KTH Machine Design

Supporting complete vehicle reliability forecasts

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Abstract
Reliability is one of the properties that customers of heavy trucks value highest. Dependent on all parts and functions of the vehicle, reliability is a complex property, which can normally be measured only towards the end of a development project. At earlier development stages, forecasts can give valuable decision support for project planning.

The main function of a heavy truck is to transport goods, but the truck also has interactive functions as the working environment of the driver. Interactive functions are functions experienced by the driver. They are subjective, in the sense of being person dependent, so that a system can be experienced as inadequate by one user but satisfactory by another. Examples of interactive functions of heavy trucks are climate comfort and ergonomics, which are experienced differently by different drivers. Failures of these functions lead to costs and limited availability for the customer. Therefore it is important to include them in reliability forecasts.

The work described in this thesis concerns some elements of the system reliability forecast. Two studies are presented, one proposing a qualitative system architecture model and the other reviewing and testing methods for evaluating the impact of varying operating conditions. Two case studies of a truck cab in a system reliability test were made. The first case study shows that the system architecture model supports reliability forecasts by including interactive functions as well as external factors, human and environmental, which affect function performance. The second case study shows that modelling uncertainty is crucial for interactive functions and recommends a method to forecast function performance while taking varying operating conditions into account.

Keywords
Reliability forecast, interactive function, operating conditions

Language
English

Sammanfattning

Tillförlitlighet är en av de egenskaper som lastbilskunder värderar högst. Det är en komplex egenskap, som beror på fordonets alla delar och funktioner, och vanligtvis kan den bara mätas mot slutet av ett utvecklingsprojekt. I tidigare utvecklingskeden kan istället prognoser ge värdefullt beslutsstöd till projektplanering.

En lastbils huvudfunktion är att transportera gods, men lastbilen har även interaktiva funktioner kopplade till förarens arbetsmiljö. Interaktiva funktioner är funktioner som upplevs av användaren. De är subjektiva, i meningen personberoende, så att samma system kan upplevas som bristfälligt av en användare och tillfredsställande av en annan. Exempel på interaktiva funktioner i tunga lastbilar är hyttklimat och ergonomi, som upplevs olika av olika förare. När dessa funktioner inte fungerar leder det till kostnader och minskad tillgänglighet för kunden. Därför är det viktigt att ta med dem i tillförlitlighetsprognoser.

Det arbete som beskrivs i den här avhandlingen behandlar några delmoment i systemtillförlitlighetsprognosen. Två studier presenteras; den första lägger fram en kvalitativ systemarkitekturmodell och den andra går igenom och testar metoder för att uppskatta effekten av varierande driftsförhållanden. Två fallstudier av en lastbilshytt i ett systemtillförlitlighetsprov har gjorts. Den första fallstudien visar att systemarkitekturmodellen stödjer tillförlitlighetsprognoser genom att inkludera även interaktiva funktioner samt alla externa faktorer, både användarfaktorer och miljöfaktorer, som påverkar funktionsprestandan. Den andra fallstudien visar att modellering av osäkerhet är kritiskt för interaktiva funktioner och rekommenderar en metod för att skatta funktionsprestanda med hänsyn tagen till varierande driftsförhållanden.

Preface

The research presented in this thesis was carried out between May 2014 and December 2016 at Scania chassis development in Södertälje and the Department of Machine Design, KTH Royal Institute of Technology, Stockholm. I would like to thank Scania CV AB for financing this work. For the opportunity to use my time to sit and think about interesting things, I feel very privileged.

Thanks to my supervisors, Ulf Sellgren and Anders Söderberg, for always finding the weakest spot, and a way to improve it.

My manager at Scania, Björn Rickfält, has given me unfailing support and enthusiasm, and I could not possibly have done this without him.

Martin, not every PhD-student has access to private tutoring in statistics and practical research knowledge. In my case, it is also done by my favourite person in the world. Thank you.

I am also happy to have original artwork in my thesis! Thank you, Viktor.

And finally, so many have put in a word of support, asked interested questions, or listened patiently when I needed to complain. You have all made the road easier and more pleasant. Thank you.

Stockholm, April 2017

Julia Lindén

List of appended publications

This thesis consists of a summary and the following appended papers:

Paper A

Julia Lindén, Ulf Sellgren, Anders Söderberg (2015) "DSM-based reliability analysis of modular architectures", 17th International DSM conference, DSM 2015, Forth Worth, Texas, USA, November 4-6, 2015.

The author participated in the planning of the research and the performance of the reported research. The author participated in the paper writing.

Paper B

Julia Lindén, Ulf Sellgren, Anders Söderberg (2016) "Model-based reliability analysis", Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 30, August 2016, pp. 277-288, DOI: 10.1017/S0890060416000251, Published online: 14 July 2016.

The author participated in the planning of the research and performed the reported research. The author did most of the paper writing.

Paper C

Julia Lindén, Anders Söderberg, Ulf Sellgren (2016) "Reliability assessment with varying operating conditions", 26th CIRP Conference, Procedia CIRP 50 (2016), 796-801, Elsevier BV, doi: 10.1016/j.procir.2016.04.139

The author planned and performed the research and the result analyses. The author did most of the paper writing.

Paper D

Julia Lindén, Anders Söderberg, Ulf Sellgren (2016) "Modelling uncertainty of reliability forecasts with varying operating conditions". Submitted for publication.

The author planned and performed the research and the result analyses. The author did most of the paper writing.

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1 INTRODUCTION

Transportation is a crucial infrastructure in all societies. In our society, over half of all inland freight is transported by trucks [1,2]. Road transportation is currently an active research area, with examples such as sustainable transport systems [3], autonomous vehicles [4,5] and logistics through connectivity [6,7]. Availability of the vehicles is essential for all of these. There is no point in improving the ways we use trucks, if the truck is at the workshop. As we invent new functionality for heavy trucks, we also invent new failure modes, and assuring the vehicle reliability becomes increasingly important.

The topic of this work is modelling of complete vehicle reliability. The holistic system view is how a customer perceives reliability. *Reliability* is “the ability of an item to perform a required function under given conditions for a given time interval” [IEC60050]. A *function* is the purpose of a component or a system and each function has a functional performance requirement, which must be met to satisfy the user. System reliability is only achieved when all functions of the system perform satisfactorily. For heavy trucks, some of the required functions are related to the truck as the working environment of the driver. These functions, for example climate comfort and ergonomics, are *interactive*. They are performed in the interface between the technical system and the user, whereas *technical* functions are performed by the system, sometimes interacting with the surrounding environment. In order to be a faithful representation of the customer’s perception, a system reliability model must also include interactive functions.

In a product development project, targets which can be measured during the project are more practical than targets which can only be evaluated after the project is concluded, since this facilitates decision making during the project, and evaluation of target completion at the end of the project. A good example is setting targets for system reliability tests rather than system reliability in customer operation, although the latter is the ultimate aim. Even so; system reliability test can only be carried out late in the development project, when the product is near completion. Project decisions at earlier stages must rely on forecasts. Early forecasts will be based on what information is available at each point in time, and can be updated as new information arrives.

The motivating objective of this research is to investigate how complete vehicle reliability tests can be forecast. Two key aspects of such a forecast are the diversity of information and the uncertainty of the forecast. Figure 1 Figure 1shows the elements of the forecast; the input data, the system model, the output forecast. Many different types of input data will be used: results from calculations, component tests, functions tests, information from design reviews, expert judgement etc. The methodology must allow input data in different formats of varying precision and accuracy. Furthermore, if operating conditions (e.g. temperature and humidity) vary between the input data source and the forecast situation this must be taken into account. The system model has a qualitative part which describes the components of the system and their relations and a quantitative part which estimates function performance and failure probability. The output is a forecast of the system reliability. Particularly the earliest forecasts will be uncertain. It is necessary to assess the uncertainty of the forecast to be able to use it as decision support.

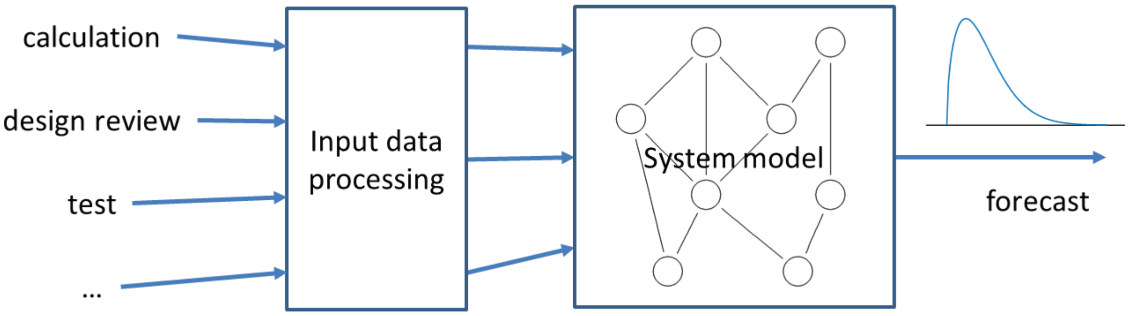

Figure 1. Elements of the system reliability forecast.

System reliability is a mature research area, with many approaches for reliability analysis [8,9], but these traditionally have only been concerned with failures of technical functions. Failures of interactive functions have been studied in different contexts [10,11], but not with a system approach. There are also various reliability methods for taking operating conditions into account, [12,13], but none of them were originally designed to evaluate interactive function performance.

1.1 Research questions

This thesis considers the qualitative system model, and methods for taking operating conditions into account. The following research questions have been formulated:

1. How can we model the system architecture qualitatively to support the reliability forecast?

2. How can we model function performance under varying operating conditions?

3. How can we estimate forecast uncertainty under varying operating conditions?

4. Can any method for taking operating conditions into account be recommended for use with technical and interactive functions?

1.2 Thesis outline

Chapter 1 gives a short introduction to the problem under study. Chapter 2 gives background information about research on system architecture representations, system reliability, interactive function performance and function performance dependence on operating conditions. Chapter 3 presents the research methodology used in the thesis and explains how the two studies were made. In chapter 4, the appended papers are summarized. Chapter 5 contains a discussion about the results, ideas for future work, and the conclusions from this thesis.

2 ASPECTS OF RELIABILITY

This section gives background to the studies in this thesis. Firstly, system architecture representations are described, followed by basics and more recent developments in system reliability, as well as research concerning failures of interactive functions. These descriptions show that current system reliability methods do not include interactive functions, and research on interactive function performance does not have a system perspective. A combination of existing methods for dealing with system reliability for technical functions and failures of interactive functions is needed. This section also describes methods to take operating conditions into account in reliability assessment, and some issues to consider when using expert judgement as a data source. The methods for operating conditions were not designed for interactive functions, and their usefulness for that purpose needs to be investigated.

2.1 System architecture

System architecture has been defined as “an abstract description of the entities of a system and the relationships between those entities” [14]. One example of this is a product breakdown structure, which shows the hierarchy of components in the system, see Figure 2. However, in order to discuss system reliability, it is also necessary to describe the required functions of the system; its purpose. A representation that connects function and form is the function-means tree, proposed by Andreasen [15], see Figure 3.

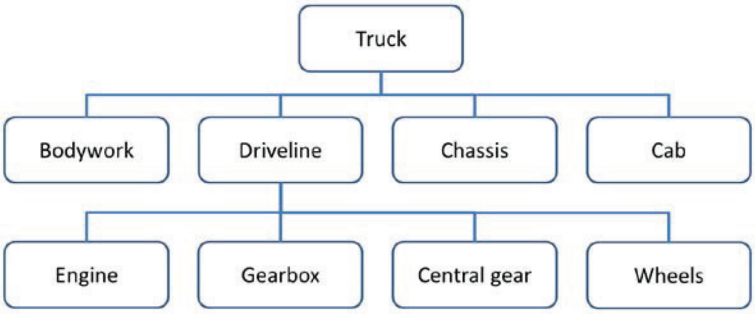

Figure 2. Product structure breakdown.

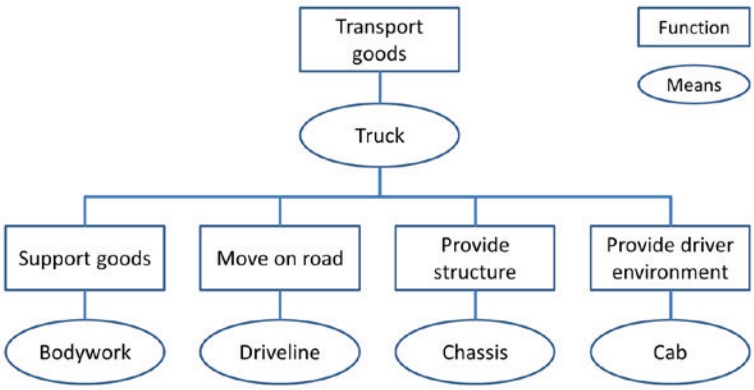

Figure 3. Function-means tree.

A widely used system architecture representation is the Design Structure Matrix (DSM). The DSM was first developed by Steward [16] to visualise planning of engineering work, but has since been applied to describe technical systems, organisations and design processes. Browning [17] gives a review of these and various other applications and extensions of the DSM. The product DSM, used to describe a technical system, is a quadratic matrix where all components are found in both rows and columns, and interactions between components are marked in the matrix. Different types of interactions can be separated. Pimmler and Eppinger [18] suggest four types of interactions: Spatial (components need to be close or attached), energy, information and material (flow of energy, signals or material between components). An example is shown in Figure 4. The strength of the connection is also indicated in the matrix. Each interaction between components in the DSM represents the performance of a function, for example transfer of energy and material between the condenser and the compressor in Figure 4.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
Radiator A		2 0 0 2			2 -2 0 0											
Engine Fan B	2 0 0 2				2 0 0 2								1 0 0 0			
Heater Core C				1 0 0 0			2 0 0 0	-1 0 0 0								0 0 0 2
Heater Hoses D			1 0 0 0						-1 0 0 0							
Condenser E	2 -2 0 0	2 0 0 2				0 2 0 2		-2 2 0 2								
Compressor F					0 2 0 2			0 2 0 2	1 0 0 2	0 0 2 0	0 0 2 0		1 0 0 0			
Evaporator Case G			2 0 0 0					2 0 0 0						2 0 0 0	2 0 0 0	2 0 0 2
Evaporator Core H			-1 0 0 0		-2 2 0 2	0 2 0 2	2 0 0 0		1 0 0 2							0 0 0 2
Accumulator I				-1 0 0 0		1 0 0 2		1 0 0 2		1 0 0 0						
Refrigeration Controls J						0 0 2 0			1 0 0 0		0 0 2 0		1 0 0 0			
Air Controls K						0 0 2 0				0 0 2 0		0 0 2 0	1 0 0 0	0 0 2 0	0 0 2 0	
Sensors L											0 0 2 0		1 0 0 0			
Command Distribution M		1 0 0 0				1 0 0 0				1 0 0 0	1 0 0 0	1 0 0 0		1 0 0 0	1 0 0 0	1 0 0 0
Actuators N							2 0 0 0				0 0 2 0		1 0 0 0			
Blower Controller O							2 0 0 0				0 0 2 0		1 0 0 0			2 0 0 2
Blower Motor P			0 0 0 2				2 0 0 2	0 0 0 2					1 0 0 0		2 0 0 2	

NOTE: BLANK MATRIX ELEMENTS INDICATE NO INTERACTION (FOUR ZERO SCORES).

Legend:

Spatial: S E :Energy
Information: I M :Materials

Figure 4. Design Structure Matrix with different types of interactions. From Pimmler and Eppinger [18].

Sellgren and Andersson [19] extend the product DSM with human and environmental domains. This extended Design Structure Matrix (eDSM) explicitly includes interfaces between the technical system and human features. This allows modelling of interactive functions, which are performed in the interfaces between the technical system and the user.

Hirtz et al. [20] propose an approach to standardise the description of functions in system architecture models. Each function is expressed by a verb and a noun, taken from a given list of expressions. The term functional basis is chosen to correspond to a geometric basis (a set of vectors which spans a room). The aim of the functional basis is to be able to "span" all functions with a given group of expressions. The advantages of using the same language are to minimise variation in descriptions made by different persons, to minimise misunderstandings and to facilitate generalization. Hirtz et al. state that uniformity of description can "support the standardized representation and to provide a basis for knowledge indexing and retrieval" [20]. The importance of using a common language when discussing knowledge has long been emphasised by scientists. This is illustrated by John Wilkins, who state that "the reducing of all things and notions, to such kind of tables, as are here proposed (were it as compleately done as it might be) would prove the shortest and plainest way for the attainment of real knowledge, that hath yet been offered to the world" [21]. The two taxonomies, the functional basis and Wilkins' Real Character, can be compared in Figure 5 and Figure 6.

Table 5. Functional basis reconciled function set

Class (Primary)	Secondary	Tertiary	Correspondents
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack

Figure 5. Extract from the functional basis of Hirtz et al. [20].

Chap. I. *Tranſcendental Relations of Action.* 39

II. *Tranſcendental Relations of Action* COMPARATE, are ſuch as do concern.

Divers things at the ſame time; whether ſuch kind of Actions as from the nature of the Agents or Patients, may be called

Corporeal; denoting the

Cauſing of things to be together or *aſunder*.

I. JOINING, *annex, Connexion, couple, link, copulation, concatenation, conjunction, Coalition, coherent, copulative, conglutinate, combine, compact, ſet* or *put together*.

SEPARATING, *Segregate, ſunder, ſever, diſſever, divide, disjoin, diſunite, diſſect, diſſolve, part, take in pieces, disjunctive*.

Continuing them *together* or *aſunder*.

Figure 6. Extract from the Real Character of Wilkins [21].

2.2 System reliability

A system is reliable if all its required functions can be performed. Often this is taken to be the same as all, or a sufficient number, of its components functioning. In addition to information about the reliability of each component, a model of how the components interact is also needed.

Fault trees have been widely used to compute the probability of a system failure, or undesired event (called top event), given the probability of failure for individual components [22]. It is a top-down approach, where the top event is decomposed into intermediate events, connected by Boolean gates (AND, OR), see Figure 7, down to finally basic events. AND-gates are used when all sub-events must happen for the event to take place. For example, no alarm is given if all fire alarm systems fail. OR-gates are used when one of the sub-events is sufficient for the event to happen. For example, a leak occurs if any pipe breaks. Quantitative analysis of fault trees is done by finding "cut sets", which are combinations of events that cause the top event to occur. By combining the probabilities of the events in cut sets, the probability for the top event can be computed.

Reliability block diagrams are a way of illustrating "paths" through the system which lead to system functionality [8]. A fault tree that has only AND-gates and OR-gates can be converted to a reliability block diagram and vice versa, see Figure 7.

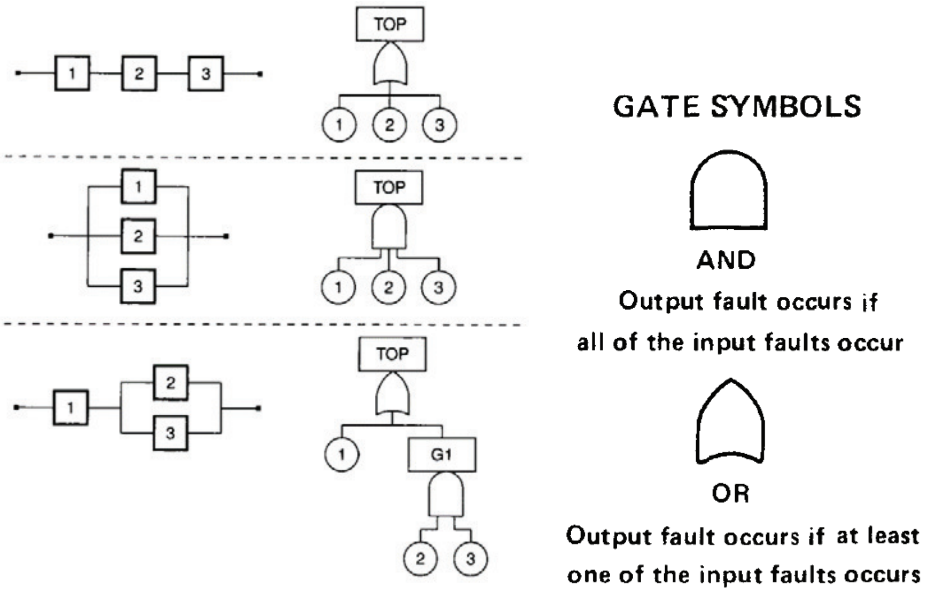

Figure 7. Relations between some simple reliability block diagrams and fault trees. From Rausand and Høyland [8]**. Legend to fault tree symbols. From Vesely et al.** [22]**.**

The two simplest system configurations are series and parallel systems. A series system (top in Figure 7) fails if any of the components fail, whereas a parallel system (middle in Figure 7) fails only of all components fail at the same time. More complicated configurations include n-out-of-k systems, where k components out of a total of n components must fail for the system to fail.

Some failure types are difficult to model with fault trees or reliability block diagrams. Common cause failures are events that cause several components, which are otherwise independent, to fail at the same time, thus invalidating the redundancy of the system. Sometimes failures are dependent, such that a failure in one component causes failure in another, or increases the risk of failure, for example in load-carrying structures, where failure of one component causes higher loads on adjacent components. Another expansion of reliability modelling is to consider components with more than one state (i.e. functioning and broken), in order to model increasing deterioration in a system. These more complicated types of failures can be modelled for example by Markov processes or Bayesian networks [8,23].

This section concludes with some examples of large-scale system reliability assessments with various mathematical techniques. Common to these is that they deal with technical functions only, not interactive functions. Lorton et al. [24] use a Markov process technique to predict the remaining useful life of a deteriorating system in operation. They use a model of how degradation changes with time, dependent on system characteristics and outside impacts. They also take into account how system degradation has evolved until the present time, if data is available. A method for reliability assessment of large, multi-state, renewal systems is used by Blokus [25], where the reliability is approximated by the reliability when the number of components tends to infinity. This asymptotic approach is applied to a bus transportation system and a pipeline system by Kołowrocki and Kwiatuszewska-Sarnecka [26]. Neil et al. [27] use Bayesian belief networks to predict the reliability of military vehicles, before they are built. They use test data from similar vehicles together with information about the development process and organization to make the predictions. However, they only consider the entire system, not any subsystems and components, except for choosing similar configurations for test data input. Lolas and Olatunbosun [28] use artificial neural networks to predict vehicle reliability over time, given a thorough inspection of the vehicle after assembly. The background information used to build the network is test data from inspection and number of failures during testing for around 20 vehicles. In a more recent study, Chatterjee et al. [29] use a support vector machine method to forecast failure times for mining dumpers. The input data set here is 43 failure times for one vehicle, and the test data set is the subsequent 6 failure times.

2.3 Failure of interactive functions

Failures of interactive functions occur when the user feels that a function is not performed satisfactorily. The failures are subjective (person-dependent) so that a failure experienced by one person, who for example feels the climate in the truck cab is too cold, is not experienced by another person. For this reason, failures of interactive functions cannot be evaluated on the technical system alone. Any product with an interface with a human has a potential interactive failure mode. They have been investigated for example in consumer electronics products, often called soft reliability, and some types are labelled No Fault Found (NFF) [30].

Koca et al. [30] report a growing trend in NFF numbers and cost and propose a tool to use in product development to improve soft reliability. Ouden et al. [11] have studied customer complaints from the consumer electronics industry and find that an exclusively technical view of reliability is not enough, but that a consumer perspective is needed and that this perspective is lacking in existing reliability approaches. Simply put, interactive failures cannot be fixed or designed out before the product reaches the user, if the designer does not know about them. In an interview study, Bly et al. [10] investigate dissatisfaction of users of home networks and find that a sizeable portion of the perceived failures are due to “broken expectations”, i.e. the product functions according to technical specifications, but does not perform the functions expected by the user. Brombacher et al. [31] states: "Many traditional reliability models assume that a product consists of components and that a failure happens when a (physical) gradual or instantaneous change occurs in a component." These models cannot handle soft reliability. The authors then propose a classification scheme for reliability problems where both hard and soft reliability is considered.

The research on failures of interactive functions relate to one function at a time, not system reliability. In the field of system testing, however, Belsus et al. [32] describe vehicle tests where both "part failures" and "customer complaints" are included in the complete vehicle reliability assessment, which can be interpreted as technical and interactive functions. Belsus et al. emphasise that both types must be taken into account when viewing reliability from a customer standpoint.

2.4 Operating conditions

Methods for taking operating conditions into account in reliability assessments can be categorized as physics-of-failure methods or data fitting methods. The latter can be separated into data heavy or sparse data methods, see Figure 8.

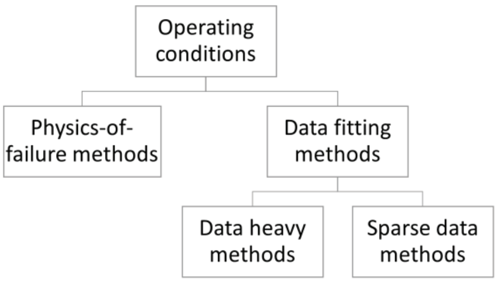

Figure 8. Overview of methods for taking operating conditions into account.

Physics-of-failure methods aim to model the physical state in the material that leads to a failure and take operating conditions into account by modelling how the material of components is affected physically by temperature or corrosive liquids, for example. These methods range from the detailed to fairly overview. Kostandyan and Sørensen [33] model crack propagation in a solder layer in a transistor, depending on load and temperature. Wang et al. [34] and Strutt et al. [35] describe general frameworks for the use of physics-of-failure methods in power electronics and vehicle design, respectively.

Data fitting methods use test data to fit statistical, empirical models, without ambition to explain causes for failures, but predict their frequency. Rausand and Høyland [8] use the term "actuarial approach", as opposed to the "physical approach", for the practice where loads and strengths are not modelled explicitly, but statistically, based on available failure information. Two main data fitting methods for taking operating conditions into account are accelerated test life methods and proportional hazards methods. These methods are used both to design test methods and predict reliability outcomes. The two types of methods are reviewed in Escobar and Meeker [13] and Kumar and Klefsjö [12].

Applications of these methods usually require a great deal of data. As an example, Kumar and Klefsjö [12] recommend a sample size larger than 40 for a model with two covariates, or influencing factors. When only a few data points are available, the data can be supplemented by expert judgement, and in these cases the methods must be adapted. Many sparse data methods are variations on common data heavy fitting methods, but have been augmented with a structured way to include expert judgement. This also gives the opportunity to include the effect of qualitative factors, such as different suppliers [36] or requests for cost reductions [37].

2.5 Expert judgement

Expert judgement elicitation is a large research area. Reviews and recommendations, both general and detailed can be found in Cooke [38] and O'Hagan et al. [39]. Askeland and Flage [40] have reviewed elicitation recommendations and suggest a procedure for elicitation with small resources. In each phase of the process, they find the essential elements, and recommend a simplified procedure.

A principal difficulty of expert judgement elicitation is estimating and reducing the uncertainty of the data from experts. A large body of research deals with the study of how well people estimate probability, and how interviews can be conducted to avoid known biases. Some of the most important types of biases or errors that people, also experts, make in probability elicitation have been categorised by Kahneman and Tversky [41]. Some of these biases are described below, together with examples relevant for a test engineer, who might be interviewed as an expert on component reliability. Note that the term *availability* in this context is not the same as availability from a reliability point of view, which means "ability to be in a state to perform as required" [IEC60050].

Availability – Probability of an event is often judged by how easy it is to call to mind an example of such an event. The easiness of recall is influenced by frequency, but also by other things, unrelated to probability, such as emotional impact. A person often judges the probability of a car accident higher if someone close to them has recently suffered a car accident. Or, for a test engineer, it is likely easier to call to mind spectacular failures than routine tests where all components functioned to the end of the test.

Figure 9. Example of availability. Illustration: Viktor Dahl.

Anchoring and adjustment – When being asked about a number, many people first think of a number, an "anchor", and then adjust their assessment up or down from the anchor. But the adjustment is often not large enough, and it is common for probability intervals to be estimated too narrowly. A natural number for a test engineer to use as an anchor might be the test acceptance criteria. This can lead to underestimating the probability of a really short or really long test life.

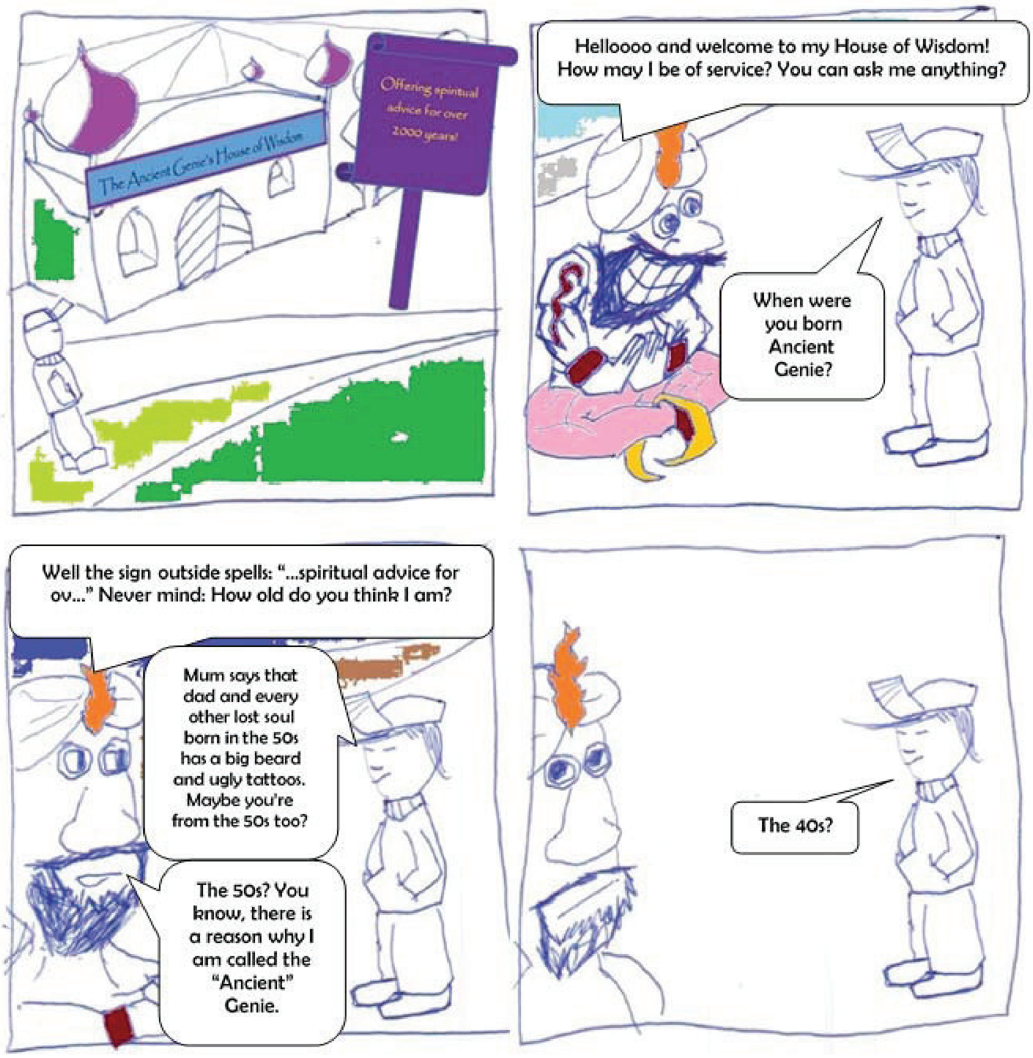

Figure 10. Example of anchoring. Illustration: Viktor Dahl.

Conjunction fallacy – This mistake occurs when a person sees detailed conditions as more likely than general conditions. In other words, it is always more likely that one event happens than two at the same time. For a test engineer these circumstances could be the probability that a component in a very demanding environment suffers a fatigue failure compared to the probability that it suffers a fatigue failure and has a corrosion problem. The former is always more probable, since the latter is a subset of the former, see Figure 11.

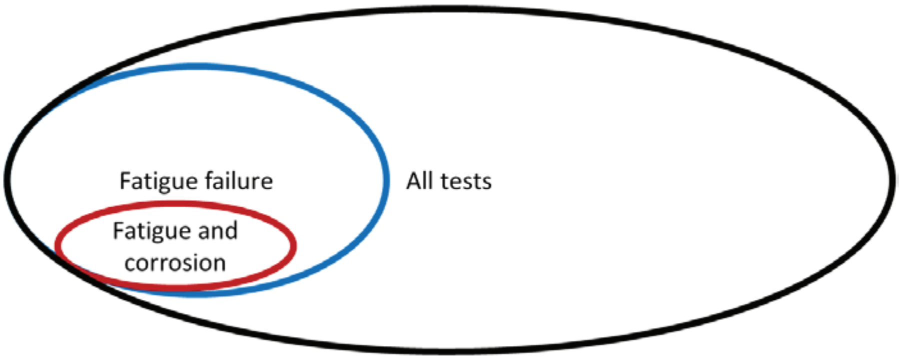

Figure 11. Illustration of single and combined failure modes.

3 RESEARCH METHODOLOGY

Two studies have been performed to answer the research questions, the first regarding the system architecture model, the other concerning methods for dealing with varying operating conditions. Both studies are case studies and have the same principal steps:

1. From research questions, formulate requirements that a suitable method must fulfil.
2. Propose method or find existing method to test in new context.
3. Test method(s) on test cases from industrial application.
4. Evaluate if method(s) fulfil the requirements

A case study is a “particular instance of something used or analysed in order to illustrate a thesis or principle” [42] and can illustrate feasibility and uncover problems, and be made with a reasonable amount of effort. The research questions are concerned with how something can be done, i.e. feasibility, which makes case studies a good choice. A possible problem with case studies is the risk of selecting poor cases, which impairs generalisability. An important step in ensuring the validity of the research is to verify the connection between the research question and the requirements, since the latter are what is in fact measured against the results of the study, see step 4 in the list. This connection will be examined for each study below.

3.1 Qualitative system architecture model

The system architecture model proposed for reliability assessment is an application of the extended Design Structure Matrix (eDSM) in Sellgren and Andersson [19]. The second part of the model is the Function Means Matrix (FMM) which shows the connections between the required functions of the system, both technical and interactive, and the components that contribute to function performance, as well as human and environmental features that impact function performance. The functions in the FMM are expressed with the functional basis of Hirtz et al. [20].

	inhibit mechanical energy	display tactile signal	driver station ergonomics	prevent acoustic energy	display aesthetic signal
Floor	x			x	x
Cab suspension	x			x	x
Anti-roll bar	x			x	x
Pedals		x	x	x	x
Instrument panel			x	x	x
Steering wheel	x	x	x	x	x
Seat	x		x	x	x
Human back	x		x		
Human hand	x	x	x		
Human feet	x	x	x		
Vibration in frame	x				

	Floor	Cab suspension	Anti-roll bar	Pedals	Instrument panel	Steering wheel	Seat	Human back	Human hand	Human feet	Vibration in frame
Floor	x	x		x		x	x			x	
Cab suspension	x	x	x								x
Anti-roll bar		x	x								
Pedals	x			x		x	x			x	
Instrument panel					x	x	x		x		
Steering wheel	x			x	x	x	x		x		
Seat	x			x	x	x	x	x			
Human back							x	x			
Human hand					x	x			x		
Human feet	x			x						x	
Vibration in frame											x

Figure 12. Function Means Matrix (FMM) and extended Design Structure Matrix (eDSM) for the cab of a heavy truck.

An example of the proposed system model is shown in Figure 12. The technical system is the cab of a heavy truck, the user is the driver and the environment is the rest of the truck, as well as the road and the rest of the world. To simplify the figure, not all components are shown. The eDSM shows that the cab floor has interfaces with the cab suspension (which connects the cab to the frame), the pedals, the steering wheel and the driver seat. Furthermore the floor has an interface with the driver's feet, which in turn are also linked with the pedals. The interactive function of achieving vibrational comfort for the driver is expressed "inhibit mechanical energy" in the functional basis. The FMM shows that the floor, cab suspension, anti-roll bar, steering wheel and seat contribute to the performance of this function, and also that it is experienced by the driver through the back, hands and feet.

3.1.1 Requirements on a system architecture model

Requirements have been defined which together determine if the system architecture model is able to support reliability assessment.

The system model must

- be suitable for both technical and interactive functions, since reliability depends on all required functions
- include components as well as human and environmental factors, since function performance depends on them all
- reflect variations in configuration, since this variation affects function performance
- be flexible as to the level of detail, since information is available at different levels of detail, and the level of detail may vary during the development process

A system architecture model that fulfils these requirements is an answer to research question 1. The proposed model has been evaluated against these requirements with two test cases, one technical function and one interactive function. The technical system in the case study is the cab of a heavy truck. The technical function is to keep the structural integrity of a storage compartment in the cab, i.e. to avoid fractures. The functional basis expressions are “support object” and “connect object”. The interactive function is to provide ride comfort for the driver by reducing vibrations. In the functional basis this is expressed “inhibit mechanical energy”, see Figure 12.

3.2 Methods for handling operating conditions

The reliability forecast will be made for a complete vehicle test on a test track. During the early stages of product development, information is available from calculations, component tests or function tests, among others. These tests were typically made with different operating conditions than the complete vehicle test will be made with, for instance in a test rig in a laboratory compared to on an outdoors test track. In order to use this information to predict reliability in the vehicle test, a method is needed to take into account the effect of the different operating conditions. A key characteristic of this forecast is uncertainty. A forecast made for a different situation than the data comes from must be more uncertain than one made for the same situation. A suitable method should reflect this. Four methods from literature, briefly described in the following, were tested in a case study. The coefficient of variation was chosen as the measure of uncertainty, since the mean value varies.

None of methods had previously been tested with interactive functions. Interactive functions differ from technical functions in that we usually do not know the “direction” of a change in function performance due to a change of user. A different user can be expected to experience the interactive function differently, but whether a new user will be more positive or negative is unknown. Thus, the mean function performance is expected to be the same, but the uncertainty increases with a new user. For some of the tested methods, small modifications are required to handle interactive functions.

3.2.1 The fuzzy method

Cizelj et al. [43] propose a method to estimate the failure rate of a component using numerical and linguistic information about operating conditions. In an example, a failure rate distribution for a component used in many nuclear plants is known from handbook data, and information about operating conditions specific to one plant is found from expert judgement. Fuzzy reasoning [44] is used to estimate the impact of each noise factor and their joint effect. The result of the fuzzy reasoning is a fuzzy set for the relative failure rate, i.e. the ratio between the failure rate in the specific plant and the failure rate in general conditions, see example in Figure 13. The next step is a defuzzification process to get a single number for the relative failure rate. Then the failure rate distribution for the specific plant is taken as the posterior distribution after updating the general failure rate distribution by a Bayesian inference procedure, using the defuzzified failure rate as a new observation. If the expert judgement is more uncertain, the fuzzy set for the relative failure rate will be wider. The defuzzification process, however, can give the same result for two fuzzy sets with different uncertainty. Such an example is shown in Figure 13. One set (dashed line) has larger uncertainty (wider interval of possible values) than the other (solid line), but the same defuzzified result, using the procedure suggested by Cizelj et al. The difference in input data uncertainty will therefore be hidden in the final result. For use with interactive functions, the *fuzzy* method has been modified by using the defuzzified result as two new observations, on either side of the original mean function performance, to handle the fact that the new user is equally likely to be positive or negative.

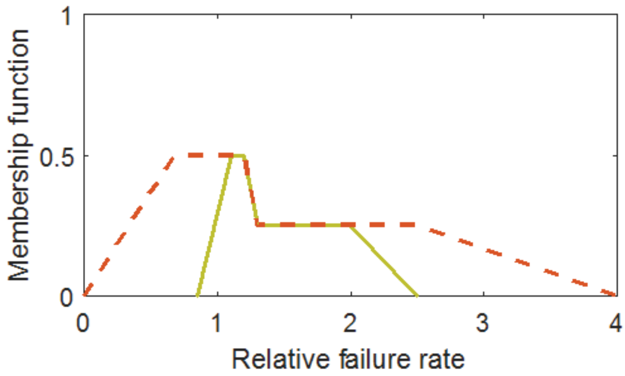

Figure 13. Two fuzzy sets with different uncertainty and the same defuzzified result.

3.2.2 Variation Mode and Effect Analysis

Johannesson et al. [45] propose the Variation Mode and Effects Analysis (*VMEA*) method as a product development tool for robust design, i.e. design insensitive to variation. The tool can be used for reliability but also for other product properties. The procedure begins by a causal breakdown of a Key Product Characteristic (KPC), for example test life, to find noise factors (NF) that affects product behaviour, see Figure 14.

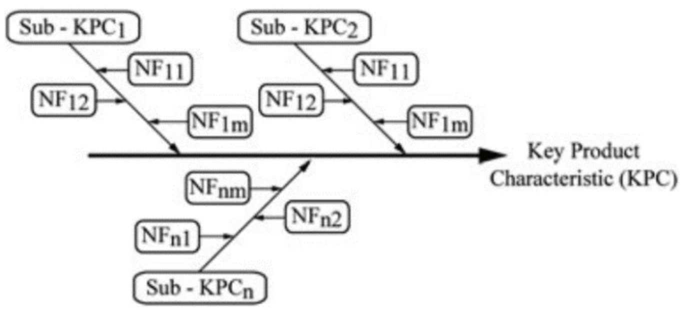

Figure 14. Breakdown of KPC to find noise factors. From Johannesson et al. [45]**.**

The sensitivity of the KPC to each noise factor, as well as the size of the variation of each noise factor is estimated from data or expert judgement. The response function, which describes how the system reacts to the noise factors, is linearized and the total variance is estimated using Gauss' approximation formula. Then the total variation of the response can be approximated. The method is a first-order (linearized response function) second-moment (uncertainty is measured by standard deviation) reliability method.

3.2.3 Failure rate evaluation with influencing factors

Brissaud et al. [46] propose a method for failure rate evaluation with influencing factors (*frewif*) with an application to safety instrumented systems (safety barrier systems in process industries). The method uses quantitative data from field experience or handbooks and qualitative data from expert judgement to improve risk analysis. Expert judgement is used to assess for each influencing factor the best and worst level, the impact on the failure rate, and the relative importance of the influencing factors. Weighted by the relative importance of the factors, their impact on the failure rate is combined to compute a relative failure rate, i.e. the ratio between the failure rate under specific conditions and the handbook failure rate. Then the estimated failure rate with the new operating conditions is calculated. The method is a variation of the proportional hazards method. For use with interactive functions, the *frewif* method has been modified by modelling separately all possible combinations of positive and negative changes due to variations in operating conditions and then combining all cases with equal probability.

3.2.4 Rahimi method

Rahimi and Rausand [47] propose another variation on the proportional hazards model to assess the reliability of a subsea pump given information about a similar pump topside (above sea level) and a comparison of the two systems, see Figure 15. The failure modes (how do we notice a failure, for example failure to start on demand) and failure causes (why did the system fail, for example blockage) are compared between both systems. Expert judgement is used to estimate relative importance between reliability influencing factors for each failure cause, and relative importance of each failure cause on topside and subsea systems. Finally the total effect of different operating conditions on the subsea systems is weighted by relative importance and summarized to a relative failure rate to be multiplied by the estimated failure rate of the topside system. A distinctive aspect of this method is that it includes the possibility to include new failure modes in the new environment which could not appear in the former environment. Naturally, the information about this failure mode remains uncertain, but the fact that this possibility is pointed out is interesting. The same modification as for the *frewif* method is used to handle the interactive function.

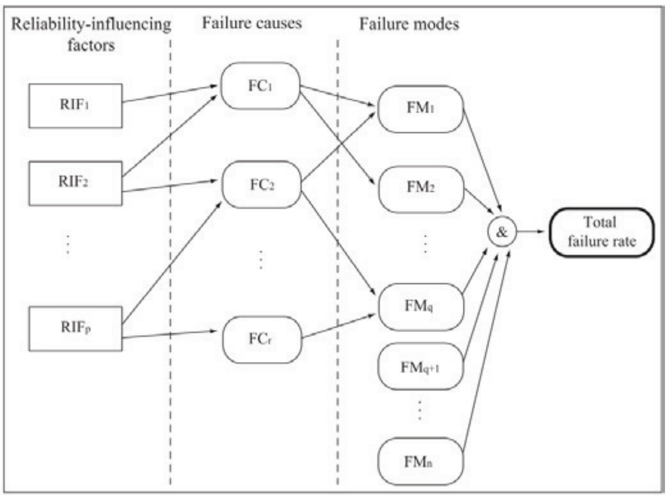

Figure 15. Influence diagram. From Rahimi and Rausand [47].

3.2.5 Requirements on a method to take operating conditions into account

Requirements have been defined, that together determine if a method is able to assess reliability under varying operating conditions.

Such a method must be

- suitable for both technical and interactive functions, since system reliability depends on all required functions
- able to use expert judgement, since, at times, data is sparse
- able to express the increased uncertainty which is the result of the forecast being made for an unknown situation

A method that fulfils these three requirements is an answer to research questions 2 and 3. The four methods have been evaluated against these requirements with two test cases, one technical function and one interactive function. The technical function is to keep the structural integrity of a component in the cab suspension. The interactive function is again “inhibit mechanical energy”; to provide the driver with a comfortable working environment.

4 SUMMARY OF APPENDED PAPERS

Paper A: DSM-based reliability analysis of modular architectures
A system architecture model is proposed for the purpose of supporting reliability forecasts. The extended Design Structure Matrix (eDSM) represents relations between components in the technical system, and is extended to include the human and environmental domains, and their interfaces with the technical system. The Function-Means matrix (FMM) represents relations between the required functions, both technical and interactive, and the components that contribute to function performance, as well as human and environmental features that affect function performance.

Paper B: Model-based reliability analysis
The system architecture model presented in paper A was evaluated in a case study of an extended truck cab and driver system. Requirements necessary for such a model to be useful for reliability assessment are specified, and the importance of interactive functions is underlined. It was found that the model can include both technical and interactive functions, due to the extension to human features. The extension to the environmental domain gives information about factors that influence function performance. The matrix-based system model allows different levels of detail and can register differences in configuration. A qualitative example shows how the system architecture model supports reliability forecasts.

Paper C: Reliability assessment with varying operating conditions
Operating conditions often differ between component tests and system tests. Therefore, reliability assessments where data from one situation is used to predict reliability in a different situation must take this variation into account. In paper C two reliability estimation methods have been evaluated to investigate if the methods can be used for interactive functions as well as for technical functions. The case study leads to the conclusion that a method for reliability estimation of interactive functions must be able to model increased uncertainty due to intrapersonal variation.

Paper D: Modelling uncertainty of reliability forecasts with varying operating conditions
Paper D extends the study from paper C. A number of currently available methods that can account for varying operating conditions have been reviewed, and four methods have been tested in a case study. The study is made in the context of system reliability for heavy trucks, where both technical functions and interactive functions affect product reliability. Two cases have been assembled from test data, one concerning a component on a truck cab, the other an interactive function of a truck. The system architecture model from papers A and B is used to organise information about influencing factors. The tested methods are; a fuzzy logic method, a first-order second-moment reliability method (*VMEA*), and two variants of the proportional hazards model. The study shows that several methods are capable of handling sparse data and both technical and interactive functions, but only *VMEA* can show how uncertainty increases when operating conditions vary. It has however the drawback of being quite sensitive to uncertainty in the input data.

5 ANSWERS TO RESEARCH QUESTIONS

How can we model the system architecture qualitatively to support the reliability forecast?

Heavy truck reliability depends on both technical and interactive functions. Failures of both types reduce uptime, increase repair costs and reduce the customer's earning capacity, and therefore both failures types must be included in complete vehicle reliability forecasts.

In paper A, it is shown how the proposed system model of two matrices (eDSM + FMM) can include technical and interactive functions by expanding the technical domain with human and environmental features. Paper B shows how the system model supports reliability analyses in two ways: all known failure modes are included, and the inclusion of human and environmental features collects all noise factors that affect function performance.

The proposed system architecture model (eDSM+FMM) is recommended as a basis for system reliability forecasts.

How can we model function performance under varying operating conditions?

The system reliability forecast must be made based on data from diverse sources, sometimes from different operating conditions than the forecast will be made for. In addition, the relation between function performance and operating conditions is often not known with precision. It is necessary to have a method, a structured process, to deal with this situation.

In paper D, four methods which have been proposed in literature to handle variation in operating conditions are tested. These methods were all designed to handle sparse data, and with minor modifications, they can be used to predict function performance also for interactive functions.

How can we estimate forecast uncertainty under varying operating conditions?

In paper C, it is concluded that uncertainty estimation is necessary for modelling of interactive functions. In general we don't know if the next user will experience the function more positively or more negatively, only that there is likely to be a difference; the drivers will experience the function differently. The direction of the change is unknown. Consequently, we expect on average the same function performance, but we are more uncertain. Simply stating this average, however, is not a good description of the situation, but a suitable method must also show how uncertainty grows when a forecast is made in a new situation.

Three of the methods tested in paper D do not model uncertainty in an adequate manner due to mathematical assumptions underlying the methods. The *VMEA* method is based on mathematical assumptions which are suited for uncertainty modelling, but is quite sensitive to input data uncertainty.

Can any method for taking operating conditions into account be recommended for use with technical and interactive functions?

The *VMEA* method is recommended to estimate function performance for both technical and interactive functions under varying operating conditions. The mathematical structure of this method allows modelling of the increased uncertainty of making forecasts in an unknown situation. The large input data sensitivity of the method demands a structured process of estimation in order to be able to compare different cases.

6 DISCUSSION

The main contribution of this thesis is to support system reliability forecasts where all required functions of the system, both technical and interactive, are taken into account. This gives a better representation of the customer's perception of a product than previous system reliability models, where technical functions only were included.

6.1 Validity and reliability

There are several aspects of validity. Wohlin et al. [48] list four types: conclusion, internal, construct and external validity. Conclusion validity and internal validity are concerned with statistical significance and causal connection between treatment and outcome in an experiment and will not be further discussed, since no conclusions about causality are attempted.

Construct validity is "the degree to which a test measures what it claims, or purports, to be measuring" [49]. This is interpreted as the degree to which the studies in fact answer the research questions. The cases have been tested against requirements, and in order to establish construct validity, the connection between the requirements and the research questions must be made clear. This has been done in sections 3.1.1 and 3.2.5.

External validity is about generalization and in this case if the conclusions are valid for other products. This has not been formally shown, but on the other hand, the conclusions do not make use of any characteristics specific to heavy trucks, and therefore it appears that the conclusions should be useful for other products which have both technical and interactive functions.

The reliability of a study means if it can be repeated by someone else with the same results, or in a wider sense, with the same conclusions. In this work, a direct application of the same methods to the same cases with the same data would give the same results and conclusion. But what would happen if other cases had been chosen?

In the system architecture model study, the truck cab could be represented with a different granularity, i.e. with a finer or coarser subdivision of components. The same human and environmental factors would still be affecting the function performance, and the reliability reasoning is dependent on how demand and capacity are represented in the model and not on the level of detail. If other cases, other technical and interactive functions, were chosen, the relevant noise factors would vary. Yet, the way the model supports reasoning about demand and capacity and function performance could still be shown, and the conclusions would be the same. If the study was made on a different product altogether, assuming it is a product with both technical and interactive functions, the same arguments apply.

In the operating conditions study, the requirement that divides the tested methods is the uncertainty modelling. If other cases were chosen, the proportional hazards method, and consequently the *frewif* and *Rahimi* methods, would still be based on a constant ratio between hazard rates, which makes them unable to show that the uncertainty increases when the forecast is made in a new situation. That conclusion must be the same. The problem with the *fuzzy* method is that in the case of the interactive method, the original probability distribution was updated with two points, symmetrically placed about the mean. In the chosen case, these points were not very far apart, which caused the posterior distribution to have a lower coefficient of variation than the prior distribution. If a different case had been chosen, where the two points were far apart, it is possible that this problem would have remained undetected. However, the problem lies in the mathematical formulation of the method. The requirement is for a method that consistently models uncertainty in a reasonable manner, and the present study shows that the *fuzzy* method does not. A case which failed to detect this would have been badly or unluckily chosen. This leads to the question of whether a different case would disqualify also the *VMEA* method. The mathematical construction of the *VMEA* method is such that each new source of uncertainty is added to the previous. When the forecast is moved to a new situation, the uncertainty concerning the impact of the variation in operating conditions in then added to the previous uncertainty, and the resulting uncertainty is larger than it was before. The uncertainty in the response function is computed from estimation of the standard deviation of the noise factors. This is in itself an uncertain estimate, but a forecast in a new situation will always be shown as more uncertain than a forecast in a known situation. This also is a consequence of the mathematical properties of the method, not a function of which case was chosen.

Consequently, construct validity is ensured by the connection between research questions and requirements, external validity is plausible but not verified. Furthermore, since the conclusions of both studies are not dependent on the choice of cases, they are reliable.

7 APPLICABILITY AND FUTURE WORK

Although the result of this thesis is not a quantitative reliability forecast, the work can contribute to a better qualitative understanding of the system reliability. The system model gives a compact overview useful for seeing which noise factors affect which functions and which functions can be affected by a component redesign. The study about operating conditions gives valuable input to system reliability forecasts.

Future work should focus on a quantitative system model. Some points to look into:

- Evaluate different mathematical tools, or system model structures, such as basic serial configuration, Bayesian network or others.

- How can information of various formats be used? Results from calculations may come as a maximum tension in a component, or results from shaker tests of electronic components may come as number of hours test life with a given PSD. How can these data be “translated” to use in a complete vehicle forecast?

- There must be an assessment of the total uncertainty of the forecast, due to parameter uncertainty, uncertainty from input data and expert judgement and model uncertainty.

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