Part One

Methodology

Contrary to most reliability texts we promote the study of variation and uncertainty as a basis for reliability work. In Davis (2006)[1] a similar framework is described and Clausing also advocated a related approach long ago, see Clausing (2005)[2]. Robust Design Methodology (RDM) is a core technique in our approach. In most texts the RDM techniques are initiated from Failure Mode and Effects Analysis (FMEA), which was suggested in the sixties and which nowadays has widespread application in industry. As a complement, or possibly, as a replacement of FMEA we suggest an enhancement of that technique – what we call VMEA – Variation Mode and Effects Analysis. In VMEA sources of variation and uncertainties affecting important outputs are identified and assessed. In our approach, we go immediately to the root causes of failures, i.e. to sources of variation and uncertainties. When important areas for improvement are identified, we suggest the utilization of Robust Design Methodology.

[1] Davis, T. P. Science, engineering, and statistics. *Applied Stochastic Models in Business and Industry*, **22**: 401–430, 2006.
[2] Clausing, D. Operating window – an engineering measure for robustness. *Technometrics*, **46** (1): 25–29, 2004.

Robust Design Methodology for Reliability: Exploring the Effects of Variation and Uncertainty
edited by B. Bergman, J. de Maré, S. Lorén, T. Svensson

1

Introduction

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1.1 Background

There is no system that always performs as intended. There are many examples of this in our daily lives; we often experience failures of automobiles, mobile telephones, computers and their software. It is also obvious in the operation of more complex systems, for example space vehicles, railway systems and nuclear power plants.

This book is about design principles and systematic methods to reduce failures and thereby improve reliability as experienced by the users of the systems. Unreliability is not only a problem for the users of the systems – the producers also suffer. Failures reduce company profitability through call-backs, warranty costs and bad will. Warranty costs alone are often estimated to be 2–15% of total sales. It is also sometimes said to be in the size of the product development costs, but that might be a problematic comparison – a small increase in product development costs to increase reliability might bring a considerable gains in reduced warranty costs. Even though warranty costs are considerable, the largest loss to a company because of low reliability is probably the loss of good will. Regardless, reliability is an important feature of current products and systems, software, hardware and combinations thereof.

Essentially, in this book we will relate to hardware systems and their reliability and how to work with reliability issues early in the product life cycle. Contrary to most reliability texts, we promote the study of variation and uncertainty as a basis for the reliability work. In Davis (2006) a similar framework is described and Clausing (2004) also puts forward a similar approach. Robust Design Methodology (RDM) plays a central role in our approach to developing high reliability hardware systems.

Even though reliability in most textbooks is given a probabilistic definition, the reliability of a product is here defined as:

> 'The ability of a product to provide the desired and promised function to the customer or user.'

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Many different approaches can be used to measure this ability; most often they are related to probability theory and concern the length of failure-free operation. In most textbooks on reliability, the concept 'reliability' is in fact defined as a probability, i.e. 'the probability of failure-free operation during a certain time period and under stated conditions of usage'. However, many other measures might be relevant. In fact, as we shall see below, such alternatives might be more relevant from the point of view of engineering design.

The conventional strategy for reliability improvement work has been to utilize feedback from testing and from field usage to understand important failure mechanisms and then, in the future, try to find engineering solutions to avoid or reduce the impact from these mechanisms. Based on past experiences it has also been the practice to make predictions of future reliability performance in order to spot weak points and subsequently make improvements with respect to these weaknesses when already in early stages of the design. In his study of the room air conditioning industry, Garvin (1988) found strong evidence that the existence of a reliability group taking care of field failure experiences and giving feedback to the designers gave a positive effect on equipment reliability.

However, the conventional reliability improvement strategy has some strong limitations, as it requires feedback from usage or from expensive reliability testing. Thus, it is fully applicable only in later stages of product development when already much of the design is fixed and changes incur high costs. Consequently, there is a need for a more proactive approach. The aim of this book is to indicate some paths towards such an approach based on relations between failure occurrence, variation and uncertainty. In fact, this approach has been available for a long time, but a systematic proactive methodology has been missing. Today, we can utilize the development of RDM to make products insensitive to variation and uncertainties and thereby improve the reliability performance of products, see e.g. Davis (2006). In Chapter 6 it is argued that countermeasures to increase the reliability of systems can be divided into three categories: 'fault avoidance', 'architectural analysis' and 'estimation of basic events'. It is further argued that an essential part of these countermeasures can be realized by designing systems that do not fail despite the existence of noise factors, i.e. the creation of robust designs.

1.1.1 Reliability and Variation

Variation is everywhere – for good and for bad! Variation is at the core of life itself and to find new solutions – for creative action – we need variation in the stream of ideas and associations. However, in the manufacturing and usage of systems variation might be a problem. Understanding variation is an important aspect of management as already emphasized by Shewhart (1931, 1939) and later by Deming (1986, 1993). Especially, understanding variation is an important aspect of engineering knowledge.

In the early history of railway development failures often occurred – a derailing of a train returning from Versailles in 1842 due to a broken locomotive axle has become a well-known example of a failure due to fatigue. Similar events were systematically investigated by August Wöhler in the mid-nineteenth century. Wöhler suggested the existence of a fatigue limit and established an empirical life–load relationship, the S–N (Stress, Number of cycles failure) curve. Fatigue is a long time effect of stress variation. In later chapters of this book, see e.g. Chapters 6, 7, 9, 10 and 12, fatigue will be studied more extensively.

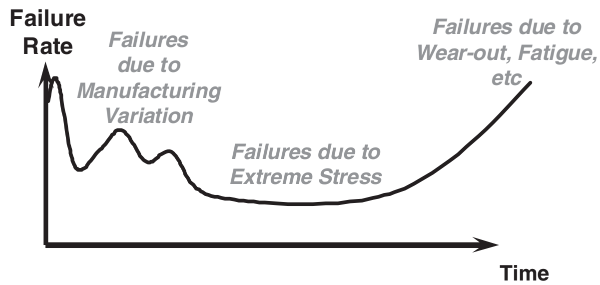

Figure 1.1 The so-called bath-tub curve, often suggested as a generic model of the failure rate of a system. The roller-coaster shape in the beginning illustrates that some of the failure mechanisms induced by the manufacturing variation might take some time (or energy) to become active.

The now well-known bath-tub curve can be used as an illustration of the relation between sources of variation and reliability, see Figure 1.1. Failures in early stages of the utilization period are usually due to variation in the manufacturing process. Due to manufacturing variation, some units are weaker than others and therefore they will fail quite early. As time passes, these weaker units will have disappeared or have been restored to a much better condition and the failure rate curve levels out. In the middle period, often called ‘the best period’, it is essentially only environmental high stresses that might sometimes be so severe that a unit fails. Thus, failures occur essentially independently of the age of the unit, which explains the essentially constant behaviour of the failure rate curve. At the end of the life of a surviving unit, accumulated environmental stresses and inner deteriorations make the unit weaker and more prone to fail. The failure rate curve increases again. The discussion above and Figure 1.1 relate to nonrepairable units, but similar reasoning also applies to repairable systems.

Chapter 2 gives a comprehensive overview of the initial development of reliability engineering and presents some classic reliability problems and their countermeasures. One such problem was the development of the V1 rocket during World War II. The aircraft designer Robert Lusser, one of Verner von Braun’s co-workers on the unreliable V1 rockets, suggested what is sometimes called Lusser’s Law: the survival probability of a (series) system is the product of the survival probabilities of the components of the system. This was not realized in the early stages of the V1 development and before Lusser joined the group. Hence the (fortunate) low survival probability.

After World War II, Lusser worked for the US military and their missile development program. He suggested a reliability design criterion based on the variation of stresses and strengths of components, see Lusser (1958). Similar types of design rules had been widely used within the mechanical industry under the name of safety margins without, however, any explicit considerations of variability. The criteria suggested by Lusser (1958) clearly take variation into account, as illustrated in Figure 1.2.

In general, the stress–strength relationship can be described as in Figure 1.3. Initially, there are varying strengths (resistances to failure) among the units produced. These units deteriorate, and as soon as a stress exceeds the strength, a failure occurs.

Chapter 4 in this book shows that the majority of failure modes identified in Failure Mode and Effects Analyses (FMEA) are actually caused by different sources of variation. Part Two of this book is basically about the relation between variation and failures.

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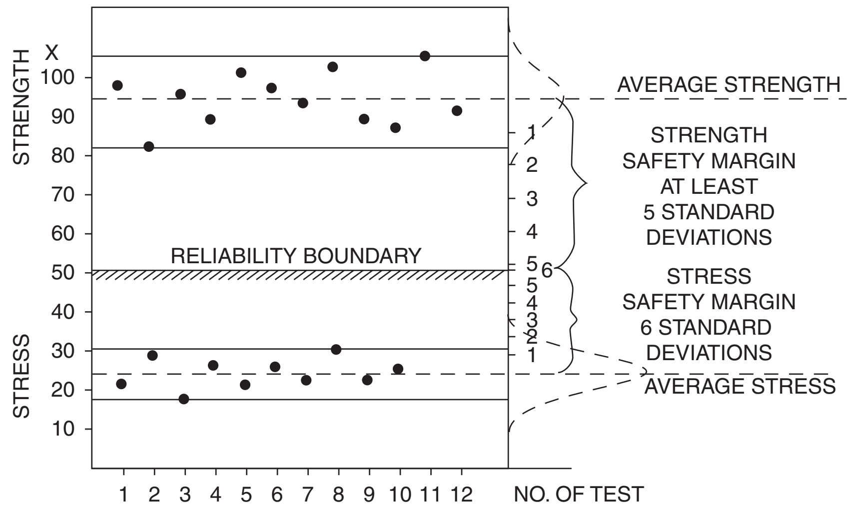

Figure 1.2 Illustration of the design criteria suggested by Lusser (1958). Lusser also related the degree of separation to the testing efforts made.

1.1.2 Sources of Variation

There is variation both in strengths and in loads. The question is what we know about them. In the RDM literature, sources of variation, also called noise factors, are often categorized as noise generated from within the system under study (also called inner noise) and as noise

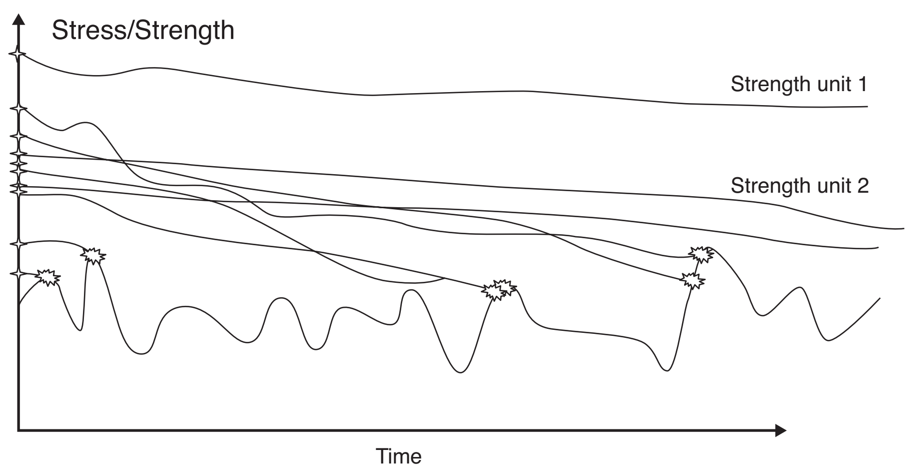

Figure 1.3 Units of different strengths deteriorate and fail as soon as a stress higher than the strength is experienced (from Bergman, 1979). It should be noted that in this figure, the strength curves of a number of units are illustrated. However, only one stress history is illustrated. In real life most units experience different stress histories.

generated from the environment or usage of the system (also called outer noise). An example of inner noise is deterioration during usage. Outer noise is illustrated by noise due to variation between customers and their use of the system and also to the environment in which the system is used. Davis (2006) instead classifies sources of variation as demand and capacity types of variation. This is a fruitful way of classification as it relates to earlier reliability work; load and strength variations can be seen as special cases of demand and capacity variations, respectively. The demand type sources of variation are:

- variation between customers (different customers/users will use the system in different ways)
- usage variation within customer (variation within and between duty cycles)
- external environmental variation (the external variation will differ between different units and also in time for the same unit)
- system environmental variation (when the unit is in fact a module in a modularized system, the demand from the system might differ depending on actual system configuration; also other types of variation in the system environment, e.g. due to deterioration of other system components, should be included here).

The sources of variation affecting capacity are:

- variation of part characteristics due to production variation
- variation of part characteristics due to usage (deterioration, fatigue, wear, corrosion, etc.). (It should be noted that here we have an interaction, e.g. between duty cycle variation and deterioration.)

In Chapter 5 we will make a more detailed analysis of different sources of variation and their impact on reliability as experienced by the customer.

Figure 1.4 displays a common view on how sources of variation influence the failure risk at a certain point in time. However, it is necessary to be cautious when viewing the influence of noises in the way indicated by the graphs in Figure 1.4. There might not be any well-defined distributions whatsoever! Many of the noises are certainly not ‘under statistical

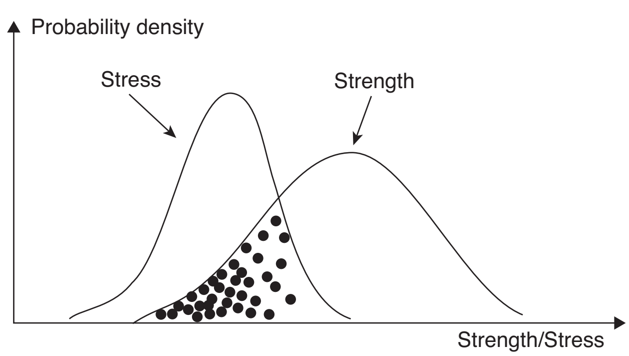

Figure 1.4 Demand/Capacity (stress/strength) distributions at a certain time.

control' according to the criteria suggested by Shewhart (1939). If they are not under statistical control we cannot utilize past history for predictions about the future.

The obvious course of action is to make the separation between demand and capacity as large as economically possible. An aid in this work could be to utilize, for whatever it is worth, past observations of demands and capacities. Chapter 7 discusses the advantages and disadvantages of two different ways of approaching this problem, the safety factor approach and the load–strength method. The apparent drawback of the experience based safety factor approach is that it cannot be updated in a rational way as its origin is difficult to analyse. In theory, the probability based load–strength approach is sound. However, as the available information about the input is often scarce and the usefulness of the result to a large extent depends upon the distributions of the input, the approach is less useful in practice. Further, Chapter 7 presents an alternative approach that combines the advantages of the two methods.

1.1.3 Sources of Uncertainties

It is possible to categorize the causes of malfunction, i.e. product inability to provide desired function, in the following way:

1. This category is related to human mistakes, such as misuse, unforeseen physical effects or unforeseen extreme events.
2. This category is lack of knowledge of identified physical behaviour, and variation in future usage (this is sometimes referred to as epistemic uncertainty)
3. There are random variations both in product features and in usage; this gives rise to uncertainties that are sometimes called aleatory.

In all these categories there is a need for a rational treatment of the uncertainties and variations in order to obtain reliable products, and in this book, for example in Chapters 6 and 7, we put forward ideas that make it possible to take advantage of statistical tools in this work.

The first category, related to human mistakes, is probably the most important cause of reliability successes or failures. However, it is difficult to describe problems from this category in mathematical terms. See also Chapter 13 where these aspects are briefly discussed. When the predominant failure modes are related to nonrandom events, it is still possible to make use of statistical tools, namely in order to make products robust against different events.

The second category can be treated with statistical tools by using the so-called Bayesian perspective: lack of knowledge may be modelled as a statistical population of unknown errors and put into the analysis by the application of statistical measures of the uncertainties from, for instance, engineering judgements. Such a methodology makes it possible to combine unknown errors with true variation effects in order to identify the most important weaknesses in the product reliability. This concept is developed in Chapter 9 of this book.

The treatment of the third category with statistical tools is straightforward and well established. Here, some important tools for treating random variables and their interactions are treated in some detail, namely the use of design of experiments for making products robust against variation.

Powerful computer simulation tools are available for treating random variables. However, there is a risk associated with the high precision probability measures that are the outcome of these advanced statistical treatments. If the uncertainties in the input variables are not taken into account, the precision in the obtained probability measures will be far less accurate than that given using the simulations. Chapter 10 uses the statistical framework for finding an optimal complexity in modelling, emphasizing the trade-off between the amount of input knowledge and the model complexity. This trade-off is treated in Chapter 9.

When failures occur, it is not always the variation itself that is the problem but rather the uncertainty about the size of the load on the equipment. Load assumptions are often based on inadequate knowledge of customer use. If misjudgments are made, seemingly harmless sources of variation might result in a failure. Thus, the probability distributions shown in Figure 1.4 should be the predictive distributions of demands and capacity, respectively. Consequently modelling uncertainties both with respect to kinds of models (e.g. linear or more complex relationships) and parameter uncertainties should also be included.

Today there is a big difference between the complexity of the models used in industry and those developed in academia. Chapter 10 deals with the question of what complexity level to use in certain situations. It is concluded that the optimal model complexity can be found by means of statistical modelling of prediction uncertainty. A particularly problematic issue is the question of future occurrences of what is called special or assignable causes of variation; i.e. if the processes underlying the demand and capacity are not under statistical control. How do we ensure that all the sources of variation and uncertainties are predictable?

1.2 Failure Mode Avoidance

1.2.1 Insensitivity to Variation – Robustness

When designing a product we want the two distributions in Figure 1.4 to be separated. Davis (2006), following recommendations made at the Xerox Company in the early eighties (see Clausing, 1994), describes his approach as *Failure Mode Avoidance* – striving to avoid failures by separating demand and capacity as much as possible. Note that we might have some problems in defining the ‘distributions’ as discussed above. It should also be noted that the separation of the ‘distributions’ in Figure 1.4 might be achieved in many different ways.

Traditionally, separation has been achieved by reducing or limiting different sources of variation (noises). Different kinds of tolerances have been imposed in manufacturing in order to achieve separation. Sometimes also limitations with respect to usage have been prescribed. Furthermore, via burn-in (or proof-testing), the left-hand tail of the capacity ‘distribution’ has been reduced before the units have been put into operation.

In some situations there exists an even better solution to reliability problems than separation of load and capacity. In situations when the system demand has to do with a specific noise factor, it is sensible to consider the possibility to redesign the system in such a manner that the system is made independent of that noise factor. This strategy is much in line with what Taguchi (1986) refers to as parameter design, where system prototypes are made insensitive to different kinds of noise factors. Only if the measures to be taken are too expensive or not quite sufficient, further separation is necessary. In such situations, utilizing tolerance design in the more traditional way of achieving separation is recommended. However, the literature has to a large extent focused on improving already existent system prototypes using parameter design backed up by experimental methods. Less focus has been put on the possibility of designing robust system concepts based on creativity. The basis for such a design is that a creative

Figure 1.5 The first self-aligning SKF ball bearing. (Reproduced by kind permission of the company Photo Library, SFK.)

solution is sought where some important noise factors are made irrelevant or at least much less important to the reliability of the product. Thus, the difference compared to parameter design is that a brand new design solution is developed, not an improved version of an already existing design. Below we first illustrate 'creative robust design'. This is followed by a discussion of Robust Design Methodology in terms of parameter design.

1.2.2 Creative Robust Design

Sometimes it is possible to make a change to the product so that the failure mode is avoided or at least its occurrence is made dramatically less probable. The self-aligning ball bearing (see Figure 1.5) invented by Sven Winqvist in 1907 is an example of a product with inherent robustness. Before the self-aligning ball bearing was introduced, misalignments of the shaft had a disastrous influence on bearing life. Such misalignments can for example be caused by subsidence in premises where machines are located. By using outer rings with spherical raceways, the self-aligning ball bearing was designed to allow for misalignments of the shaft. Looking for such solutions with inherent robustness is an important issue for increasing reliability.

At SKF[1] this tradition of creating products robust against sources of variation has continued. In 1919 Palmgren created a similar robust roller bearing also insensitive to shaft angle variations, and in 1995 Kellstrom created the toroidal roller bearing CARB$^{\circledR}$, which is insensitive to both radial and axial displacements.

1.3 Robust Design

The objective of Robust Design Methodology is to create insensitivity to existing sources of variation without elimination of these sources. Thus, parts of the creative robust design discussed above are also included. It might not be possible to suggest a strict methodology

[1] SFK Group is the leading global supplier of products, solutions and services within rolling bearings, seals, mechationics, services and lubrication systems. Services include technical support, maintenance, condition monitoring and training.

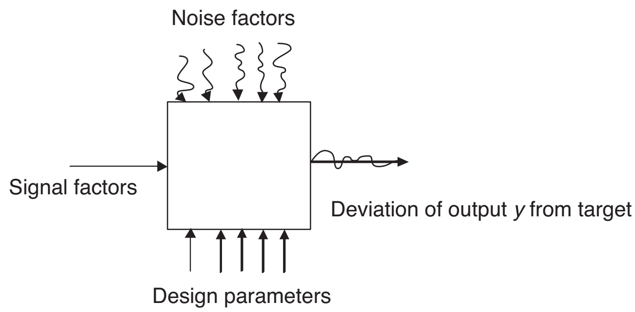

Figure 1.6 The P-diagram. (Adapted from Phadke, 1989.)

to identify creative solutions. However, some necessary prerequisite could be achieved in a systematic way. One such prerequisite is the understanding of important sources of variation when already in the very early stages of product development.

In this section we will discuss RDM to some extent. However, we will not go into depth on this as there are a lot of RDM descriptions already in many different settings (see e.g. Gremyr, 2005, and references given there). Davis (2006) also has an interesting discussion with special emphasis on reliability.

Chapter 3 discusses agreements and disagreements on the view of the robust design concept. Efforts to create robust designs have often been seen as synonymous to parameter design on already existent system concepts. Almost no focus has been put on the development of tools and aids helpful to come up with creative robust design solutions. The main conclusion drawn in Chapter 3 is that robust design is an aim that should be emphasized in all stages of design.

1.3.1 Product Modelling

In RDM the output from systems are described as functions of signal factors, design parameters (often denoted control factors) and noise factors as illustrated in the P-diagram (P stands for product/process) in Figure 1.6. These functions are commonly denoted transfer functions. The levels of the signal factors are set by the user of the system to express the intended value of the output. The levels of the design parameters can be determined by the designer of the system whereas the levels of the noise factors cannot be controlled during operating conditions. The problem focused in RDM is to identify system solutions with small output variation for different levels of the signal factors despite the existence of noise factors.

One problem in system design is that there might be a large number of outputs potentially affected by noise factors of different kinds. There is a need to give more attention to a few very important outputs and corresponding design elements. It is unwise to start working on issues of minor reliability importance as long as more important issues are not adequately handled. One way to select important areas for further analysis is to use FMEA, a well-known tool within reliability engineering. At the same time, a checklist with relevant noise factors can serve as inspiration when tracking possible causes to failure modes identified in FMEAs. Chapter 4 concludes that the majority of failure causes can be attributed to noise factors whereas a minor number of failure causes are related to the nominal performance of products.

Chapter 5 presents a systematic tool similar to those of fault tree analysis and FMEA. The tool is called Variation Mode and Effects Analysis (VMEA) and there exist a number of different variants depending on how detailed knowledge is available of the studied system. Different variants might be thought of as the different variants of FMEA. Unlike FMEA, however, this tool is top-down rather than bottom-up. When extensive knowledge is available of the system studied, it is possible to perform a variant of VMEA called probabilistic VMEA. Not only random variation but also uncertainties are considered. A case study where this kind of VMEA is applied to fatigue life prediction is presented in Chapter 6.

Once it is understood how outputs are affected by signal factors, design parameters and noise factors (as a mathematical function or as a simulation model), possible interactions between design parameters and noise factors can be utilized to reduce output variation of the system. This is achieved by appropriate settings of design parameters that make the system insensitive to noise factors.

When the transfer function is known or has been estimated by use of design of experiments, the error transmission formula and Monte Carlo simulation are often tools used to study how variation in input variables transmits to one or many output variables. However, the usefulness of these methods is largest when there is variation around the nominal values of design parameters. Such a noise factor is for example variation of part characteristics due to production variation. In Chapter 8 advantages and disadvantages of using the error transmission formula and Monte Carlo simulation are discussed. One important conclusion is that the error transmission formula is advantageous when seeking robust design solutions.

It is often favourable to conduct a computer experiment using Design of Experiment principles even though the transfer function is known in principle. The reason for this is that it is often too complicated to see through when it comes to failure mode avoidance, i.e. finding design parameter settings making the product insensitive to the noise factors. If by analytical means it is not possible to find the transfer function, physical experiments utilizing the Design of Experiment principles have to be made. The basic idea when searching robust solutions by use of Design of Experiments is to vary design parameters and noise factors in the same experiment.

An experiment of this type was conducted at Saab AB Sweden. The aim of the experiment was to improve the robustness of the manufacturing process of composite material used in military fighter airplanes. Three design parameters were identified by operating personnel and quality engineers: curing temperature, pressure and holding time. Five noise factors characterizing the incoming material were identified: proportion of hardener, thermoplastic content, proportion of epoxy, material storage time and type of process. All eight factors included in the experiment were varied at two levels each. The response variable bending strength was used for characterization of the composite material. For the sake of confidentiality, the levels are here coded -1 and $+1$.

An analysis of the experiment showed that the process pressure, the material storage time and the interaction between these two factors had a significant effect on the bending strength. The direction of this influence is shown in Figure 1.7, which shows that keeping the pressure on a high level makes the bending strength of the composite material more insensitive to the influence of the material storage time. Thus, if the pressure is kept at the high level there is no reason to control the material storage time, which means a cost saving.

In many situations it is too expensive or even impossible to vary noise factors at fixed levels in experiments. An alternative in these cases is to allow noise factors to vary randomly during

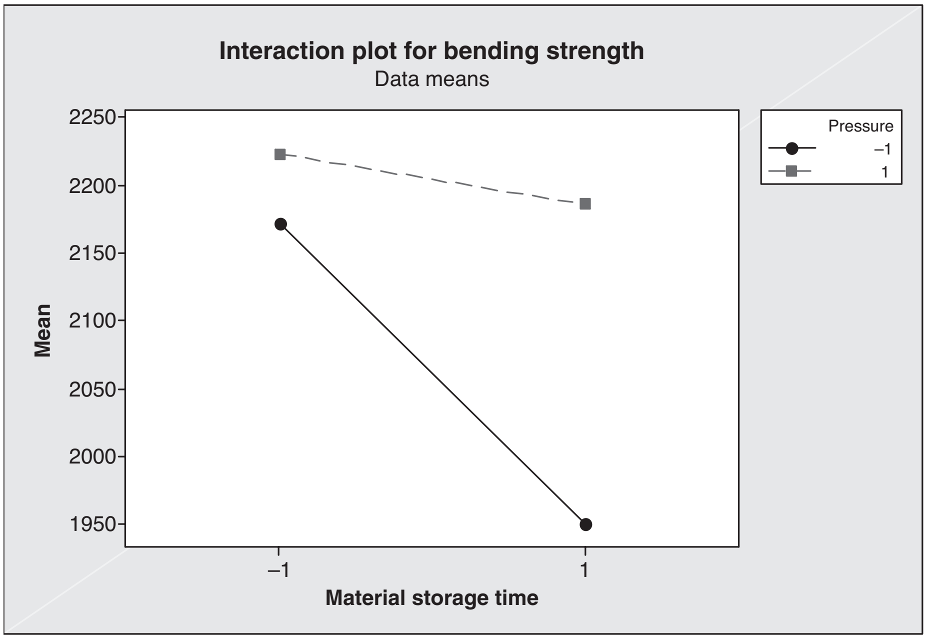

Figure 1.7 Interaction plot.

the experiment and to capture the influence of noise factors via replicates of experiments. Since replication of experiments is often not an alternative for economic reasons, the influence of noise factors that vary randomly has to be captured by use of residual based dispersion analysis. In Chapter 11 it is shown how interactions between design parameters and noise factors that vary randomly during the experiment are manifested as dispersion effects of the design parameters.

1.4 Comments and Suggestions for Further Reading

For early discussions on the economic impact of unreliability, see e.g. Garvin (1988). For some more recent references, see e.g. Johnson and Nilsson (2002) and Curkovic et al. (1999), who show a strong relationship between reliability of products and business performance in the automotive industry.

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