companies, as they grow, develop structures that tend to distance designers from the outcome of their work: once there are e.g. dedicated product support departments, designers are relieved from "trouble-shooting" visits of customers and may dedicate themselves again to their core competence: designing. Still, the side-effect might be that possibilities for feedback are diminished.

In general, no indications were found that would support the possibility that company structures in which designers are supposedly more distanced from those who might be confronted with design flaws impair the potential to learn from design flaws. On the contrary, successful companies seem to be those where designers have more responsibility in rather traditional functions.

The only exceptions from this observation are the findings that a) generally successful companies are characterised by their designers being significantly more closely involved in conducting surveys of users and customers and b) that among these companies, those who received feedback about the design flaw from internal stakeholders had their designers more closely involved in marketing (albeit with likely significance only; see Table 7-26).

What might become apparent is that gaining feedback could be more important in terms of building experience (see 6.3) than in terms of enabling designers to successfully correct a specific design flaw – possibly in a "trouble-shooting" fashion. It is likely that this holds true for designers conducting customer and user surveys. While as a general responsibility, closer involvement in customer and user surveys is characteristic of successful cases, as a source of feedback, it is relatively more often stated among unsuccessful ones (Table 7-21 in 7.6.3).

The fact that the two sources of feedback that were significantly more often stated in cases of successfully correcting a design flaw, product tests and warranty claims (Table 7-21), do not correspond with a significantly closer involvement of designers in these responsibilities shows that these functions are important for learning from design flaws, but that it is not necessarily designers who need to attend to them.

8 Conclusions

8.1 General

8.1.1 Summary

In this thesis, design flaws, their feedback and the factors that characterise the situations in which designers were able to correct (and possibly learn from) them have been studied.

To begin with, chapter 2 exemplarily showed how severe and wide-reaching the consequences of design flaws can be for all stakeholders in a product, discussing not only technological but also economic and legal implications. It also raised the question of (alleged) product misuse.

Based on the perception that design flaws impair the quality of products, chapter 3 reviewed existing concepts of quality and common approaches to achieving it. It concluded that current research in this area explains some but not all aspects of design flaws, hence being an insufficient theoretical basis for understanding design flaws.

This theoretical basis was established in chapter 4, where a generic model of design-related product quality was proposed. It describes an interaction between designers, product attributes and stakeholders. The model augments existing concepts of quality as to provide a framework for the definition and interpretation of design flaws. By defining product quality as the degree to which perceived product attributes match with expected attributes and design flaws as design-related product attributes which impair quality according to this definition, the so far implicit relation between product quality and design flaws has been made explicit.

A concomitant of design flaws and an important aspect of the model is design feedback which was the focus of chapter 5. It showed that feedback is an important element of design and product development processes. Also, various potential sources from which companies might obtain feedback about their products after the products are launched were analysed for their applicability to reveal design flaws. In conclusion, the need for more research into design feedback was identified as existing studies gave too little detail on key questions related to this topic – especially in the context of design flaws.

Chapter 6 elaborated on the notion that a design flaw (of a product) is the result of a design failure (of the process). According to the generic model of design-related product quality it is designers who determine the relevant product attributes. The conditions under which this (design) process might fail so that the resulting product is flawed were analysed. Showing that designing takes place in an environment that is complex, dynamic and intransparent, it was pointed out that many studies agree that design experience is one of the most important human factors for succeeding in such a setting. In accordance with the generic model from chapter 4, four major failure modes were proposed.

As all theoretical findings proved to be unsatisfactory in terms of answering the questions as to the nature of design flaws, their feedback, as well as what influences the likelihood of designers to correct design flaws, an exploratory study of the German manufacturing industry was undertaken. Its design and its results were presented in chapter 7. Among other things, the study revealed deficiencies in the post-project communication between manufacturing and design and showed that successfully correcting design flaws is not necessarily a matter of closer involvement of designers in non-design-related activities.

8.1.2 Contribution

The contribution of the research presented in this thesis is twofold. It adds to a *theoretical understanding* of design flaws by proposing a model that explains their relation to aspects like quality, feedback and designing. Moreover, this research adds to a *practical understanding* of design flaws by studying their characteristics in reality.

The generic model of design-related product quality explains design flaws as a quality deficit. Therefore, it encourages a perspective which considers the stakeholders in a product. These non-designers are primarily interested in the fulfilment of their needs – and do not necessarily care about the design-related issues which inhibit this fulfilment.

It has been shown that the first step to correcting design flaws is feedback. While various prescriptive and descriptive studies (implicitly or explicitly) deal with the issue of design feedback during design and product development, this research highlights the need to also consider feedback which is received outside this scope.

In terms of designing, this research contributes to a better conception of how design processes can fail such that the designed products feature design flaws. While acknowledging that this kind of failure is based on human error, the identification of four major failure modes (misinterpreting the expectations of the stakeholders, poorly communicating product-related information to stakeholders, not understanding the product as the stakeholders would and failing to implement the product attributes as intended) allows for recognising and avoiding potential “hot spots” early.

The practical understanding of design flaws, their characteristics, their feedback and the factors that influence the likelihood of designers to correct them is provided by an empirical study of designers in the German manufacturing industry. The obtained results contribute to research inasmuch as revealing the role that the above issues play in the everyday work of designers. The study described in this thesis differs from existing studies of issues related to design flaws and their feedback by investigating a large spectrum of products, companies and industries. Due to the relatively large sample (n = 171), some general validity of the findings can be assumed.

The conclusions that can be drawn from the study not only reveal areas of product development which need to be improved but also show that some conceptions that seem sensible in theory not always hold in practice.

8.1.3 Reflection on the Research Methods

The Design Research Methodology (DRM; see 1.3), which was generally followed in this thesis, has greatly helped in structuring and focusing the research as to provide a framework for formulating a model of and generating knowledge about a particular phenomenon of design. Being rather descriptive in terms of DRM, this thesis comprised theoretical as well as practical research in industry.

The theoretical research was mainly based on literature studies. These studies, however, can probably never be comprehensive. In this thesis, the studied phenomenon (i.e. design flaws), made it necessary to address issues from a large spectrum of different scientific disciplines outside the traditional scope of design research, e.g. management and marketing science, cognitive psychology, etc. Therefore, only the most important sources could be consulted.

The practical (i.e. empirical) research in this thesis consisted of a mail survey in industry. The reasons for choosing this method over other alternatives (see 7.2.1) as well as its limitations in light of the obtained results (see 7.7.3) have already been discussed. The experiences made with planning and conducting a mail survey of designing companies as part of this research have partly been addressed in [Gries & Blessing 2005].

The overall effort for planning, conducting and analysing a mail survey of 1,000 companies was largely underestimated. The necessary resources to handle and mail hundreds of questionnaires were considerable. It was also expected that more addressees would decide to fill out the online version of the questionnaire. Given the relatively few participants who actually did, preparing an online version of the questionnaire was probably not necessary.

Another lesson learned was that in following an exploratory, data driven approach, care must be taken not to cram too many questions into the questionnaire. While it can only be speculated whether a shorter questionnaire would have benefited the response rate, the quality of the data obtained from the final questions probably did suffer (for which reason they were excluded from the analysis; see 7.7.3). Despite the already high effort, it would have been perhaps advisable to expand the preliminary tests by adding a “dry run”: sending the questionnaire to a random sample of suitable companies and analysing the responses with regard to the consistency of the data and not the data itself.

8.2 Recommendations for Product Development

Based on the findings of this thesis, the following basic recommendations for product development can be given:

1. Improve Company-Internal Cross-Project Communication

The call for more effective and efficient company-internal communication e.g. in terms of concurrent/simultaneous engineering [Ehrlenspiel 2003], Integrated Product Development [Andreasen & Hein 2000], or cross-functional integration [Wheelwright & Clark 1992] is in principle not new. However, as pointed out in 7.7.4.1, once development projects are finished, so might be any collaboration. It can be assumed that in some cases, design flaws revealed by manufacturing are not fed back to design either because a) manufacturers see no reason to do so or b) do not know whom to address.

In the case of a) one could argue that if they see no reason, the problem could not be too serious. Such a belief would be short-sighted, however. Firstly, design would be deprived of an opportunity for learning. While the design flaw's magnitude (see 7.4.3) might have been too low to trigger feedback on this occasion, the underlying design failure (see chapter 6) could be repeated another time – possibly with more serious consequences. Secondly, manufacturing is not necessarily the best authority to decide whether a design flaw is worth reporting as it probably lacks the capability to evaluate the magnitude that the design flaw might have on other stakeholders.

There are two major parameters that determine the scenario implied by b). The first parameter is the organisation which, in case of many (especially large) companies, can be quite complex (see also 6.2.1). Often, not only production is distributed (and/or sub-contracted) globally but also, as an increasing trend, product development. The second parameter is time. The longer it takes between the completion of design (and possibly the disbandment of the design team) and the detection of the design flaw, the more difficult it becomes to find someone responsible.

So what is necessary are structures, procedures and responsibilities which ensure that company-internal communication of feedback about (potential) design flaws is not limited to the scope of dedicated development projects – also a basis for managing the feedback from company-external stakeholders.

2. Enhance the Robustness of Product Development Projects

The conclusion that under certain conditions, design flaws discovered in product development are not (or cannot be) prevented from reaching the customer (see 7.7.4.2) reveals the need to enhance the robustness of product development projects. Gericke and Blessing [2006] define a development project as robust if it is completed successfully despite of unwanted and unexpected events.

Clearly, the revelation of product attributes that might pose a design flaw qualifies as such an event during development. The decision to market the product despite a design flaw can in this context only be interpreted as the attempt to complete the project "successfully" anyhow. Such a strategy, however, means that – in terms of the traditional success criteria of project management – quality is "sacrificed" for the sake time and costs. It is plausible that a development project in which such "damage control" measures are taken cannot be called robust.

There are three major factors that determine the robustness of product development projects [Gericke & Blessing 2006]: a) the suitability of the project planning, b) the handling of unwanted and unexpected events (see above) and c) the actions of the project members.

As far as a) is concerned, development projects often lack robustness as e.g. the timing of product tests is such that the design feedback that these tests provide simply cannot be implemented anymore. While the occurrence of unexpected events (b) can never be ruled out, effective risk management provides a means of attenuating the consequences for the project [McMahon & Busby 2005]. In anticipating the "risk" that product tests reveal potential design flaws, such an event, while still unwanted, at least will not come unexpectedly. Finally, all planning and risk management must be sustained by the project members (c) (see also Table 6-3).

While all related literature – directly or indirectly – aims at improving design processes, the concept of process robustness seems particularly suitable to deal with design flaws, as a design flaw represents the ultimate unwanted event in design: failing to meet the expectations of those who are confronted with the outcome.

3. Allow for Effective Knowledge Management in Design

As already indicated in 7.7.4.3, the expected advantage that adaptive and variant designs might have in terms of successfully correcting their potential flaws does not hold. This expected advantage is based on two major ideas: a) that correcting the design flaws of adaptive or variant designs is potentially easier as fundamental technological challenges have been already solved in the original design upon which they are based and b) that companies already have the know-how and experience with the design of the product as its original predecessor was also designed there.

While the idea in a) is somewhat speculative, the study reveals that the advantage described in b) – should it exist – is not leveraged. On the contrary, there is a higher percentage of designers *failing* to correct the design flaws of adaptive and variant designs than of designers who succeed (see Figure 7-31 in 7.6.4).

A likely explanation for this finding is that in reality, design know-how and experience does not stay with the company but with its designers – and those who did the adaptive designs were not necessarily involved in the original design process.

If no effective knowledge management is in place, which, in its most basic form means the availability of design documents, the border between an adaptive design process and unintended reverse engineering becomes blurry. Design flaws of adaptive designs could be the result of design changes that demonstrate poor understanding of the original solution principles, dimensioning calculations, choice of third-party components, etc. – a typical failure to understand the product (see 6.4.2).

A historic example illustrates this phenomenon: in the late 1940s the Soviet designers of the Tu-4 (which was the result of reverse engineering some captured US B-29 bombers) even copied the repair patch panels of the original that were used to cover anti-aircraft damages.

4. Let Designers Do What They Do Best: Design

The conclusion in 7.7.4.4 implies that organisational structures which tend to distance designers from the outcome of their work not necessarily impair the designers' ability to successfully correct design flaws. Consequently, designers do not have to be particularly closely involved in e.g. the manufacturing, repair, or maintenance of the products they have designed.

Designers being generalists (as postulated by e.g. [Beitz & Helbig 1997]) certainly benefits product development in many situations, e.g. correcting design flaws. They should, however, focus on their core competence which is designing. In doing so, they should keep their mind on the early phases of design in order to ensure that they understand who the stakeholders in the product are and which of their needs need to be met.

While feedback is essential for designers, going after it is probably not – and not necessary given the *right* organisational structures (see recommendation 1).

8.3 Suggestions for Future Research

As already discussed, there is a direct need for future research arising from the exploratory character of the empirical study described in this thesis. The conclusions that were drawn in 7.7.4 are based on results which describe the “what”, “how”, “how many”, etc. of the phenomenon. Any follow-up studies should focus on the “why” of each conclusion, taking a hypothesis-driven approach. For these studies, empirical methods other than a mail survey should be considered, aiming at a smaller sample, but a higher reliability and validity (cf. 7.2.1).

With regard to the conclusion that post-project communication between manufacturing and design is inadequate (see 7.7.4.1), it would be worthwhile to analyse the ways in which this communication takes place in companies. For that purpose, the focus should not only be on designers but also e.g. production engineers.

The conclusion that products can enter the market despite their designers knowing of potential design flaws (see 7.7.4.2) calls for research into the decision making processes behind this scenario. Such a study could focus on situations in product development in which designers were unsure whether a specific product attribute – revealed by prototype or virtual testing or during a design review – would constitute a design flaw.

A comparative study of original and adaptive/variant design processes would allow for a better understanding of the processes which lead to the conclusion that original design processes are a more favourable setting for successfully correcting design flaws (see 7.7.4.3). Some hypotheses for this finding have already been suggested: e.g. that companies are more risk-aware when they launch an original design project and that products based on an original design need more testing.

Research into the organisational structures of designing companies should identify the reasons behind the conclusion that effective company structures are more instrumental to successfully correcting design flaws than individual commitment of designers in non-design activities (see 7.7.4.4). The aim of these studies should be to isolate the factors which contribute to this effectiveness, i.e. the organisational factors that favour the ability of designers to learn from design flaws through feedback.

A better understanding of the reasons behind the phenomena described in this thesis is a prerequisite for developing design support. A possible starting point of this support could be existing quality methods and tools which might be adapted for documenting design flaws (as suggested in 3.6).

Apart from opportunities for research that accrue from the results of the study described in this thesis, there are also other aspects of design flaws which might be interesting to study.

One aspect would be how external stakeholders in a product, particularly customers and users, experience design flaws. Hence, a study into "design flaws as seen by customers and users" would be of great value in complementing the already obtained picture. Such a study would also be helpful for appraising to what extent design flaws are not fed back and for understanding the reasons why external stakeholders decide against reporting them.

Another important aspect of design flaws not dealt with in this thesis is their role in encouraging innovation. Von Hippel [2005] states that once customers are dissatisfied with certain products and the producing companies fail to eliminate the reasons for this dissatisfaction some customers will take innovation into their own hands. He refers to the example of mountain bikes whose emergence in the early 1980s was the result of a small but active community of users finding that commercially available bicycles did not meet their needs.

A key element of innovation is improvement. By indicating the need for improvement, design flaws can be a driver of innovation. This potential, however, needs to be recognised. As the Hungarian physiologist and Nobel Prize winner Albert Szent-Györgi put it: "Discovery consists of looking at the same thing as anyone else and thinking something different." Looking at design flaws and thinking of them as an opportunity for innovation remains a challenge for designers. Helping designers in meeting this challenge should be an area of future design research.

Appendix A: Terminology

Design (process)	A sequence of activities undertaken to progress from idea or need to product description [Blessing 1994, p. 236].
Design Error	An outcome within the design process which is unexpected, unfavourable and not entirely attributable to chance or circumstances [Busby 2000; 2001] (see 6.4.1).
Design Failure	A lack of success in meeting stated or implied design goals (see 6.4).
Design Feedback	Information related to the outcome of a design process given by a stakeholder.
Design Flaw	A design-related product attribute that impairs product quality (see 4.2).
Design Risk	The inherent possibility of design failure (see 6.4.1).
Designer	An individual who is professionally engaged in the process of design.
Exploratory study	A study which is theory-building instead of theory-based [Stebbins 2001]; usually conducted by collecting and analysing a large body of data, finding structures not known before [Adler & Clark 2003] (see 7.2).
Perception	The process of acquiring, interpreting, selecting and organising sensory information [Wessells 1982; Anderson 2005] (see 4.1.2).
Product	An item that satisfies someone's want or need [Gabler 1992, p. 2652].
Product attribute	A product property which is of interest for some stakeholder (see 4.1.1).
Product development	A sequence of activities undertaken to progress from idea or need to product launch [Blessing 1994, p. 236].
Product property	A dimension along which a product can be described (see 4.1.1).
Quality	The degree to which perceived product attributes match with expected attributes (see 4.2).
Quality defect	A mismatch between perceived and expected product attributes.
Stakeholder	A group or an individual whose legitimate interests in a product need to be met (see 4.1.2).

Appendix B: Questionnaire

Technische Universität Berlin

Studie zur Handhabung von Produktschwachstellen in der industriellen Entwicklungspraxis

KONSTRUKTIONSTECHNIK UND ENTWICKLUNGSMETHODIK

Fakultät V
Verkehrs- und Maschinensysteme

Fragebogen

Wichtige allgemeine Hinweise:

- **Vertraulichkeit**
  Sämtliche Angaben dienen reinen Forschungszwecken und werden streng vertraulich und anonym behandelt: Der Fragebogen lässt sich nicht dem Unternehmen zuordnen, vom dem die Angaben stammen. Eine Weitergabe der Daten an Dritte erfolgt nicht.
- **Bearbeitungsdauer**
  Tests mit Versuchspersonen haben ergeben, dass das Ausfüllen durchschnittlich ca. 12 Minuten in Anspruch nimmt.
- **Beantwortung der Fragen**
  Die Fragen sind so gestaltet, dass sie sich auch dann beantworten lassen, wenn in Ihrem Unternehmen keine Produktentwicklung stattfindet. Auch in diesem Fall sind Ihre Angaben für die Forschung von großem Interesse.
  - Bitte lesen Sie sich erst alle Antwortmöglichkeiten zu einer Frage durch, **bevor** Sie ein Feld markieren.
  - Sofern nichts Anderes angegeben ist, markieren Sie bitte **alle zutreffenden Antworten**.
  - Bitte markieren Sie die Felder mit einem **Kreuz** (×) oder einem **Häkchen** (✓).
  - Falls Sie ein Feld **irrtümlich** angekreuzt haben, machen Sie bitte ihre Auswahl dadurch rückgängig, indem Sie das Feld ausfüllen (■).
  - Falls Sie eine Frage nicht beantworten können, zögern Sie bitte nicht, das Feld **„Ist mir nicht bekannt"** anzukreuzen. Dies ist für die spätere Auswertung von großer Bedeutung.
  - Kommentare in Form von **Randbemerkungen** sind immer willkommen.
- **Rückfragen**
  Für Rückfragen stehen wir Ihnen jederzeit gerne zur Verfügung. Unsere Kontaktdaten finden Sie auf der Rückseite dieses Fragebogens.
- **Rücksendung**
  Bitte senden Sie den ausgefüllten Fragebogen umgehend im beigefügten frankierten und adressierten Rückumschlag an uns zurück.
- **Online-Fragebogen**
  Alternativ zum Ausfüllen und Zurückschicken des Papierfragebogens haben Sie die Möglichkeit, unter **www.ktem.tu-berlin.de/umfrage** sämtliche Angaben online zu machen. Weitere Details erfahren Sie dort.

Abschnitt I: Fragen zum Unternehmen

Hinweise:

- Falls Ihr Unternehmen ein Tochterunternehmen bzw. Teil eines Konzernverbunds ist, beziehen sich die folgenden Fragen ausschließlich auf Ihr Unternehmen und **nicht** auf den Gesamtkonzern.
- Mitarbeiter, die hauptsächlich im Bereich der **Produktentwicklung einschließlich der Vorentwicklung** tätig sind, sind in diesem Abschnitt unter dem Begriff **PRODUKTENTWICKLER** zusammengefasst. Hierzu zählen beispielsweise:
  - Konstrukteure
  - Designer
  - Softwareentwickler
  - Technische Zeichner
  - Versuchs- und Berechnungsingenieure, usw.

I.1. Wie viele Mitarbeiter sind in ihren Unternehmen insgesamt beschäftigt?

ca. ____________________ Mitarbeiter

☐ ist mir nicht bekannt

I.2. Wie viele PRODUKTENTWICKLER sind in ihrem Unternehmen beschäftigt?

ca. ____________________ PRODUKTENTWICKLER

☐ ist mir nicht bekannt

I.3. Welchen Jahresumsatz erwirtschaftet ihr Unternehmen?

ca. ____________________ €

☐ ist mir nicht bekannt

I.4. Welche der folgenden Tätigkeiten werden in ihrem Unternehmen – insbesondere von den eigenen PRODUKTENWICKLERN – durchgeführt?

Bitte in jeder Zeile genau eine Antwort ankreuzen (diejenige, die am ehesten zutrifft).

		PRODUKT-ENTWICKLER **beteiligt** bzw. **verantwortlich**	PRODUKT-ENTWICKLER **nicht beteiligt** bzw. **externe Durchführung**	Wird für gewöhnlich **nicht** durchgeführt	Ist mir nicht bekannt
Produktplanung	Technisch-wirtsch. Machbarkeitsstudien	☐	☐	☐	☐
	Nutzer- bzw. Kundenbefragungen	☐	☐	☐	☐
	Benchmarking	☐	☐	☐	☐
	Analyse von Wettbewerbsprodukten	☐	☐	☐	☐
	Erfassen von Produktanforderungen	☐	☐	☐	☐
Entwicklung	Vorentwicklung	☐	☐	☐	☐
	Konstruktion	☐	☐	☐	☐
	Produktdatenmanagement (PDM)	☐	☐	☐	☐
	Berechnung/ Simulation (z.B. FEM)	☐	☐	☐	☐
	Produkttests	☐	☐	☐	☐
	Musterbau/ Rapid Prototyping	☐	☐	☐	☐
Produktion	Produktionsplanung	☐	☐	☐	☐
	Werkzeug-/ Vorrichtungsbau	☐	☐	☐	☐
	Fertigung	☐	☐	☐	☐
After Sales/Sonstiges	Marketing	☐	☐	☐	☐
	Vertrieb	☐	☐	☐	☐
	Produktpflege/ Produktbetreuung	☐	☐	☐	☐
	Gewährleistungsabwicklung	☐	☐	☐	☐
	Reparatur/ Wartung/Service	☐	☐	☐	☐
	Rücknahme von Altprodukten	☐	☐	☐	☐
	Demontage/Recycling	☐	☐	☐	☐

Abschnitt II: Fragen zum Produkt und seiner Entstehung

Hinweise:

- Die folgenden Fragen beziehen sich **ausschließlich** auf ein **im Umlauf befindliches** Produkt (im folgenden **PRODUKT** genannt), mit dessen Entwicklung Sie persönlich am besten vertraut sind.
- Bitte beziehen Sie die Fragen in jedem Fall auf **ein und das selbe Produkt**.

II.1. Bitte ordnen Sie das PRODUKT einer der folgenden Kategorien zu:
Bitte nur eine Antwort ankreuzen.

- ☐ Konsumgut
- ☐ Investitionsgut
- ☐ Zulieferteil/OEM-Produkt
- ☐ Sonstiges, und zwar: ______________________________
- ☐ ist mir nicht bekannt

II.2. Wie viele Einheiten des PRODUKTS werden bzw. wurden im Durchschnitt pro Jahr produziert?

ca. __________________ Einheiten

- ☐ ist mir nicht bekannt

II.3. Wie hoch ist die übliche Lebensdauer des PRODUKTS?
Gemeint ist die Gesamtzeit in der das Produkt in der Regel benutzt wird.

ca. __________________ Wochen / Monate / Jahre (Zutreffendes unterstreichen)

- ☐ ist mir nicht bekannt

II.4. Welche Technologien sind im PRODUKT realisiert?

- ☐ Mechanik
- ☐ Feinmechanik
- ☐ Elektrotechnik
- ☐ Elektronik
- ☐ Mikroelektronik
- ☐ Software
- ☐ Messtechnik/Sensorik
- ☐ Antriebs-/Getriebetechnik
- ☐ Prozess-/Anlagentechnik
- ☐ Wärme-/Energietechnik
- ☐ Akustik
- ☐ Optik
- ☐ Sonstiges, und zwar: ______________________________
- ☐ ist mir nicht bekannt

II.5. Aus wie vielen unterschiedlichen Teilen besteht das PRODUKT?
Möglicher Anhaltspunkt: Anzahl der Einträge auf der Gesamtstückliste. Als Teil zählen hier auch Norm- und Zulieferteile sowie zugekaufte Baugruppen.

ca. ____________________ Teile

☐ ist mir nicht bekannt

II.6. Wie lange dauerte die Entwicklung des PRODUKTS?
Hier zählt die Zeit zwischen Projektbeginn bis Produktionsbeginn.

ca. ____________________ Wochen / Monate / Jahre (Zutreffendes unterstreichen)

☐ ist mir nicht bekannt

II.7. Welche Faktoren waren für die Entscheidung das PRODUKT zu entwickeln maßgeblich?

☐ Veränderte Kundenanforderungen
☐ Erschließen einer Marktlücke
☐ Veränderte Marktbedingungen allgemein
☐ Veränderte Gesetze, Normen, (Umwelt-)Auflagen
☐ Senkung von Herstellkosten
☐ Neu verfügbare technische Lösungen
☐ Veränderte Zulieferbedingungen
☐ Veränderte Fertigungsbedingungen
☐ Veränderte Demontage-/Recyclingbedingungen
☐ Schwachstellen eigener Produkte
☐ Schwachstellen von Wettbewerbsprodukten
☐ Sonstiges, und zwar: ____________________
☐ ist mir nicht bekannt

II.8. Welche der folgenden Entwicklungstätigkeiten beschreibt die Entstehung des PRODUKTS am besten?
Bitte nur eine Antwort ankreuzen.

☐ Entwicklung neuer Lösungsprinzipien für ein grundsätzlich neues Problem/ Aufgabenstellung bzw. Betreten von technischem Neuland
☐ Anpassung einer Konstruktion an veränderte Randbedingungen unter Verwendung bewährter Lösungsprinzipien; Aufgabenstellung nicht grundsätzlich neu
☐ Anpassung an veränderte Randbedingungen durch Variation vorhandener Teile/ Baugruppen im Rahmen einer Auftragsabwicklung.
☐ ist mir nicht bekannt

II.9. Auf welche Weise wurde das PRODUKT im Rahmen seiner Entwicklung getestet?

- ☐ Es wurden keine Produkttests durchgeführt.
- ☐ Tests/Versuche an einzelnen Baugruppen
- ☐ Tests/Versuche an einzelnen Bauteilen
- ☐ Tests/Versuche an fertigen Prototypen bzw. Vorserienmustern
- ☐ Vorgeschriebene Tests (z.B. für Bauartzulassungen)
- ☐ Usability-Tests mit Versuchspersonen
- ☐ Probeweiser Einsatz durch ausgewählte Kunden/Benutzer („Lead-User“)
- ☐ Sonstiges, und zwar: ______________________________
- ☐ ist mir nicht bekannt

II.10. Wer nimmt die regelmäßige Wartung des PRODUKTS vor?
Bitte den zutreffenden Zeitmaßstab unterstreichen. Falls Wartungsintervall unbekannt, bitte „0“ eintragen

	Typisches Wartungsintervall
☐ Eigenes Unternehmen	_______ Tage/Wochen/Monate/Jahre
☐ Vertragsunternehmen	_______ Tage/Wochen/Monate/Jahre
☐ Fremdunternehmen	_______ Tage/Wochen/Monate/Jahre
☐ Kunde	_______ Tage/Wochen/Monate/Jahre
☐ Sonstige: ______________________	_______ Tage/Wochen/Monate/Jahre

- ☐ PRODUKT unterliegt keiner regelmäßigen Wartung

II.11. Wer führt normalerweise Reparaturen am PRODUKT durch?
Gemeint ist die Behebung unerwartet aufgetretener Defekte.

- ☐ Eigenes Unternehmen
- ☐ Vertragsunternehmen
- ☐ Fremdunternehmen
- ☐ Kunde
- ☐ Sonstige, und zwar: ______________________________
- ☐ PRODUKT wird normalerweise nicht repariert.

Abschnitt III: Fragen zur Produktschwachstelle

Hinweise:

- Die folgenden Fragen beziehen sich auf ein **ungewolltes Verhalten des PRODUKTS**, das im Wesentlichen auf seine Konstruktion zurückzuführen ist (im Folgenden **SCHWACHSTELLE** genannt). Reine Montage- bzw. Fertigungsfehler beispielsweise zählen daher nicht als SCHWACHSTELLE, außer sie sind eindeutig konstruktiv bedingt.
- In dieser Untersuchung wird davon ausgegangen, dass **jedes** Produkt nach der obigen Definition zu einem gewissen Grad schwachstellenbehaftet ist. Die folgenden Fragen sind daher so gestaltet, dass sie sich (und sei es aus der Perspektive der Produktoptimierung) auf jeden Fall beantworten lassen.
- Bitte beziehen Sie die folgenden Fragen ausschließlich auf die **aus Ihrer Sicht wesentlichste SCHWACHSTELLE** des PRODUKTS.

III.1. Wie äußert sich die SCHWACHSTELLE?

- ☐ Probleme bei der Fertigung/Montage
- ☐ Unwirtschaftlichkeit des PRODUKTS
- ☐ Schlechte Bedienbarkeit/Ergonomie
- ☐ Schlechte Funktionserfüllung
- ☐ Bauteilversagen
- ☐ Unerwartet hoher Verschleiß/ Korrosion/Verschmutzung
- ☐ Schlechte Wartbarkeit
- ☐ Schlechte Demontage-/ Recyclingeigenschaften
- ☐ Sonstiges, und zwar: ______________________________
- ☐ ist mir nicht bekannt

III.2. In welchen Bereichen liegen die Ursachen der SCHWACHSTELLE?

- ☐ Mechanik
- ☐ Feinmechanik
- ☐ Elektrotechnik
- ☐ Elektronik
- ☐ Mikroelektronik
- ☐ Software
- ☐ Messtechnik/Sensorik
- ☐ Antriebs-/Getriebetechnik
- ☐ Prozess-/Anlagentechnik
- ☐ Wärme-/Energietechnik
- ☐ Akustik
- ☐ Optik
- ☐ Sonstiges, und zwar: ______________________________
- ☐ ist mir nicht bekannt

III.3. Wird die SCHWACHSTELLE durch den <u>Konstruktionsfehler eines Zulieferteils</u> verursacht?

- ☐ ja
- ☐ nein
- ☐ ist mir nicht bekannt

III.4. Bitte beurteilen Sie die Schwere der SCHWACHSTELLE zum Zeitpunkt ihres Auftretens:

Der Begriff „System“ bezieht sich hierbei auf das technische Gesamtgebilde in das das PRODUKT ggf. eingebettet ist. Bitte nur eine Antwort ankreuzen.

- ☐ Benutzer bemerkt Auswirkungen nicht
- ☐ Minimale Einschränkung des Gebrauchsnutzens
- ☐ Spürbare Einschränkung des Gebrauchsnutzens
- ☐ Empfindliche Einschränkung des Gebrauchsnutzens
- ☐ Ausfall des PRODUKTS bzw. Systems ohne nennenswerte Schäden
- ☐ Ausfall des PRODUKTS bzw. Systems mit reparaturbedürftigen Schäden
- ☐ Ausfall des PRODUKTS bzw. Systems mit schweren, aber noch reparablen Schäden
- ☐ Zerstörung des PRODUKTS bzw. Systems
- ☐ Unmittelbare Gefährdung des Benutzers in bestimmten (Betriebs-)Situationen
- ☐ Unmittelbare Gefährdung des Benutzers in unvorhersehbaren Situationen
- ☐ ist mir nicht bekannt

III.5. Bitte beurteilen Sie die Wahrscheinlichkeit, mit der die SCHWACHSTELLE beim Kunden/Benutzer auftritt, auf der folgenden Skala:

Bitte nur eine Antwort ankreuzen.

		1	2	3	4	5	6	7	8	9	10		
Auftreten praktisch ausgeschlossen	➡	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	⬅	Auftreten sicher

- ☐ ist mir nicht bekannt

III.6. Auf welche Weise bzw. wann ist die SCHWACHSTELLE bekannt geworden?

- ☐ Während der Konstruktion
- ☐ Während entwicklungsbegleitender Produkttests
- ☐ Bei der Fertigung/Montage
- ☐ Bei der Bearbeitung von Gewährleistungsfällen
- ☐ Während regelmäßiger Wartung
- ☐ Während Reparaturen
- ☐ Bei der Demontage/Recycling
- ☐ Unvermitteltes Feedback von direkten Benutzern/Kunden
- ☐ Aufgrund von Befragungen von direkten Benutzern/Kunden
- ☐ Feedback von Dritten oder aus den Medien (z.B. Stiftung Warentest)
  (Bitte angeben:____)
- ☐ Sonstiges, und zwar: ____
- ☐ ist mir nicht bekannt

III.7. Welche Schritte wurden nach Bekanntwerden der SCHWACHSTELLE unternommen?

- ☐ Keine
- ☐ Analyse der Entwicklungsunterlagen
- ☐ Austausch des betroffenen PRODUKTS / der betroffenen PRODUKTE
- ☐ Untersuchung des betroffenen PRODUKTS
- ☐ Untersuchung weiterer potenziell betroffener Produkte aus der gleichen Serie/ Produktlinie
- ☐ Dokumentation der SCHWACHSTELLE
- ☐ Vorübergehende Einstellung der Produktion
- ☐ Permanente Einstellung der Produktion
- ☐ Kontaktaufnahme mit dem Hersteller des fehlerhaften Zulieferteils
- ☐ Benachrichtigung der Kunden/Benutzer über die SCHWACHSTELLE
- ☐ Start einer Rückrufaktion
- ☐ Sonstiges, und zwar: ______________________________
- ☐ ist mir nicht bekannt

III.8. Welche der folgenden Aussagen trifft am ehesten zu?
Bitte nur eine Antwort ankreuzen.

- ☐ Die SCHWACHSTELLE wurde entwicklungsseitig **nicht angegangen.**
- ☐ Es wurde **versucht**, eine Lösung für die SCHWACHSTELLE zu entwickeln, allerdings **ohne Erfolg.**
- ☐ Es wurde eine Lösung für die SCHWACHSTELLE entwickelt. Diese **wurde bzw. wird** jedoch im jetzigen PRODUKT **nicht umgesetzt.**
- ☐ Die SCHWACHSTELLE wurde behoben und **wurde bzw. wird** im jetzigen PRODUKT **umgesetzt**.

III.9. Aus welchen Gründen wurde die SCHWACHSTELLE ggf. nicht oder nicht erfolgreich behoben?

- ☐ Erforderliche Änderungen der Fertigungsprozesse zu umfangreich
- ☐ Entwicklungsaufwand zu hoch
- ☐ Keine entwicklungsseitigen Alternativen erkennbar
- ☐ Unzureichende Informationen über die SCHWACHSTELLE
- ☐ Sonstiges, und zwar: ______________________________
- ☐ Frage trifft nicht zu
- ☐ ist mir nicht bekannt

III.10. Wies ein eventueller Vorgänger des jetzigen PRODUKTS zu irgendeinem Zeitpunkt die prinzipiell gleiche Schwachstelle auf?

Bitte nur eine Antwort ankreuzen.

- ☐ ja
- ☐ nein
- ☐ Frage trifft nicht zu
- ☐ ist mir nicht bekannt

III.11. Wies ein eventueller Nachfolger des jetzigen PRODUKTS zu irgendeinem Zeitpunkt die prinzipiell gleiche Schwachstelle auf?

Bitte nur eine Antwort ankreuzen.

- ☐ ja
- ☐ nein
- ☐ Frage trifft nicht zu
- ☐ ist mir nicht bekannt

III.12. Welche Informationen stehen Ihnen bei einer Untersuchung eines einzelnen PRODUKTS zur Verfügung?

Gemeint ist ein PRODUKT, das bereits im realen Umfeld im Einsatz war, d.h. kein Prototyp, Versuchsträger o.ä.

- ☐ Anzahl Lastwechsel, Betriebsstunden, Kilometer, usw.
- ☐ Äußere Einsatzbedingungen
- ☐ Anzahl betroffener Produkte
- ☐ Art der Benutzung
- ☐ Wartungsintervalle
- ☐ Verschleißzustand
- ☐ Beschädigungszustand
- ☐ Alter des Produkts
- ☐ Sonstiges, und zwar: ____________________
- ☐ ist mir nicht bekannt

III.13. Welche Informationen wurden bei der eventuellen Untersuchung eines von der SCHWACHSTELLE betroffenen PRODUKTS tatsächlich ausgewertet?

- ☐ Anzahl Lastwechsel, Betriebsstunden, Kilometer, usw.
- ☐ Äußere Einsatzbedingungen
- ☐ Anzahl betroffener Produkte
- ☐ Art der Benutzung
- ☐ Wartungsintervalle
- ☐ Verschleißzustand
- ☐ Beschädigungszustand
- ☐ Alter des Produkts
- ☐ Sonstiges, und zwar: ____________________
- ☐ Frage trifft nicht zu
- ☐ ist mir nicht bekannt

Abschließend interessieren wir uns für eventuelle Bemerkungen Ihrerseits:

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Ihr Ansprechpartner:

Dipl.-Ing. Bruno Gries
Fachgebiet Konstruktionstechnik und Entwicklungsmethodik
Technische Universität Berlin, Sekretariat H10
Straße des 17. Juni 135, 10623 Berlin

Tel.: (030) 314-23161
Fax: (030) 314-26481

E-Mail: gries@ktem.tu-berlin.de

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