KOTEL

PROJECT REPORT

KOTEL 256

31.12.2008

INTEGRATED BUSINESS AND TECHNICAL PRODUCT RELIABILITY DESIGN

FOREWORD

The traditional and still dominating method for product design is focused on optimising the technical performance of a product. The reason for this is simple, there does not exist easily available and comprehensive design method or tool to integrate the reliability and maintainability (R&M) considerations and effects in product design.

As more the companies' management have experienced the meaning of Product's R&M as competitive factors in their business, as more they have started to invest R&M engineering and development. This was also a starting point from where this project was launched.

The purpose of the project was to develop a design methodology that includes the interactions and links between the customer needs, the manufacturer business targets and the product R&M performance. This makes it possible to find and simulate in detail, which are the specific customer product R&M requirements and what influence the R&M performance has on the customer satisfaction. The method enables product R&M facts to be taken into account at business decision level.

This research project was carried out by Tampere University of Technology with co-operation University of Queensland, Australian. KOTEL ry was responsible for managing the project with the help of project steering group. The project was funded by TEKES, ABB Oy, Kone Oyj, MacGregor Oy and Wärtsilä Oyj.

On behalf of KOTEL ry I would like to thank all who have participated in this project.

Espoo 2008-12-31

KOTEL ry

Antti Turtola

CONTENTS

1. INTRODUCTION

The customer expectations are today increasingly integrated as design requirements into the design process. However, the reliability and maintainability (R&M) aspects of the product are still today very poorly integrated into the design process. This is a problem today when both the customer expectations and the societal requirements are increasingly focusing more on R&M aspects instead of purely technical performance.

In the design methods used today it is very much the design engineer that is responsible for the product's R&M engineering. How well this is in agreement with the customer expectations depends on how well the engineer knows the end user and how well the R&M requirements have been specified. Typical problems arise when either 1) such an R&M performance is promised to the customer that cannot be achieved or 2) achieving the promised performance becomes very expensive for the company.

A company that has a good control of the R&M performance of its products has a considerable competition advantage both in the case of consumer products and when negotiating about maintenance service contracts for large industrial systems.

One basis for this research project has been carried out by prof. Seppo Virtanen's research team at Tampere University of Technology. Since 1996 eleven Finnish companies have participated in the research project which objective was to develop computer supported probabilistic based method for the design and development of the equipment's reliability, safety and maintenance service.

The research project consists of three parts:

1) Modelling and analysis of causes and consequences of failures,
2) Specification and allocation of reliability, availability and maintenance cost requirements, and
3) Simulation and calculation of reliability performance and maintenance costs.

Based on the experience, and with the help of the methods, it is possible to find out those problem areas during the design stage, which can reduce product R&M, increase product life cycle costs and delay product development.

Professor D.N.P. Murthy from the University of Queensland in Australia is one of the leading experts and scientists in reliability engineering in the world. He has published a great number of scientific papers, books and carried out industrial consultancy in many countries in different parts of the world. He has recently developed together with Ostreas and Rausand from Norwegian University of Science and Technology in Trondheim a new method called "Reliability Performance and Specifications in New Product Development". The novel feature of this is focusing on the front end in the product development process. This new approach as well as the large experience of professor Murthy was benefited in this research project.

2. PROJECT ISSUES ANALYSIS

In the project preparation phase seven research issues were analyzed and ranked according to the industrial companies (Kone, Wärtsilä, ABB, Nokia and Metso) point of view. A summary of the study is below.

<table>
<tr><th>Issue No</th><th>Integrated Business and Technical Product Reliability Design (BRED)</th><th colspan="2">The issues importance from BRED project point of view</th></tr>
<tr><td>6</td><td>How to include the customer view into the reliability of a product? Transferring customer needs to product roadmaps / top management strategy deployment</td><td rowspan="3">0.56</td><td rowspan="4">0.70</td></tr>
<tr><td>4</td><td>Need to formulate reliability parameters on terms of cash > profit. The LCC perspective</td></tr>
<tr><td>2</td><td>Simple tool to make reliability facts visible for top management is needed</td></tr>
<tr><td>3</td><td>A structure and procedure forming basis for making warranty strategy decisions and maintenance contracts / extended warranty is needed</td><td>0.14</td></tr>
<tr><td>5</td><td>How to get good (=reliable) data for the reliability calculations/estimations</td><td colspan="2">0.14</td></tr>
<tr><td>7</td><td>How to include the uncertainty of middlemen (between supplier and end user) and small subcontractors in the reliability estimations</td><td colspan="2">0.09</td></tr>
<tr><td>1</td><td>Small cheap components cause much trouble - time between stoppages important</td><td colspan="2">0.07</td></tr>
</table>

3. OBJECTIVES AND WORK PLAN

The objective of the project was to develop a design methodology that includes the interactions and links between the customer needs, the manufacturer business targets and the product reliability and maintenance performance. This makes it possible to find and simulate in detail, which are the specific customer product R&M requirements and what influence the R&M performance has on the customer satisfaction. In addition the method enables to assure at different phases of the design process that the promised R&M performance can be delivered to the customer in accordance with the business expectations of the top management. Thus the method enables product R&M facts to be taken into account at business decision level.

The work includes two parts: I) the development of “Decision model” and its integration to the developed “RAM design methods and software” (see Figure 1) and II) in parallel its implementation to four industrial cases. The “Decision model” consists of a holistic business-reliability structure which includes elements such as: a tool for making R&M facts visible for business level decisions and a tool for including the customer view into the R&M of the product. The experience from the industrial cases will during the process directly be used in the further development of the generic model.

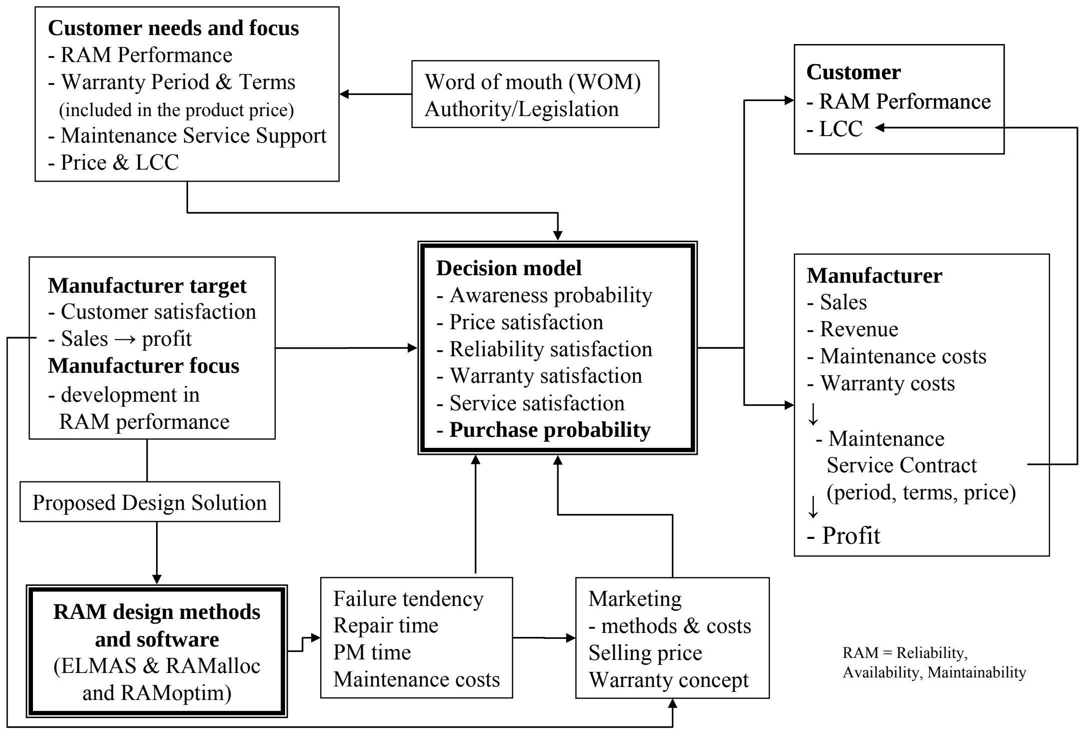

Figure 1. Concept to link the customer needs and focus, the manufacturer's target and focus and the product RAM performance

4. RESOURCES AND SCHEDULE

The work was carried out by Tampere University of Technology with co-operation University of Queensland, Australian.

KOTEL ry was responsible for managing the project with the help of project steering group.

Practically project started in 1st of May 2005 and finished 31.12.2008. The different subtasks, which were carried out during the project, are illustrated in Figure 2.

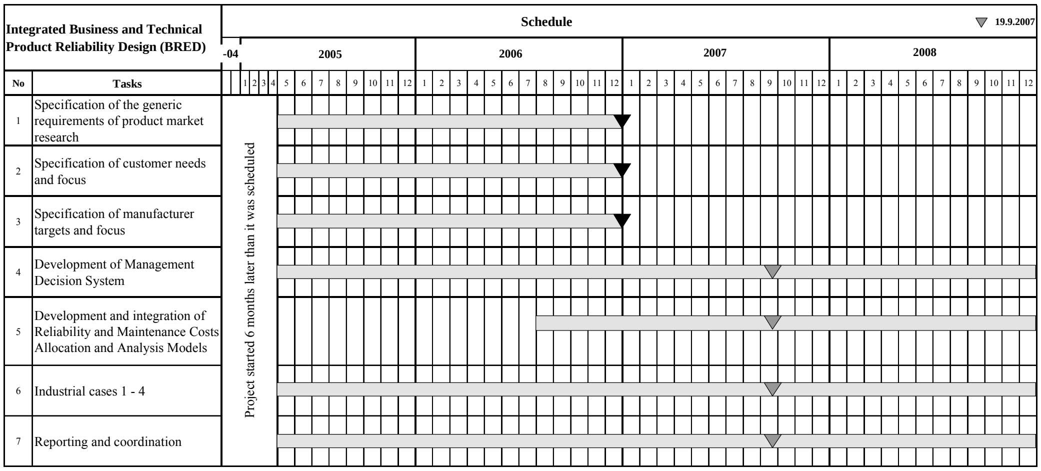

Figure 2. Project schedule

5. RESULTS

Result of the project is presented in the following appendixes:

1. Publications
2. Master Thesis
3. Developed Models
4. Case-Studies: Companies Presentations

APPENDIX 1

PUBLICATIONS

Total number of pages in Appendix 14

BRED-projektin yhteydessä valmistuneet julkaisut:

Author(s)	Title	Publisher
Per-Erik Hagmark, Seppo Virtanen	Specification and Allocation of Reliability and Availability Requirements.	IEEE, Proceeding: Annual Reliability and Maintainability Symposium (RAMS). January 23 – 26, 2006. Newport Beach, CA, USA. pp. 304 – 309.
Seppo Virtanen, Per-Erik Hagmark, Jussi-Pekka Penttinen,	Modeling and analysis of causes and consequences of failures	IEEE, Proceeding: Annual Reliability and Maintainability Symposium (RAMS). January 23 – 26, 2006. Newport Beach, CA, USA. pp. 506 – 511.
Per-Erik Hagmark, Seppo Virtanen	Simulation and Calculation of Reliability Performance and Maintenance Costs	IEEE, Proceeding: Annual Reliability and Maintainability Symposium (RAMS). January 22 – 25, 2007. Orlando, FL, USA. pp. 34 – 40.
K. Åström, E.Fontell, S.Virtanen	Reliability analysis and initial requirements for FC systems and stacks	Elsevier: Journal of Power Sources 171 (2007) 46–54
Hagmark, P-E., Pernu, H.	Risk evaluation of a spare part stock by stochastic simulation	Coxmoor Publishing Company: Proceedings of the 2nd WCEAM-CM 2007. ISBN 978-1-901892-22-2. PP. 708 - 715
Per-Erik Hagmark	On construction and simulation of count data models	Elsevier: Mathematics and Computers in Simulation 77 (2008) 72–80
Seppo Virtanen, Per-Erik Hagmark,	Determining Reliability Performance and Maintenance Costs of Selected Design Solution and Maintenance Strategy	Springer-Verlag London Ltd: Proceedings of the 3rd WCEAM-IMS 2009. ISBN 978-1-84882-216-0. pp. 1568 - 1579
Pernu H., Hagmark P-H	A Simulation Model for Optimization of Maintenance Strategy in Asset Management	Springer-Verlag London Ltd: Proceedings of the 3rd WCEAM-IMS 2009. ISBN 978-1-84882-216-0. pp. 1292 - 1298
Nevavuori L	Product Reliability and Availability in Field data	Springer-Verlag London Ltd: Proceedings of the 3rd WCEAM-IMS 2009. ISBN 978-1-84882-216-0. pp. 1177 - 1185
D.N.P. Murthy, M. Rausand, S.Virtanen	Investment in new product reliability	Elsevier: Reliability Engineering and System Safety 94 (2009) 1593–1600
D.N.P.Murthy, P.-E. Hagmark, S.Virtanen	Product variety and reliability	Elsevier: Reliability Engineering and System Safety 94 (2009) 1601–1608
D.N.P. Murthy, T. Østerås, M. Rausand	Component reliability specification	Elsevier: Reliability Engineering and System Safety 94 (2009) 1609–1617
Per-Erik Hagmark	A new concept for count distribution	Elsevier: Statistics and Probability Letters 79 (2009) 1120 - 1124

Specification and Allocation of Reliability and Availability Requirements

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Seppo Virtanen, PhD, Tampere University of Technology

Key Words: availability, failure tendency, generalized fault tree, product requirements, repair time, simulation.

SUMMARY & CONCLUSIONS

Our model for allocation of requirements is based on a generalized fault tree approach, where the TOP represents the product to be designed. The other parts of the fault tree represent entities, which affect essentially the failure tendency and the repair time of the product. Relations between parts are modeled by two mechanisms. The "gates" determine the partly logical and partly stochastic propagation of faults (primary states). The "strategies" define other relations between TOP and the deepest entities. A consequence of the strategies is that two types of "waiting" (secondary states) can occur.

Customer and/or manufacturer data influences the design of product reliability, availability and repair time. The proposed methods can deal with quite different types of requirements. Requirements related to failure tendency can involve number of failures, time between failures, reliability and availability as a function of age, or data concerning first failure. Requirements related to product's repair time again could involve mean time to repair, standard deviation, minimum repair time (0%), and maximum repair time (with corresponding quantile %).

The allocation of the failure tendency of a gate (entity) down to its input entities is guided by assessing "importance" and "complexity". Importance takes into account customer's perspective and complexity represent the technical standpoint. The aim is that the more important an entity is, the less it is allowed to fail, and the more complex an entity is, the more it is allowed to fail. The repair time allocation again is based on a direct assessment of repair time ratios between the input entities. The failure tendency and the repair time of an entity can also be locked, whereas the designer can focus only on the unlocked entities.

The requirements for TOP are summarized in two "dependability functions" - one for failure tendency and one for repair time. A stepwise allocation process downward in the fault tree leads gate by gate to equivalent dependability functions for other entities. These functions are in every stage tested via simulation and comparison to TOP requirements.

The last simulation confirms the final dependability of entities, especially of those to which attention will be paid in a later design process. The simulation produces also a complete list of events, states of entities, their duration, etc. This "logbook" is of course detailed raw material for various supplemental calculations, conclusions, and even further programming.

1. *INTRODUCTION*

This paper presents, a computer-supported method for specifying reliability, repair time, and availability requirements for a product and allocating them into the product's design entities. The general term "entity" can stand for function, system, equipment, mechanism, or any kind of part.

The developed method is one of the main results from the research project, which lasted about nine years and was carried out by Tampere University of Technology. Since 1996 eleven Finnish companies have participated in the research project, which objective was to develop computer supported probabilistic based method for the development of the equipment's and systems' reliability and safety. The participating companies are both manufacturers and users of equipment, in metal, energy, process and electronics industries. Their products and systems have to correspond to high safety and reliability demands. The research project was completed in February 2005.

The corresponding software (RAMalloc) forces the designer to work out which customer and manufacturer needs should be used to determine the product's quantitative reliability, availability and repair time goals, early in the design stage. Rather detailed product specific requirements can be modeled. For example, there is from both the customer's and the manufacturer's perspective, an opportunity to accept a different probability of failure during the burn-in phase than after it, or there is possibility to accept different failure tendencies during the warranty and the post warranty periods. With the software, the requirements can be allocated to functions, systems, mechanisms or any parts as the design work proceeds.

The effect of reliability, availability and repair time requirements defined by the customer and manufacturer on the known technical solution of a product can be demonstrated with the developed method and software. This connection is important in order to avoid promising something that cannot be achieved or something, which is very expensive to achieve. The applicability of the developed methods and software has been tested in companies that have been involved in the research project. At this moment, most of the participating

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Modeling and analysis of causes and consequences of failures

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Key Words: cause, consequence, event, logic, modeling, simulation

SUMMARY & CONCLUSIONS

This paper presents a computer-supported method for modeling and analyzing causes and consequences of failures. The developed method is one of the main results from a nine-year research project, which was completed in February 2005 and carried out by Tampere University of Technology.

The applicability of the developed methods and software has been tested in the companies, which have been involved in the research project. The participating companies are both manufacturers and users in metal, energy, process and electronics industries. Their products and systems have to respond to high safety and reliability demands. Most of the participating companies have started to apply the proposed method and software for modeling and analysis of failure logic for their products and systems. The application of the method forces experts to identify all potential component hardware failures, human errors, possible disturbances and deviations in the process, and environmental conditions related to the selected TOP-event. Based on experience, and with the help of the methods, it is possible to find out those problem areas of the design stage, which can delay product development and/or reduce safety and reliability.

1. *INTRODUCTION*

Modeling and analysis of causes and consequences of failures form a foundation for quantitative investigation of the reliability, safety and risks related to a design entity. The general term "entity" or "design entity" can stand for function, system, equipment, mechanism, or any kind of part.

A "cause tree" consists of such (well-defined) causes and interconnected causalities that can lead to the occurrence of a TOP-event. Thus, a cause tree structure forms a basis for a failure logic model of the design entity in question. A "consequence tree" again describes the possible chains of consequences initiated from a TOP-event. A consequence may further cause other consequences, either exclusively or independently. Finally, a combination of cause trees and a consequence tree, illustrated in Figure 1, will be called a "cause-consequence tree". A cause-consequence tree may for example contain several separate chains of events that lead to the same consequence. (Note the chains to consequences 1 and 2 in Figure 1.)

The cause tree model is used to define the occurrence of the TOP-event, from which the consequences to be studied originate. Conditional relations between consequences may also be modeled precisely by using cause trees. The developed method can further describe relations and shared causes between cause and consequence structures. The consequence tree does not offer any additional logical structure, but it makes it possible to model such consequences, which have conditional relations to the cause tree structures. It is also possible to model and analyze several TOP-events simultaneously.

For the analysis of causes and consequences of failures, the root cause probabilities and the gate probabilities are first estimated, and then the modeled failure logic is analyzed through stochastic simulation. The developed method is simple enough to be applicable also for the analysis of very large models. Notwithstanding, it is still capable to produce exact and useful results.

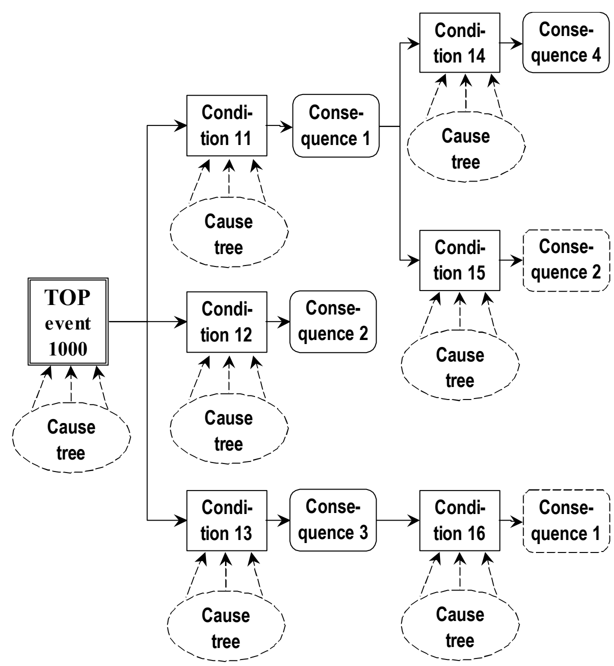

Figure 1. Cause-consequence Structure

The structure of the paper is as follows: In section 2, the developed cause tree model is introduced, and in section 3 the developed method for modeling and analyzing a consequence tree is presented.

Simulation and Calculation of Reliability Performance and Maintenance Costs

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Seppo Virtanen, PhD, Tampere University of Technology

Key Words: reliability performance, maintenance costs, failure logic, simulation, semi-Markov processes

SUMMARY & CONCLUSION

This paper provides a short description of an extensive method for simulation and calculation of reliability, availability and maintenance costs of a product (system, function, equipment, mechanism, part, etc). The key elements are the following.

(a) A quite general stochastic logic generalizes the usual FTA concept. A failure of the TOP-entity (product in use) is the logical-stochastic short-time consequence of changes in the state of the basic entities.

(b) A simple model for deterministic relations between the TOP and the basic entities is introduced. This leads to the existence of two additional intermediate "wait states".

(c) The long-time statistical behavior of each basic entity is modeled with the repair time distribution and a generalized non-homogenous Poisson failure process. (About 20 models to fit different kind of data are available.)

(d) A stochastic simulation along the time axis produces a logbook of all events in chronological order. The effect of age and corrective maintenance (CM) on reliability is also taken into account.

(e) Many examples exist for how the detailed data in the logbook can be used for calculation of figures, graphs, tables, etc.

(f) Our method contains a model for the effect of changes of scheduled preventative maintenance (PM) procedures on failure tendency, but this paper considers PM only concerning cost and staff assessment.

Our method helps the designer to determine at an early stage of the design what level of reliability performance and corrective and preventive maintenance costs can be achieved under the selected design solution, maintenance and operation strategies, and maintenance resources. The versatility of the method promotes also the introduction of expertise from areas that strongly affect the success of the design process, namely the manufacturing, testing, operation, and maintenance.

RAMoptim software has been developed to implement this method. The software is integrated with other software, as indicated in Fig. 1. The failure logic can be designed using ELMAS. The reliability and availability obtained from RAMoptim should be compared with the requirements, set e.g. by using our allocation method RAMalloc. If these or other defined requirements have not been achieved, the designer must return to the drawing table to consider other solutions. Further, our method enables also repair time delays due to external causes. E.g., using StockOptim one can assess the delay caused by the lack of spare parts.

Finally, the development of the method and the related software continues. The effect of PM (e.g. condition monitoring and diagnostic resources) on failure tendency is a particularly important and challenging subject for further research.

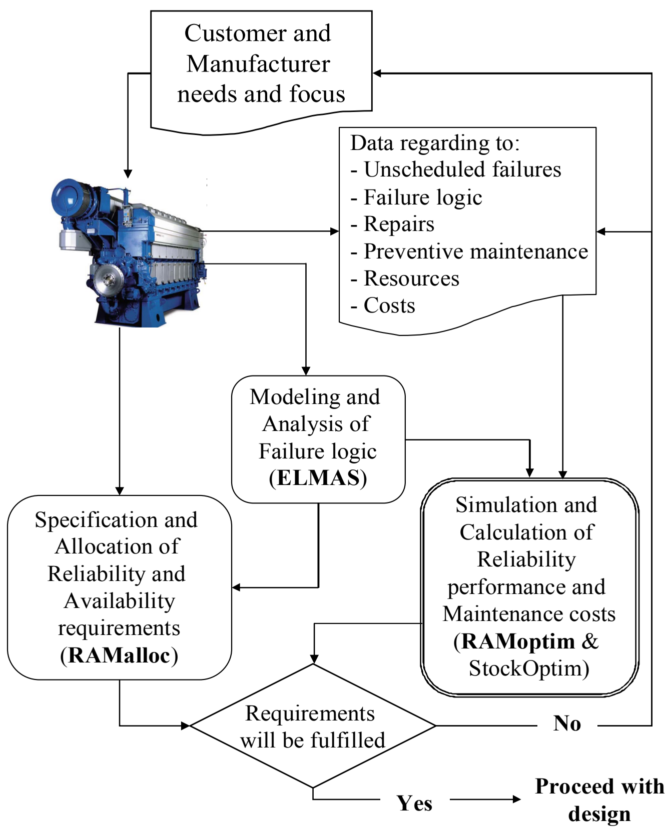

Figure 1 - Probabilistic approach to defining Reliability and Availability requirements for the product and to assess that a proposed design solution fulfils the numeric requirements set for its Reliability performance and Maintenance costs

1 INTRODUCTION

The method presented in this paper is one of the main

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Reliability analysis and initial requirements for FC systems and stacks

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Abstract

In the year 2000 Wärtsilä Corporation started an R&D program to develop SOFC systems for CHP applications. The program aims to bring to the market highly efficient, clean and cost competitive fuel cell systems with rated power output in the range of 50–250 kW for distributed generation and marine applications.

In the program Wärtsilä focuses on system integration and development. System reliability and availability are key issues determining the competitiveness of the SOFC technology. In Wärtsilä, methods have been implemented for analysing the system in respect to reliability and safety as well as for defining reliability requirements for system components. A fault tree representation is used as the basis for reliability prediction analysis. A dynamic simulation technique has been developed to allow for non-static properties in the fault tree logic modelling.

Special emphasis has been placed on reliability analysis of the fuel cell stacks in the system. A method for assessing reliability and critical failure predictability requirements for fuel cell stacks in a system consisting of several stacks has been developed. The method is based on a qualitative model of the stack configuration where each stack can be in a functional, partially failed or critically failed state, each of the states having different failure rates and effects on the system behaviour. The main purpose of the method is to understand the effect of stack reliability, critical failure predictability and operating strategy on the system reliability and availability. An example configuration, consisting of 5×5 stacks (series of 5 sets of 5 parallel stacks) is analysed in respect to stack reliability requirements as a function of predictability of critical failures and Weibull shape factor of failure rate distributions.

Keywords: Reliability analysis; Fault tree analysis; SOFC system; Stack reliability

1. Introduction

Increasing customer awareness of reliability and its influence on lifetime costs and safety, together with increasing complexity of industrial plants and equipment has resulted in an escalating need for systematic methods of accounting for reliability in design and manufacturing. Traditionally, the use of such methods has essentially been limited to aviation, space and nuclear applications. More recently these methods have been adapted in several other industry branches. Reliability is expected to become a key competitive factor in applications where safety and availability are important [1].

Since the year 2000, Wärtsilä has developed planar SOFC systems for distributed power generation and marine applications. Wärtsilä focuses on system design and integration, balance of plant (BoP) development, and the interface between the SOFC power unit and the application. The SOFC stack being an integrated part of the FC system, optimal interaction between the stack and the BoP is an essential part of system optimization, which calls for close cooperation between the stack manufacturers and system integrators. Wärtsilä Corporation and Haldor Topsøe A/S, whose fuel cell program is managed by Topsøe Fuel Cell A/S, are running a joint development program within the planar SOFC technology. The program aims to bring highly efficient, clean, reliable and cost-competitive fuel cell products to the market for stationary power generation and marine applications. Within the program, a conceptual study of a 250 kW planar SOFC system for combined heat and power (CHP) applications was presented in 2003 [2], along with strategies to counter-

Abbreviations: ac, alternating current; BoP, balance of plant; CHP, combined heat and power; dc, direct current; FMEA, failure mode and effect analysis; FTA, fault tree analysis; HAZOP, Hazard and Operability Analysis; MTBF, mean time between failure; MTTF, mean time to fail; R&D, research and development; SOFC, solid oxide fuel cell; VBA, Visual Basic for Applications; WFC, Wärtsilä fuel cell

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Spare part stock asset management by stochastic simulation

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ABSTRACT: The design of a spare part inventory is a multi-phase task including contradictory economical and technical requirements. New methods and software for this area of problems have been developed in Tampere University of Technology in collaboration with Finnish industry. The inventory model to be presented is an effort toward a concrete and broad-based methodology. A practical example as well as comparisons with the current literature is also given.

The model can be characterized as a versatile simulation-calculation scheme that connects spare part consumption, storage costs, and shortage probability and costs with existing maintenance strategies e.g. corrective, preventive and predictive maintenance. Stochastic simulation in the sub-models imitates the reality in time order, and the multitude of variables and concepts makes the model flexible for interpretations and new features. The inventory policy is ‘continuous review’, and the actors are: one stock, one critical part (or group of parts), one or more part suppliers, and one or more part consumers (customers).

The software developing around the model increases continuously the applicability. At present, automatic optimization of any selected cost combination can be performed, and the set of partaking variables will gradually be extended. Constraint checking during optimization has also been implemented to some extent.

KEYWORDS: Inventory design and control, stock asset management, spare parts, stochastic simulation, genetic algorithm.

1. INTRODUCTION

Spare part inventory control and management has been intensively researched for many decades. Extensive literature and research reports have been published. Kennedy et al. (2002) have provided a comprehensive literature overview. A large part of the reported methods seem to be case specific and restrictive in scope. The model in question consists often of a few analytic-numeric formulas and a small number of variables.

Simulation-based and more versatile models exist, but a more comprising methodology would be desirable. Our model contributes to a generic approach. The kernel, a time-ordered simulation-calculation scheme (Fig. 1), is readily open for extensions and new details, and not so exposed to distorting and restricting assumptions as analytic-numeric methods. The inventory policy is based on continuous review. The actors are one stock, one critical part (or group of parts), one or more part suppliers, and one or more part consumers (customers).

We start with a superficial description following Figure 1 below. The first module, *PartRel*, offers several methods for the construction of life distributions for different stress levels.

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Mathematics and Computers in Simulation 77 (2008) 72–80

MATHEMATICS AND COMPUTERS IN SIMULATION

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On construction and simulation of count data models

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Available online 2 February 2007

Abstract

The mean–variance range and the shape flexibility are important measures of the applicability of a count data model. This paper develops a method for constructing nonnegative integer-valued random variables with any interval domain, any theoretically possible mean–variance pair, and different shapes. The basic tool is a simple mean-preserving discretization procedure for random variables. Two corresponding variate generation algorithms are derived, and shown to be comparable to the alias method. As an application, our method enables production of count data models with full under- and over-dispersion flexibility and desired shape.

MSC: 65C10; 65C20; 68U20

Keywords: Count data model; Under/over-dispersion; Discretization; Variate generation; Alias method

1. Introduction

Many count data models suffer from dispersion inflexibility. Although a model is theoretically appropriate for an application, the data variance can be too big (over-dispersion) or too small (under-dispersion) for the scope of the model, due to additional effects as censoring, clustering, correlations, diagnostic maintenance, etc. A variety of improvements/generalizations exists. We mention a few examples:

- The negative binomial distribution where the Poisson parameter itself is a Gamma distributed random variable [7].
- The beta-binomial distribution that results from allowing the event probability in the binomial distribution to have a Beta distribution [7].
- The meritorious generalized Poisson distribution of Consul and Jain [2].
- The 'generalized Poisson law' arising from a renewal process with Gamma distributed intervals, and probably first presented by Morlat [8].

The first three models do not possess 'full dispersion flexibility' (definition in Section 2). The last model does, but the connection between the parameters and the mean–variance pair is not desirably simple, so approximations are often used, e.g. [4].

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DETERMINING RELIABILITY PERFORMANCE AND MAINTENANCE COSTS OF SELECTED DESIGN SOLUTION AND MAINTENANCE STRATEGY

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This paper discusses the application of a developed method for determining the reliability performance and maintenance costs of selected design solution and maintenance strategy. Along with the conceptual presentation we follow numerical results of a power generation unit (PGU) which is our case example. With the help of the method, the engineer can determine the early stage of the development project to which level of reliability performance and maintenance costs can be achieved by using the selected design solution and maintenance strategy. If the defined requirements have not been achieved, the engineer must go back to the drawing table to consider other solutions and/or maintenance strategy for achieving the requirements. The method is one of the main results from the research project, which has been carried out in collaboration with eleven top Finnish industrial companies. The applicability of the method has been tested in the companies participating in the research project. Ramentor (www.ramentor.com) is responsible for commercializing, marketing and supplying technical support of the ELMAS software which has been developed to implement the method.

Key Words: Design Solution, Reliability Performance, Maintenance Strategy and Costs, Simulation, Calculation

1 INTRODUCTION

The outline of the paper is as follows. In section 2 we introduce our case example (PGU) and a developed method to model its failure logic. Three operation strategies concerning deterministic relationships between the TOP entity (PGU failure) and the basic entities, and a rescue mechanism for gates are introduced.

In section 3 we discuss the design for long-time statistical behaviour of the basic entities, i.e., repair time distributions and the point process for failures. Then, the parameters for the effect of age and corrective maintenance (CM) on the occurrence of failures are introduced. Thereafter the simulation process, consisting of simultaneous and interacting "semi-Markov-like" processes (one for each entity), can be started.

The simulation produces a detailed time-ordered logbook of all events, the raw material for subsequent calculation. Section 4 describes reliability and availability calculations for the PGU and its basic entities, and their relations. Many examples are given of how the detailed data in the logbook can be used for calculation of figures, graphs, and tables. After additional inputs and the definition concerning failures and preventive maintenance, section 5 discusses results on costs and resource calculation for both corrective and preventive maintenance. Finally the assessment of the variation of PGU's part's failure probability impact on its maintenance costs and reliability performance is introduced.

2 Failure and operation structures

2.1 Definition of PGU's Failure Logic

The PGU which is our case example consists of two identical generators (GE1 and GE2) and a back-up generator (BUGE). GE1 and GE2 have to run simultaneously in order PGU to produce required output. In case GE1 or GE2 fails or either of them is taken to the maintenance service, BUGE is called for operation until GE1 or GE2 is repaired or the service is completed. BUGE can fail either in the star-up or running phases. GE1 or GE2 can be repaired or serviced concurrently while the other is still running. In case BUGE fails, the one running is not shut down.

A SIMULATION MODEL FOR OPTIMIZATION OF MAINTENANCE STRATEGY IN ASSET MANAGEMENT

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The optimization of the maintenance strategy of a company is a multi-phase task including contradictory economical and technical requirements. A new simulation model for this area of problems has been developed in Tampere University of Technology in collaboration with Finnish industry. The simulation model can be used for determining the reliability requirements of the system under study (manufacturer's viewpoint), for determining the maintenance strategy of the system (owner's viewpoint), and for balancing warranty and the risk of failure (manufacturer's and service provider's viewpoint).

The primary concepts of the model are scheduled preventive maintenance (PM), unexpected preventive maintenance (UPM), corrective maintenance (CM) (when a breakdown has occurred), and system's usage and cost profiles during the calendar year. The model connects these concepts by using a multitude of variables, which make the model flexible for interpretations. Stochastic simulation imitates the reality through the life cycle of the system.

A critical rolling bearing of a ship propulsion system is used for demonstration. The stochastic failure propagation mechanism after failure detection gives room for a dynamic docking scheduling scheme for cost minimization. The maintenance model is based on replacement of the bearing at regular PM docking and possibly extra replacements at UPM dockings. The failure model is divided into two parts; service life i.e. the lifetime before the detection of a failure and remaining life i.e. the time before the final breakdown of the bearing. If the service life of the bearing ends before the next scheduled PM, and if the remaining life ends with a breakdown, then the ship is unavailable until the planned UPM.

In the model the cost of a replacement is fixed, and operator's shortage costs depend on the season when the maintenance takes place. By varying the maintenance strategies, the total cost minimization can be performed. In addition to the cost minimization and the maintenance strategy specification, the simulation model is a tool for evaluation of the risk of unexpected failure against the selected warranty terms.

Key Words: Life model, Maintenance, Optimization, Reliability, Simulation, Unavailability cost, Warranty

1 INTRODUCTION

Modeling and analysis of failures form a foundation for quantitative investigation of the reliability, availability and costs of a design entity, e.g. a system, equipment, mechanism, part, or part location. The method presented in this paper can be applied to many kinds of entities, whose failing can be modeled by two consecutive independent stochastic events: The first event is related to the end of normal operation when the failure is observed, and the second event to the growth of failure until the final breakdown. The entity to be studied in this paper is a thrust bearing of the propulsion system of a cruise ship.

PRODUCT RELIABILITY AND AVAILABILITY IN FIELD DATA

Nevavuori L

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KONE is one of the world's leading elevator and escalator companies. It provides customers with industry-leading elevators and escalators and innovative solutions for maintenance and modernization. KONE was established 1910 in Finland. Currently the company has approximately 32,500 employees.

Demands for the dependability have risen in the elevator industry during the recent years. The aim of the paper is to introduce a case study that was performed by KONE's reliability and maintenance departments in the beginning of year 2007. The case is about products' perceived dependability follow-up. Moreover, a target is to present how reliability data was collected as well as utilized in reliability centered maintenance planning. In this case the starting point for a dependability follow-up was the back reported field data from maintenance actions.

One of the main objectives of the case was to construct a new method for modeling the lifetime of a component based on the failure data. In the first phase of the case study, a reliability function was modeled for the studied component by utilizing the Kaplan-Meier estimation method. Both complete and censored lifetime observations were exploited. In the second phase, the cost factors of corrective and preventive maintenance were evaluated. Then, by utilizing the modeled reliability function and simulation software the most suitable maintenance strategy for the component was optimized.

The paper summarizes the experiences collected from the methods of the case study. As the second conclusion, requirements and advantages for a systematic dependability follow-up process are outlined. It is generally clarified which are the main challenges to utilize field data, and how back reporting procedures and follow-up tools can be developed in the industry.

Key Words: Field data, Reliability engineering, RCM

1 INTRODUCTION

Customers expect reliable products. The reputation of a company can be lost in a short time, if a product fails dramatically. KONE has researched reliability many years as a part of product development and adopted several methods to increase the degree of durability of products. However, the designed reliability of elevators is not the only factor relating to finally perceived dependability. Also manufacturing, transportation, installation, and maintenance as well as operational environment have effects on dependability [1]. To understand previous effects a large number of different field data studies were performed for MonoSpace elevators, the one of KONE's global volume products. The first release of MonoSpace was introduced in 1996. It was the world's first affordable and efficient "machine-room-less" elevator concept. It is operated by a disc-shaped KONE EcoDisc™ hoisting machine which fits inside a standard elevator hoist way.

The performed field data analyses have identified that elevator cabin lighting failure is one of the most frequently reported call-out root cause in MonoSpace elevators. A term call-out is defined by: "Any request for an intervention coming from a customer or a remote monitoring system, which triggers a repair visit to equipment by a service technician". KONE aims to

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Investment in new product reliability

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ABSTRACT

Product reliability is of great importance to both manufacturers and customers. Building reliability into a new product is costly, but the consequences of inadequate product reliability can be costlier. This implies that manufacturers need to decide on the optimal investment in new product reliability by achieving a suitable trade-off between the two costs. This paper develops a framework and proposes an approach to help manufacturers decide on the investment in new product reliability.

1. Introduction

Modern industrial societies are characterised by new products appearing on the market at an ever increasing pace. Some of the reasons for this are (i) rapid advances in technology, (ii) increasing consumer expectations and, (iii) global competition. As a result, the complexity of products and the cost of product development are increasing and the product life cycle is getting shorter with each new generation. Consumers are getting more concerned with the performance of the product over its useful life, and increasing power of consumer groups has resulted in stronger legislation to protect consumer interests. All of these have implications for manufacturers of all kinds (consumer, commercial and industrial) of products.

A product is designated by its characteristics and attributes. The distinction between these two is best explained by the statement "product characteristics physically define the product and influence the formation of product attributes; product attributes define consumer perceptions and are more abstract than characteristics" from Tarasewich and Nair [1]. Consumers view products in terms of attributes.

The reliability of a product is a characteristic, which conveys the notion of dependence or absence of failure. Unreliability is the opposite. According to IEC 60050-191 [2], the reliability of a product (system) is the probability that the product (system) will perform its intended function for a specified time period when operating under normal (or stated) environmental conditions.

One way for manufacturers to assure consumers about product performance is through warranty. A warranty is a contractual obligation, which requires the manufacturer to rectify, replace or provide compensation, should the product not perform satisfactorily over the warranty period. It can be viewed as a product characteristic that serves two important roles for a manufacturer—(i) to signal product reliability (as better warranty terms indicate a more reliable product) and, (ii) to differentiate the product from competitors as warranty is bundled with the product and sold as a an element of product support.

Product reliability depends on the decisions made during the design and production of the product. Building-in product reliability is costly as it involves considerable expenditure during the design, development and production phases of the product life cycle. Not having adequate reliability is costlier as failures result not only in higher warranty costs but also reduced sales and revenue due to the negative impact of customer dissatisfaction resulting from product failures. As reported in Warranty Week [3] the warranty costs vary from 1% to 4% of sale price depending on the product and the manufacturer. Viewed as a fraction of profits, this figure jumps by an order of magnitude. In the long run it affects the reputation of the manufacturer, impacts on the bottom line of the balance sheet and the survival of the manufacturer. From the customer's point of view, unreliability reduces availability and increases maintenance costs over the useful life of the product. This implies that manufacturers need to decide on the investment in product reliability from an overall business viewpoint. This topic has received some limited

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Product variety and reliability

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A B S T R A C T

Murthy et al. [Murthy DNP, Rausand M, Virtanen S. Investment in new product reliability, Reliability Engineering & System Safety (accepted for publication)] proposed an approach to decide on product reliability in the context of new product development and identified two tasks for execution as part of the overall process. In this paper, we focus on the first task—determining the product reliability requirements.

1. Introduction

Building product reliability is costly but not having adequate reliability can be costlier. Murthy et al. [1] developed a framework (which integrates various technical and commercial elements) and proposed an approach (involving product life cycle perspective and use of mathematical models) to decide on the optimal investment in new product reliability. This involves decision making during the execution of the following two tasks.

- Task 1: Defining the reliability requirements at the product level.
- Task 2: Deriving the reliability specifications at the component level.

Product reliability depends on the usage rate, operating environment and many other variables. When these vary significantly, a strategy for the manufacturer is to build a variety of products (with differing reliabilities) instead of a single product.

In this paper, we focus on Task 1 and look at product variety, and the reliability for each type, using the framework and approach discussed in [1]. The outline of the paper is as follows. We start with a brief discussion of product variety in Section 2. Section 3 looks at product reliability and the modelling of it. Deciding on the product reliability involves solving an optimisation problem with reliability and non-reliability decision variables and is discussed in Section 4. We illustrate by looking at two cases in Sections 5 and 6. In Section 7 we discuss the software developed for executing Task 1 as part of the BRED project at the Tampere University of Technology. Section 8 deals with some concluding comments.

2. Product variety

When needs vary significantly across the customer population, achieving the business objectives with a single product design might not be possible. In this case, the optimal strategy is to offer a variety of products using a common product platform. Product variety is achieved by variations in the attributes and/or characteristics. For example, in the case of washing machine, it could be the load (kilogram per wash) leading to small, medium and large machines and in the case of photocopier it could be the throughput (number of pages printed per minute) leading to slow and high-speed printers. There is a vast literature on product variety and these deal with many different issues, see for example, [2–9]. In this paper we focus on variety where products differ in their reliability characteristics.

3. Product reliability

Let $F(t;\theta)$ denote the distribution function for the time to first failure. The reliability of the product is given by $R(t;\theta) = 1-F(t;\theta)$. Let $f(t;\theta)$ and $h(t;\theta)$ denote the density and hazard functions associated with $F(t;\theta)$.

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Component reliability specification

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A B S T R A C T

Building reliability into a product is costly and needs to be traded against the consequences of product unreliability. This article is the third in a series of three articles, where the first deals with optimal investment in reliability, which involves executing two tasks—(i) deciding on the reliability requirements and (ii) deciding on component specifications (SP) to achieve the desired reliability. The second article deals with the first task and in this third article, we focus on the second task.

1. Introduction

Product reliability is of importance to both manufacturers and consumers since inadequate reliability results in higher costs to both parties. Murthy et al. [1] examine this issue and look at the optimal investment in reliability. It involves two tasks—(i) deciding on the reliability requirements and (ii) deciding on component specifications (SP) to achieve the desired reliability. Murthy et al. [2] deal with the first task and in this article we discuss the second task.

The design process defines how the product is to be built. This involves decomposing the product, starting at the product level and proceeding down to the component level, with several intermediate levels. At each level there are several elements. The specification of an element at any level is derived from the performance of the elements at the level above it. As a result, there is a sequence of performances and specifications that leads to specifications at the component level.

In this article we focus on the sequence of performances and specification throughout the design process, and define the reliability specification at the component level that will ensure that the product reliability requirements are met. The outline of the article is as follows. We start with a brief general discussion of performance and specification and the links between the two in the context of new product development in Section 2. This is followed by a brief discussion of the design process in Section 3. Section 4 deals with the process of arriving at the reliability specifications at the component level. Two key elements of the process are discussed in the next two sections. In Section 5, we look at reliability allocation and the alternative options to ensure that the target values assigned for component reliability are achieved. Section 6 deals with optimal decision making in reliability specification at component level.

2. Performances and specifications

2.1. Definitions

There are several different notions of performance and specifications in the context of the new product development process and these are discussed in detail in [3]. We confine our attention to a subset of these that is relevant for deriving the reliability specification at component level:

- *Desired performance* (*DP*) is a statement about the performance desired from an object (product or component).
- *Specifications* describe how the desired performance can be achieved (using a synthesis process involving evaluation of potential solutions to select the best), with desired performance as input to the process.
- *Predicted performance* (*PP*) is an estimate of the performance of the object for a given set of specifications.

2.2. Relationship between performance and specifications

Performance and specifications are strongly interlinked, and play a central role in the new product development process (e.g., [4–6] discuss the critical importance of performance and

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A new concept for count distributions

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ABSTRACT

A new concept, called silhouette, and the related parameterization are introduced and studied. Applications show how to extend maximally the mean–variance domain of a count distribution, and how to construct a single variable for any mean–variance and any requirements on distribution shape.

1. Introduction

We consider *count variables*, i.e. nonnegative integer-valued random variables, whose mean μ and deviation σ are finite. A *$\mu\sigma$-domain*, i.e. the set of all pairs (μ, σ) of a set of count variables, will be called *maximal* if it contains all pairs (μ, σ) satisfying

$$(\mu - [\mu])([\mu] + 1 - \mu) < \sigma^2 < \mu(N - \mu), \quad (1)$$

where N is the supremum of the variables (possibly $N = \infty$, and $[\mu]$ is the largest integer not exceeding μ. On the other hand, no $\mu\sigma$-domain exceeds the closure of (1).

In commonly used count distributions, the $\mu\sigma$-domain is very seldom maximal, and good general shape flexibility is practically non-existent. In count data modeling this can mean that the $\mu\sigma$-domain of the planned model does not contain the mean–deviation pair estimated from the data, or that no distribution shape offered by the model matches the data. The famous distribution of Consul and Jain (1973) is a typical example with seriously incomplete underdispersion ability, i.e. σ stays on a nonzero distance from the left side of (1). The so-called 'generalized Poisson law' again does have maximal $\mu\sigma$-domain, but the shape is always unimodal, and besides, the relations between the parameters and the $\mu\sigma$-pair are laborious (Morlat, 1952; Winkelmann, 1995). For theory and practice of count models, see e.g. Johnson et al. (1992), Ridout and Besbeas (2004), Castillo and Perez-Casany (2005), and Hagmark (2008).

This study develops a new general approach. We introduce a new concept, the 'silhouette', and a related one-parameter extension for non-binary bounded count variables. Basic theoretical results with examples are presented in Sections 2–5, applications follow in Sections 6–8, and a summary in Section 9.

2. Basic concepts and formulas

Let $F_0, F_1, F_2, \ldots$ be a non-decreasing sequence with $0 \le F_n \le 1$ and $\lim_{n\to\infty} F_n = 1$. In other words, F_n is the (cumulative) distribution of a count variable (Cv). The related sequence $Y_0 = 0$, $Y_{n+1} = Y_n + F_n$ will be called *integral distribution* (Id).

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APPENDIX 2

MASTER THESIS

Total number of pages in Appendix 11

BRED-projektin yhteydessä valmistuneet opinnäytetyöt

Tekijä	Työn aihe	Teettäjä - valmistusvuosi
Kim Åström	Reliability analysis of solid oxide fuel cell system	Wärtsilä – 2006
Juha Pirkkalainen	Potkurilaitteen luotettavuusanalyysi	ABB Marine - 2006
Kalle Lehtinen	Laivan perärampin käyttövarmuusanalyysi	MacGregor - 2007
Lauri Nevavuori	Product dependability follow-up based on field data	Kone - 2007
Ville Leppänen	Customer value-driven design for reliability in product development	Kone - 2008

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Department of Engineering
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Kim Åström

Reliability Analysis of Solid Oxide Fuel Cell System

Master's thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology

Espoo, 13.02.2006

Supervisor: Prof. Peter Lund

Instructor: Prof. Seppo Virtanen

HELSINKI UNIVERSITY OF TECHNOLOGY
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ABSTRACT OF MASTER'S THESIS

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Supervisor:	Prof. Peter Lund
Instructor:	Prof. Seppo Virtanen

Abstract:

Fuel cells are energy conversion devices with potential for high efficiencies with low emissions. Solid oxide fuel cells (SOFC) are seen as one of the most promising technologies for distributed combined heat and power production (CHP).

Wärtsilä is developing a 20kW SOFC prototype unit aimed for demonstration in various application environments by 2007-2008. Accounting for reliability related issues has been adapted as an important aspect of the system design. Increasing customer awareness of these issues has highlighted the need for systematic methods for accounting for reliability in design and manufacturing. In the SOFC system, the importance of reliability is further pronounced by safety and durability considerations.

In this thesis, different methodologies deployed in reliability engineering are discussed, with special emphasis on their applicability for analysing the SOFC system. A combination of different methodologies is chosen and implemented. A fault tree approach is chosen for describing the logical interrelations between failures and consequences. An extensive failure mode and effects analysis (FMEA) formed the foundation for constructing the fault tree. A simulation tool has been implemented for dynamic modelling of the system in respect to failures and hazards. A customized model for analysing the fuel cell stacks is implemented.

This thesis provides the theoretical foundation based on which the developed methods have been successfully applied for analysis of the SOFC system.

Keywords: Reliability analysis, simulation, solid oxide fuel cell

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TAMPEREEN TEKNILLINEN YLIOPISTO

Konetekniikan osasto

JUHA PIRKKALAINEN

POTKURILAITTEEN LUOTETTAVUUSANALYYSI

Diplomityö

Tarkastaja prof. Seppo Virtanen

Määrätty osastoneuvoston kokouksessa

16.8.2006

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
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Tarkastaja: prof. Seppo Virtanen
Rahoittaja: ABB Marine Oy
Syyskuu 2006

Hakusanat: luotettavuus, toimintavarmuus, potkurilaite

Tässä työssä on toteutettu sähköisellä perämoottoriperiaatteella toimivan laivan potkurilaitteen Azipod Large-propulsiojärjestelmän luotettavuusanalyysi. Työn päätavoitteena on ollut identifioida kohteesta kriittisimmät epäluotettavuuden riskitekijät, jotka voivat johtaa laivan kuivatelakoimiseen viiden vuoden tarkasteluvälin aikana. Samalla on pyritty luomaan uusi toimintamalli erilaisten epäluotettavuuden riskitekijöiden määrittämiseen ja hallintaan ABB Marine:n tuotekehityksen sekä suunnittelun tarpeisiin.

Työ on jaettu kvalitatiivisiin ja kvantitatiivisiin tarkasteluihin. Kvalitatiivisissa vaiheissa on laadittu kohteesta vikapuuanalyysit ELMAS-ohjelman avulla. Vikapuuanalyysien avulla on tunnistettu kohteesta epäluotettavin osajärjestelmä ja siinä olevat kuivatelakoimiseen johtavat kriittisimmät epäluotettavuuden riskitekijät. Kvantitatiivisessa osuudessa on tutkittu epäluotettavimman osajärjestelmän ja sen kriittisten epäluotettavuustekijöiden luotettavuusvaatimusten hallintaa RAMalloc-ohjelman avulla.

Ensisijaisesti työn tulokset osoittivat inhimillisten tekijöiden merkityksen kuivatelakointiriskin suuruuteen suhteessa tekniikkaan. Inhimillisistä riskitekijöistä merkittävimpiä olivat erilaiset kokoonpanon ja valmistuksen aikana tapahtuvat inhimilliset virheet, joiden yhteydessä kriittisiin kohteisiin jää erilaisia epäpuhtauksia. Käyttö- ja huoltovirheet osoittautuivat myös kriittisiksi. Tekniikan osalta merkittävimmät riskitekijät ovat irtoosien aiheuttama oikosulkuvaara päämoottorilla ja magnetointikoneella sekä painelaakerin voitelulinjan toimintavarmuus laakereiden eliniän takaamiseksi.

Työssä toteutetun toimintamallin avulla potkurilaitteen järjestelmäsuunnitteluun kuuluvien luotettavuusvaatimusten määrittäminen ja hallinta on mahdollista jatkossa toteuttaa nykyistä perusteellisemmin.

TAMPEREEN TEKNILLINEN YLIOPISTO
Konetekniikan koulutusohjelma

KALLE LEHTINEN
LAIVAN PERÄRAMPIN KAYTTÖVARMUUSANALYYSI
Diplomityö

Tarkastaja: Professori Seppo Virtanen
Tarkastaja ja aihe hyväksytty
Konetekniikan osastoneuvoston
kokouksessa 14.2.2007

TAMPEREEN TEKNILLINEN YLIOPISTO
Konetekniikan koulutusohjelma
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Diplomityö 57 sivua, 3 liitesivua
Huhtikuu 2007
Pääaine: Kunnossapitotekniikka
Tarkastaja: Professori Seppo Virtanen
Avainsanat: Käyttövarmuus, laiva, perärampi, luotettavuus, huollettavuus

Laitteen käyttövarmuus muodostuu laitteelle suunnitellusta luotettavuudesta ja huollettavuudesta, sekä kunnossapito-organisaation huoltovarmuudesta. Käyttövarmuusanalyysissä tutkitaan näitä kaikkia kolmea käyttövarmuuden osatekijää. Tämän tutkimuksen tavoitteena on selvittää olemassa olevan laivan perärampin käyttövarmuutta kuvaavia tunnuslukuja ja keinoja käyttövarmuuden parantamiseksi. Käyttövarmuusanalyysin taustalla on halu selvittää huoltopalvelun tuottamisesta aiheutuvia kustannuksia ja löytää keinoja niiden pienentämiseksi.

Laivan perärampin käyttövarmuusanalyysissä tutkittavalle kohteelle tehtiin vika- ja vaikutusanalyysi. Vika- ja vaikutusanalyysin tuloksia käytettiin lähtötietoina perärampin vikapuuanalyysin tekemisessä. Vikapuuta analysoitiin Tampereen teknillisessä yliopistossa kehitetyllä simulointimenetelmällä. Vikapuun simulointia varten kerättiin perärampin osilta vika ja korjaustietoa. Tämä tieto kerättiin pääasiassa asiantuntijahaastatteluin.

Vikapuun simulointituloksista tunnistettiin perärampin käyttövarmuuden ja kunnossapitokustannusten kannalta kriittisimpiä osia. Kunnossapitokustannuksia katsottiin syntyvän ennakkohuollosta, korjaavasta kunnossapidosta ja epäkäytettävyydestä tulevista sopimussakoista. Käyttövarmuusanalyysin tuloksena saatiin myös laitteen hydraulijärjestelmään perustuva modulaarinen malli vikapuidenkin laatimista varten. Modulaarista mallia voidaan käyttää tehokkaasti hyväksi muiden laitteiden vikapuuanalyyseissä. Perärampin vikapuumallista kehitettiin myös malli perärampin vianhakua varten. Tätä rampin ohjausjärjestelmään perustuvaa mallia voidaan käyttää jatkossa kun kehitetään perärampin vianhakumenettelyjä.

Perärampin käyttövarmuusanalyysin tulosten perusteella tehtiin päätelmiä perärampin käyttövarmuuden parantamiseen tähtäävistä tärkeimmistä toimenpiteistä. Tärkeimpinä toimenpiteinä nähtiin kunnossapitotiedon tarkempi kerääminen ja perärampin kunnossapitokustannusten kannalta kriittisimpien osien tarkempi vikaantumisen tutkiminen.

TAMPERE UNIVERSITY OF TECHNOLOGY
Degree Programme in
Mechanical Engineering

LAURI NEVAVUORI

PRODUCT DEPENDABILITY FOLLOW-UP BASED ON FIELD DATA

Master of Science Thesis

Examiner: Professor Seppo Virtanen
Examiner and topic approved in the
Mechanical Engineering Department
Council meeting on 18 April 2007

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
Master's Degree Programme in Mechanical Engineering
NEVAVUORI, LAURI: Product Dependability Follow-up based on Field Data
Master of Science Thesis, 84 pages, 2 Appendix pages
August 2007
Major: Maintenance Engineering
Examiner: Professor Seppo Virtanen
Keywords: Reliability engineering, dependability, field data, maintenance

Demands for the dependability have risen in the elevator industry during the recent years. This master's thesis examines products' perceived dependability follow-up and reliability centred maintenance planning. A starting point for a follow-up is the back reported field data from maintenance actions, which includes for example the reason and target of the work as well as the performed actions.

The aim of the thesis is to evaluate the current level of field data at Kone. Moreover, the possibility to utilise the data in maintenance planning is studied. One of the main objectives is to construct a method for modelling the lifetime of a component based on the failure data. The material for this study was collected from four countries, starting from year 2003. At the beginning, the extracted field data was analysed in general level. In addition, comparisons between countries were performed.

The major part of the thesis consists of a dependability case study that was done for a component. The field data analyses showed that the component in question has caused a large number of failures that were detected by customers. In the first phase of the case study, a reliability function was modelled for the component. The Kaplan-Meier estimation method was utilised for modelling. After that, the cost factors of corrective and preventive maintenance were evaluated for the component. Then, by utilising the modelled reliability function and ELMAS and RAMoptim computer programs the most suitable maintenance strategy for the component was optimised. The dependability simulations proved that preventive replacements of the component at the predefined intervals would improve dependability and decrease total maintenance costs. In the second phase of the case study a fault tree analysis was performed. The aim was to simulate the root causes of the component's failures. The fault tree model was tested and it was found to be functional in failure analysis. A similar fault tree model could also be used in product design phase. It provides a possibility to compare the effects of different parts on the dependability of the designed product.

In the conclusion of the thesis, there are outlined demands and advantages for more systematic dependability follow-up process. The main demands include the further development of back reporting procedures and follow-up tools. In this way maintenance processes can be developed. Moreover, possibilities to improve product dependability would be achieved by increasing the number of preventive component replacements and the further development of remote monitoring utilisation. The experiences collected from the methods of the thesis and the reliability software used in preventive maintenance optimisation were promising.

TAMPERE UNIVERSITY OF TECHNOLOGY
Degree Programme in Industrial Engineering and Management

VILLE LEPPÄNEN

CUSTOMER VALUE-DRIVEN DESIGN FOR RELIABILITY IN PRODUCT DEVELOPMENT

Master of Science Thesis

Examiners: Professor Olavi Uusitalo
& Professor Seppo Virtanen
Examiners and topic approved in the Faculty of Business and Technology Management Council meeting on 5 November 2008

ABSTRACT

TAMPERE UNIVERSITY OF TECHNOLOGY
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Examiners: Professor Olavi Uusitalo & Professor Seppo Virtanen
Keywords: Reliability, customer-perceived value, customer requirements, conjoint analysis, quality function deployment, product development

The elevator industry has become more aware of the importance of product reliability. In order to remain competitive in the market, companies need to direct their product development efforts into attributes providing the highest added value to customers. The purpose of this research was to assess the impact of elevator reliability on customer-perceived value, develop a methodology for translating customer perceptions into measurable reliability requirements of an elevator, and find effective means to implement customer focus in the management of reliability requirements in product development at KONE.

The theoretical impact of reliability on customer-perceived value was studied by means of literature research. The methodology developed to translate customer perceptions into reliability requirements utilizes an adaptation of Conjoint Analysis, a self-developed method of rank-ordering failure effects and open-ended interview questions to capture customer views and preferences on reliability. Customer perceptions are then reflected on actual reliability performance of elevators by studying KONE maintenance records, and related to technical aspects for requirement specification utilizing an adaptation of quality function deployment. The methodology also enables competitive analysis. Empirical evidence on the impact of elevator reliability on customer-perceived value was gathered by means of a case study using the developed methodology. The case study involved interviews of eight facility managers of high-rise buildings in the United Arab Emirates. Information on elevator reliability performance was researched by studying KONE maintenance records on high-rise elevators, and performing a competitive analysis on elevators of one competitive manufacturer under KONE maintenance. KONE product development processes and two projects on high-rise elevators were studied to find means for effective implementation of customer focus.

It was found that reliability has a high impact on customer-perceived value especially in the high-rise segment. Customers however tended not to consider the technical reliability of elevators, but rather regarded reliability as a maintenance issue. This KONE should exploit by improving maintenance visibility and performing proactive service repairs. Also there were strong differences in customer reactions to elevator faults depending on the effect of failure. By combining customer preferences to the studied reliability performance of elevators and benchmarking the reliability of a competitor, clear design priorities were identified, into which KONE should direct improvement efforts. Potentials to improve reliability in product development were found to be already restricted upon first consideration of reliability in the project. Therefore, reliability should be reviewed already in the genesis of product concepts.

APPENDIX 3

DEVELOPED MODELS

Total number of pages in Appendix 82

BRED-projektia varten tehdyt mallit (proto-ohjelmat)

Seuraavista pdf-kopioista ilmenevät mallien syöttö- ja tulostusrakenteet, mutta ei laskentakoodi. Kunkin mallin alussa on lyhyt yleiskuvaus.

Quick Model

Comments: Per-Erik.Hagmark@tut.fi

Tämä on yksinkertainen yhden tuotteen *metamalli*, eli ylemmän tason malli, jonka syötöt ovat alimallien tai muun laajankin esityön tulosteita. Keskeisiä käsitteitä ovat *luotettavuus*, *takuu*, *kustannus*, *myynti ja profiitti*. Malli on staattinen, eli suureet edustavat sovitun ajanjakson tai muun kokonaisuuden keskiarvoa. Poikkeuksena on takuumallinnus, jossa vikataipumuksen riippuvuus tuoteyksilön *iästä* täytyy ottaa ja otetaan huomioon.

Sovelluskohteeseen liittyvät suureet mallinnetaan analyyttis-numeerisilla *mallifunktioilla*, joiden vapaina variaabeleina toimivat seuraavat perusmuuttujat eli suunnittelumuuttujat

y	*tuotteen luotettavuus* (parametri jonka selitys alempana)
P	*myyntihinta /tuoteyksilö*
W	*takuuajan pituus.*

Pyrkimys on että mallifunktiot pätisivät sovelluskohteen *perustilan* (y_0, P_0, W_0) *lähiympäristössä* (Δ-tekniikka). Perustila voi tarkoittaa esimerkiksi vanhan hyvin tunnetun kohteen tilaa, joka toimii nyt uuden suunnitelman lähtökohtana (origona). Jos tällaista referenssiä ei ole (eli kyseessä täysin uusi kohde), niin perustilan arvioimiseksi ollaan asiantuntijoiden tietämyksen ja esityön varassa.

Lopullisena kohdefunktiona on profiitti. Malli näyttää - halutuissa rajoissa - minkälaisilla arvokombinaatioilla (y, P, W) saadaan suuri kokonaisprofiitti. Tämän ja muiden tuloksien valossa sekä tietenkin käytännön toteutuskelpoisuuden rajoissa voidaan hakea realistisia suunnitteluratkaisuja.

Syötöt keltaisella!

1. Basic quantities, dependences, and constants

Tarkasteltavaksi voidaan valita mikä tahansa kokonaisuus, esim. tietty markkinajakso tai tietty tuote-erää.

Seuraavan taulukon ensimmäisessä sarakkeessa arvioidaan perustila (y_0, P_0, W_0) (*nominal state*) sekä tätä vastaavat muut perussuureet: S_0 (myyntimäärä), CD_0 (suunnittelu- ja kehityskustannukset), CP_0 (valmistus- ja asennuskustannukset). Malli tarvitsee lähtötietona myös kolmen muun tilan sekä kolmen vakion (β, S_m, c_r) arviot seuraavasti:

Dependences	*Nominal State*	*State* 1	*State* 2	*State* 3
Reliability parameter*	$y_0 := 3$	$y_1 := 3.5$	$y_2 := y_0$	$y_3 := y_0$
Sale price /item**	$P_0 := 80$	$P_1 := 80$	$P_2 := 72$	$P_3 := P_0$
Warranty period	$W_0 := 1$	$W_1 := 1$	$W_2 := 1$	$W_3 := 2$
Sales (items sold)	$S_0 := 1900$	$S_1 := 1950$	$S_2 := 2200$	$S_3 := 2400$
Prod&InsCosts /item	$CP_0 := 20$	$CP_1 := 25$	$CP_2 := 19$	
Des&DevCosts (total)	$CD_0 := 60000$	$CD_1 := 65000$		

Constants Reliability shape* Maximum sales** Warranty cost /repair

$\beta := 1.6$ $S_m := 2900$ $c_r := 80$

* Keskimääräinen vikalukumäärä ikävälillä 0...t mallinnetaan mallifunktiolla $\Lambda(t,y) = (t/y)^\beta$, missä *muotovakio* β>0 oletetaan arvioidun tavalla tai toisella erikseen. Mitä suurempi *luotettatettavuusparametri* y>0, sitä vähemmän vikoja. (Täsmällisemmin: Ikävälillä 0...y syntyy keskimäärin yksi vika.)

** S_m = absolute upper bound of S.

2. Model functions and model parameters

Mallifunktioiden rakenne on valittu ilmiöiden ja riippuvuuksien yleisen luonteen perusteella (kirjallisuus, case-tutkimukset, ym.). Malliparametrien valinnassa ja lukumäärässä on huomioitu sekä datan luonne ja niukkuus että "ilmiöiden riittävä pelastus".

Sales (items sold) $$S(y,P,W) := S_m \cdot \left[1 - C^{\left(\frac{y}{y_0}\right)^{\xi_1} \cdot \left(\frac{P}{P_0}\right)^{\xi_2} \cdot \left(\frac{W}{W_0}\right)^{\xi_3}}\right]$$

Production Costs /item $$CP(y,S) := CP_0 \cdot \left(\frac{y}{y_0}\right)^{\delta_1} \cdot \left(\frac{S}{S_0}\right)^{\delta_2}$$

Develpoment Costs $$CD(y) := CD_0 \cdot \left(\frac{y}{y_0}\right)^{\varepsilon}$$

#failures /item 0...L $$\Lambda(t,y) := \left(\frac{t}{y}\right)^{\beta} \qquad \text{(cumulative ROCOF)}$$

Warranty Costs /item $$CW(y,W) := c_r \cdot \Lambda(W,y)$$

Total Profit /item $$J(y,P,W,S) := (P - CP(y,S) - CW(y,W)) \cdot S - CD(y)$$

i.e. $$Prof(y,P,W) := J(y,P,W,S(y,P,W))$$

Malliparametrien numeeriset arvot seuraavat yksikäsitteisesti edellisessä kappaleessa syötetystä datasta.

$S_m = 2900$	$\xi_1 = 0.305229$	$\delta_1 = 1.506525$	$\varepsilon = 0.51925$
$C = 0.344828$	$\xi_2 = -2.74229$	$\delta_2 = -0.349878$	$\beta = 1.6$
	$\xi_3 = 0.723357$		$c_r = 80$

Huomautus: Mallifunktioiden edustamia suureita voidaan nyt laskea *kaikilla* kolmikoilla (y, W, P), mutta malli on uskottavin perustilan ($y_0 = 3$ $P_0 = 80$ $W_0 = 1$) lähiympäristössä.

3. Profit calculation and optimization

Area to be studied. Suunnittelukolmikon (y, P, W) alue, jota halutaan tutkia:

$y_{min} := 2$	$P_{min} := 50$	$W_{min} := 0.2$
$y_{max} := 4$	$P_{max} := 120$	$W_{max} := 3$

F9

Solution near maximum profit. Simulointi näyttää missä päin profiitin maksimi suurin piirtein sijaitsee.

State			*Profit*	*Items sold*
$y' = 2.004$	$P' = 61.34$	$W' = 0.539$	$Prof(y', P', W') = 36034.68$	$S(y', P', W') = 2067$
$y_0 = 3$	$P_0 = 80$	$W_0 = 1$	$Prof(y_0, P_0, W_0) = 27791.05$	$S(y_0, P_0, W_0) = 1900$

Try New Design. Valitse uusi suunnittelukolmikko (y, P, W) kokeiltavaksi.

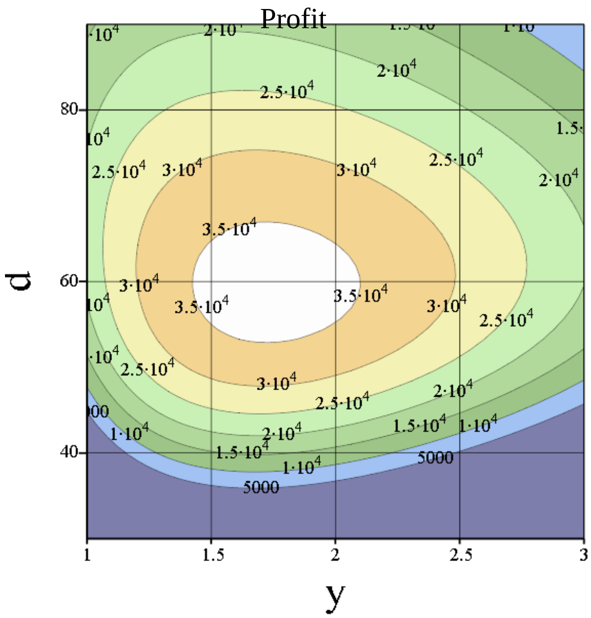
$y' := 2$	$P' := 60$	$W' := 0.5$	$Prof(y', P', W') = 35873.34$	$S(y', P', W') = 2073$

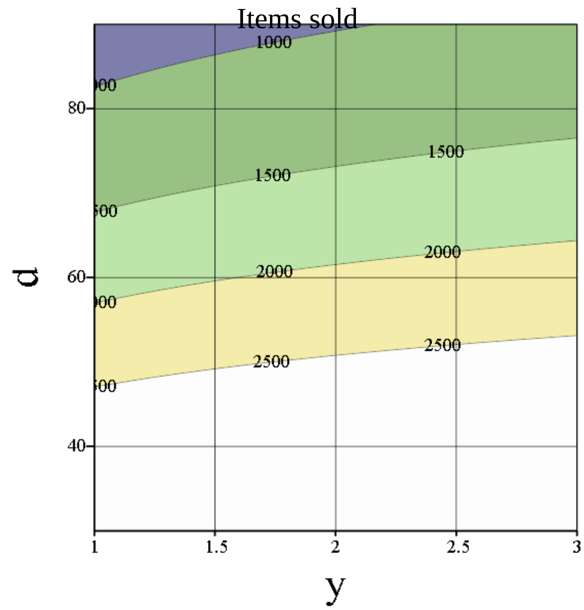
4. Profit and sale plots

Tutkitaan tarkemmin profitia ja myyntiä kiinnittämällä kerrallaan yksi muuttuja kolmikosta y', P', W'.

(y,P)-plots $(W' = 0.5 \quad \text{constant})$

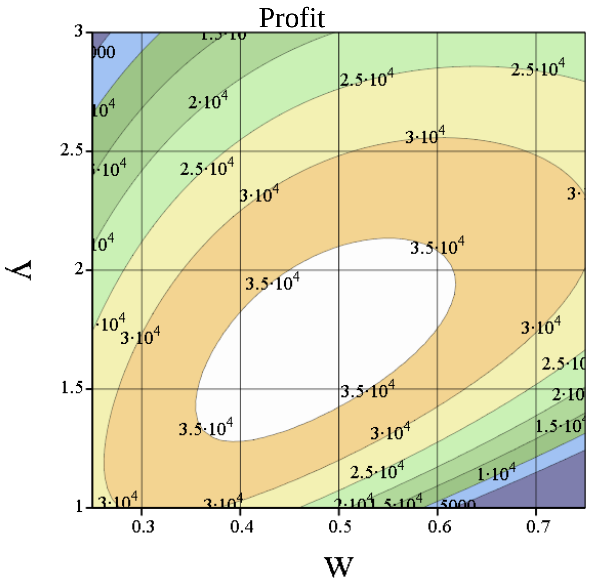
Double click and OK
to update the graph!





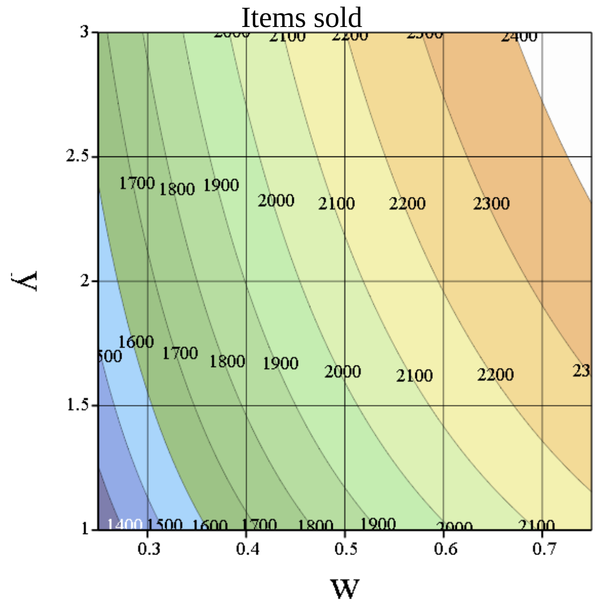
a

(W,y)-plots (P´ = 60 constant)



b

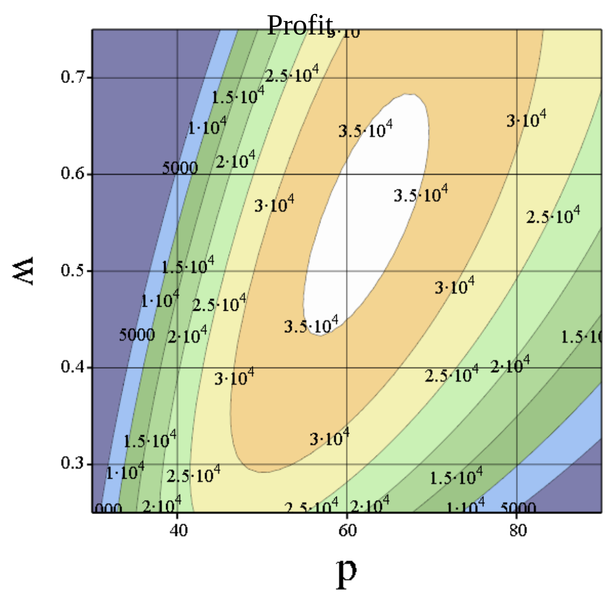
Double click and OK
to update the graph!



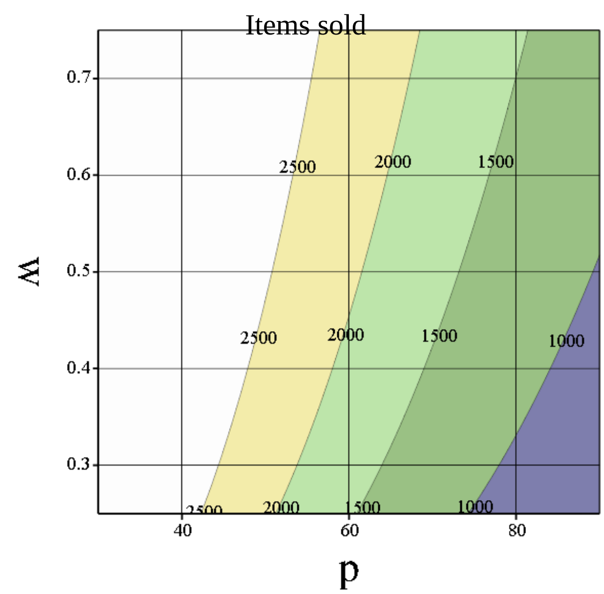
a

b

(P,W)-plots (y´ = 2 constant)



Double click and OK
to update the graph!



a

b

5. Final results

	New design (chosen in §3)	*Nominal state*
Design parameters	$\begin{pmatrix} y' \\ P' \\ W' \end{pmatrix} = \begin{pmatrix} 2 \\ 60 \\ 0.5 \end{pmatrix}$	$\begin{pmatrix} y_0 \\ P_0 \\ W_0 \end{pmatrix} = \begin{pmatrix} 3 \\ 80 \\ 1 \end{pmatrix}$
Total Profit	$Prof(y', P', W') = 35873.34$	$Prof_0 = 27791.05$
Total Sales	$S(y', P', W') = 2072.6$	$S_0 = 1900$
Reliability 0...W	$e^{-\Lambda(W', y')} = 0.896893$	$e^{-\Lambda(W_0, y_0)} = 0.841619$
# failures 0...W	$\Lambda(W', y') = 0.109$	$\Lambda(W_0, y_0) = 0.172$
Revenue	$P' \cdot S(y', P', W') = 124354.62$	$P_0 \cdot S_0 = 152000.00$
DevCosts	$CD(y') = 48608.91$	$CD_0 = 60000.00$
ProdCosts /item	$CP(y', S(y', P', W')) = 10.53$	$CP_0 = 20.00$
WarrCosts /item	$CW(y', W') = 8.71$	$CW(y_0, W_0) = 13.79$
Percentages	$\frac{CD(y')}{P' \cdot S(y', P', W')} = 39.1\%$	$\frac{CD_0}{P_0 \cdot S_0} = 39.5\%$
	$\frac{CP(y', S(y', P', W'))}{P'} = 17.6\%$	$\frac{CP_0}{P_0} = 25\%$
	$\frac{CW(y', W')}{P'} = 14.5\%$	$\frac{CW(y_0, W_0)}{P_0} = 17.2\%$
	$\frac{Prof(y', P', W')}{P' \cdot S(y', P', W')} = 28.8\%$	$\frac{Prof(y_0, P_0, W_0)}{P_0 \cdot S_0} = 18.3\%$

Profit Optimization

Comments: Per-Erik.Hagmark@tut.fi

Tämä metamalli muistuttaa mallia QuickModel siinä että se on yhden tuotteen staattinen *luotettavuus-, takuu-, kustannus-, myynti- ja profiittimalli*, mutta se sisältää paljon uusia piirteitä ja on dynaamisempi kuin QuickModel.

Suunnittelumuuttujat, joiden avulla mallinnetaan muut perussuureet, ovat nyt

F *# failures /item during* 0...L
U *unavailability time /failure*
P *sale price /item*
W *warranty period* 0...W ($0 \le W < L$),

missä L on tuoteyksilön oleellisen *eliniän pituus* (aika). Perusssuureita ja riippuvuuksia mallinnetaan edelleen tietyn perustilan (origon) lähiympäristössä, mutta nyt kompleksisemmilla mallifunktioilla. Epäkäytettävyysajan U vaikutus myyntiin ja myyntiä edeltäviin kustannuksiin voidaan mallintaa, ja PM-kustannukset ja vikojen aiheuttamat FR-kustannukset voivat riippua muuttujista F ja U, vastaavasti. Tärkeä lisäalue on *takuu- ja huoltosopimuskehys,* jossa voidaan mallintaa sopimuksien aikavälit ja valmistajan kustannusvastuut. Tätä varten täytyy mallintaa myös PM-kustannusten ja vikataipumuksen kumulatiiviset *profiilit.*

Mallin avulla voi tarkastella erityisesti myynnin, koko profiitin ja tuoteyksilön profiitin käyttäytymistä suunnittelumuuttujien funktioina, sekä löytää optimaalisia suunnitteluratkaisuja eri näkökulmista katsoen. Kun ratkaisu on kiinnitetty, saadaan tuloksina vielä valmistajan kumulatiiviset takuu- ja huolto-kustannukset eriteltynä PM:n ja FR:n mukaan, sekä kumulatiivinen profiitti /tuoteyksilö.

Syötöt keltaisella!

1. Basic quantities, dependences, and constants

Tarkasteltavaksi voidaan valita mikä tahansa kokonaisuus, esim. tietty markkinajakso tai tietty tuote-erää.

Life of item (time) $L := 15 \cdot 365$ $L = 5475$ Time unit e.g. days.
Cost unit, e.g. $euro \cdot 10^n$.

Constants

Maximum Sales (items sold)	$S_m := 36$	$(S < S_m)$
Minimum Production & Installation Cost /item	$PrC_m := 2$	$(PrC \ge PrC_m)$
Minimum Design & Development Cost /item	$DeC_m := 2$	$(DeC \ge DeC_m)$

Seuraavan taulukon ensimmäisessä sarakkeessa arvioidaan sovelluskohteen eli systeemin perustila, eli perusnelikkö F_0, U_0, P_0, W_0 ja sitä vastaavien perussuureiden S, PrC, arvot. Perustila voi tarkoittaa esimerkiksi vanhaa kohdetta, joka tunnetaan hyvin, ja joka nyt toimii muutossuunnitelmassa "origona".

Muissa sarakkeissa arvioidaan neljä muuta lähellä perustilaa olevaa ja mahdollista systeemin tilaa. Tässä ollaan asiantuntijoiden arvion ja/tai esitutkimuksen varassa.

Dependences	*Nominal State*	*State* 1	*State* 2	*State* 3	*State* 4
#failures /item 0...L	$F_0 := 1.5$	$F_1 := 1.2$	$F_2 := 1.5$	$F_3 := 1.5$	$F_4 := 1.5$
Unav. time /failure	$U_0 := 2$	$U_1 := 2$	$U_2 := 2.5$	$U_3 := 2$	$U_4 := 2$
Sale price /item	$P_0 := 80$	$P_1 := 80$	$P_2 := 80$	$P_3 := 72$	$P_4 := 80$
Warranty period	$W_0 := 2 \cdot 365$	$W_1 := 2 \cdot 365$	$W_2 := 2 \cdot 365$	$W_3 := 2 \cdot 365$	$W_4 := 3 \cdot 365$
Sales (items sold)	$S_0 := 20$	$S_1 := 21$	$S_2 := 19$	$S_3 := 25$	$S_4 := 24$
Prod&InsCost /item	$PrC_0 := 25$	$PrC_1 := 29$	$PrC_2 := 24$	$PrC_3 := 22$	
Des&DevCost /item	$DeC_0 := 30$	$DeC_1 := 40$	$DeC_2 := 29$	$DeC_3 := 25$	
PM-cost /item 0...L	$PmC_0 := 14$	$PmC_1 := 16$			
FR-cost /failure	$FrC_0 := 15$		$FrC_2 := 18$		

PM = Prev. Maintenance
FR = Failure Related

2. Basic model functions and parameters

Perussuureiden mallifunktiot muuttujineen (F, U, P, W) ja parametreineen ovat muotoa

Sales (items sold)
$$S(F,U,P,W) = S_m \cdot \left[1 - e^{-\left[\alpha \cdot \left(\frac{F}{F_0} - 1\right) + \beta \cdot \left(\frac{U}{U_0} - 1\right) + \gamma \cdot \left(\frac{P}{P_0} - 1\right) + \delta \cdot \left(\frac{W}{W_0} - 1\right) + \varepsilon\right]^2}\right]$$

PrC /item
$$PrC(F,U,S) := PrC_m + A \cdot \left(\frac{F}{F_0}\right)^{\delta_F} \cdot \left(\frac{U}{U_0}\right)^{\delta_U} \cdot \left(\frac{S}{S_0}\right)^{\delta_S}$$

DeC /item
$$DeC(F,U,S) := DeC_m + B \cdot \left(\frac{F}{F_0}\right)^{\varepsilon_F} \cdot \left(\frac{U}{U_0}\right)^{\varepsilon_U} \cdot \left(\frac{S}{S_0}\right)^{\varepsilon_S}$$

Total PM-cost /item 0...L
$$PmC(F) := PmC_0 \cdot \left(\frac{F}{F_0}\right)^{\eta}$$

Total FR-cost /failure
$$FrC(U) := FrC_0 \cdot \left(\frac{U}{U_0}\right)^{\theta}$$

Edellisessä kappaleessa syötetty data määrää mallifunktioihin sisältyvien malliparametrien numeeriset arvot yksikäsitteisesti.

$$\begin{pmatrix}\alpha & \beta & \gamma & \delta & \varepsilon\end{pmatrix} = \begin{pmatrix}-0.176 & -0.137 & -1.883 & 0.295 & 0.901\end{pmatrix}$$
$$\begin{pmatrix}\delta_F & \delta_U & \delta_S & A\end{pmatrix} = \begin{pmatrix}-0.856 & -0.343 & -0.626 & 23\end{pmatrix}$$
$$\begin{pmatrix}\varepsilon_F & \varepsilon_U & \varepsilon_S & B\end{pmatrix} = \begin{pmatrix}-1.561 & -0.366 & -0.882 & 28\end{pmatrix}$$

$\eta = -0.598 \quad \theta = 0.817$

Mallifunktioiden edustamia suureita voidaan nyt laskea *kaikille* tiloille (F, U, P, W), mutta malli on uskottavin perustilan ($F_0 = 1.5 \quad U_0 = 2 \quad P_0 = 80 \quad W_0 = 730$) lähiympäristössä.

3. Warranty contract and service contracts

Takuusopimuksien suunnittelussa on otettava huomioon miten viat ja PM-kustannukset jakaantuvat tuoteyksilön elinjaksolle 0...L. Arvioidaan seuraavat kumulaiiviset profiilit.

Normalized profile for #failures y **in** 0...x: $y = \Lambda(x) = y \qquad \Lambda(0) = 0,\ \Lambda(L) = 1$

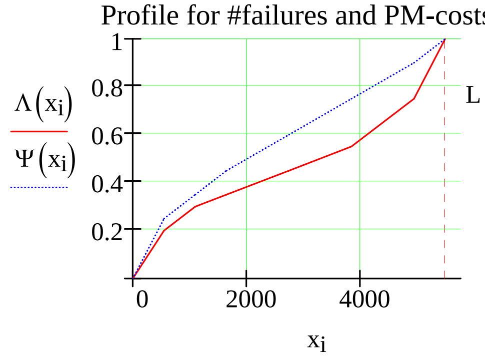
Normalized profile for PM-costs z **in** 0...x: $z = \Psi(x) = z \qquad \Psi(0) = 0,\ \Psi(L) = 1$

$$\begin{pmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 \\ y_1 & y_2 & y_3 & y_4 & y_5 & y_6 & y_7 \\ z_1 & z_2 & z_3 & z_4 & z_5 & z_6 & z_7 \end{pmatrix} := \begin{pmatrix} 0.1\cdot L & 0.2\cdot L & 0.3\cdot L & 0.5\cdot L & 0.7\cdot L & 0.9\cdot L & L \\ 0.2 & 0.3 & 0.35 & 0.45 & 0.55 & 0.75 & 1 \\ 0.25 & 0.35 & 0.45 & 0.6 & 0.75 & 0.9 & 1 \end{pmatrix}$$

Tulkinta: Ikään x_3 mennessä sattuu keskimäärin 100 y_3 % vioista.

Valmistajan myynnin jälkeinen kustannusvastuu (takuu ja huoltosopimus) määritellään osuuksina. Takuun hinta sisältyy tuotteen myyntihintaan P. Huoltosopimus sijoittuu takuuajan jälkeen ja sillä on omat ehtonsa.

Profile for #failures and PM-costs



Manufacturer's cost fractions	FR-fraction	PM-fraction
Warranty (0...W)	$Wf := 1$	$Wp := 0.5$
Service (W...W+V)	$Sf := 1$	$Sp := 0.8$

More data for Service Contract	Time period	Sale price	Prob(purchase)
	$V := 730$	$Psc := 20$	$Q := 0.5$

Model functions for manufacturer's costs

Warranty (0, W) — *FR-cost /item* $WaFr(F,U,W) := Wf\cdot FrC(U)\cdot F\cdot \Lambda(W)$

PM-cost /item $WaPm(F,W) := Wp\cdot PmC(F)\cdot \Psi(W)$

Service (W, W+V) — *FR-cost /item* $SeFr(F,U,W) := Q\cdot Sf\cdot FrC(U)\cdot F\cdot (\Lambda(W+V) - \Lambda(W))$

PM-cost /item $SePm(F,W) := Q\cdot Sp\cdot PmC(F)\cdot (\Psi(W+V) - \Psi(W))$

4. Profit calculation and optimization

Area to be studied. Suunnittelunelikön (F, U, P, W) alue, jota halutaan tutkia.

	Nominal	*Lower bound*	*Upper bound*
F = #failures /item during 0...L	$F_0 = 1.5$	$a_0 := 0.5$	$b_0 := 3$
U = unavailability time /failure	$U_0 = 2$	$a_1 := 1$	$b_1 := 4$
P = sale price /item	$P_0 = 80$	$a_2 := 60$	$b_2 := 100$
W = warranty period 0...W	$W_0 = 730$	$a_3 := 365$	$b_3 := 4 \cdot 365$

Huom. Sovelluskohteen todellisuus saattaa asettaa absoluuttiset rajoitukset FUPW:lle.

F9

Hints for good profit. Seuraavaksi mallin ehdotus hyvän profiitin tuottavaksi FUPW-nelikoksi. (Eo. F9!) =>

$$\begin{pmatrix} F_0 & F' \\ U_0 & U' \\ P_0 & P' \\ W_0 & W' \\ Pr_0 & Pr' \\ S_0 & S' \end{pmatrix} = \begin{pmatrix} 1.5 & 2.96 \\ 2 & 1.09 \\ 80 & 68.59 \\ 730 & 1453.5 \\ 717.9 & 1563.87 \\ 20 & 30.24 \end{pmatrix}$$

Choose New design

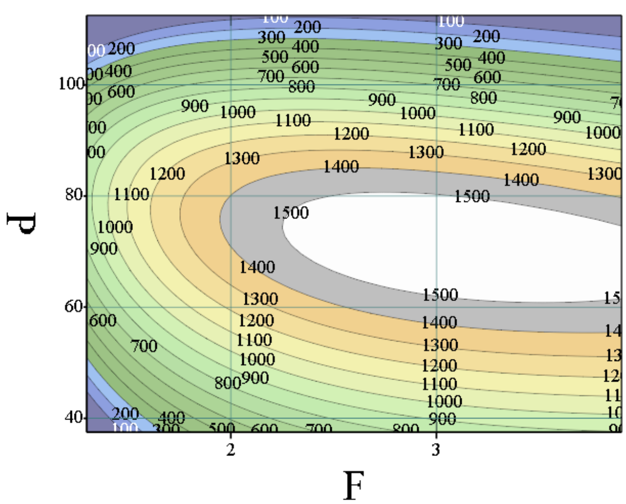
$$\begin{pmatrix} F' \\ U' \\ P' \\ W' \end{pmatrix} := \begin{pmatrix} 2.6 \\ 1 \\ 75 \\ 4 \cdot 365 \end{pmatrix}$$

=> Profits: $Profs(F', U', P', W') = 1556.16$ Sales: $S(F', U', P', W') = 28.5$

5. Profit and sale plots

Kiinnitetään ed. annetut muuttujat $U' = 1$ ja $W' = 1460$ ja tutkitaan profitia ja myyntiä FP-tasossa.

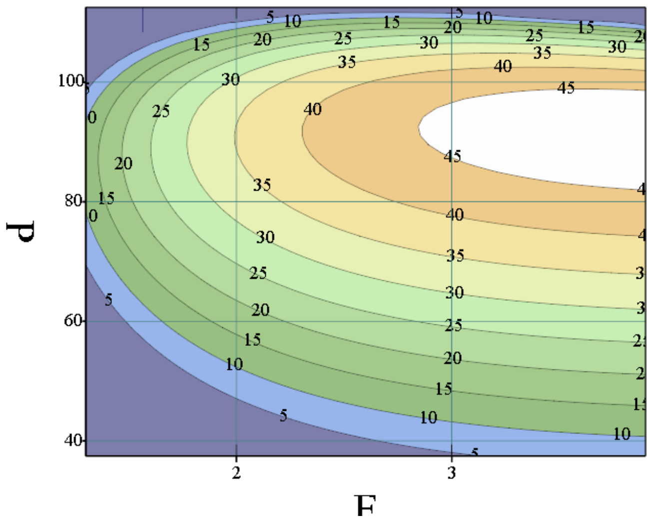
Total profit $Profs(F', U', P', W') = 1556.16$



Double click and OK to update the graph!

$$\begin{pmatrix} F' \\ P' \end{pmatrix} = \begin{pmatrix} 2.6 \\ 75 \end{pmatrix}$$

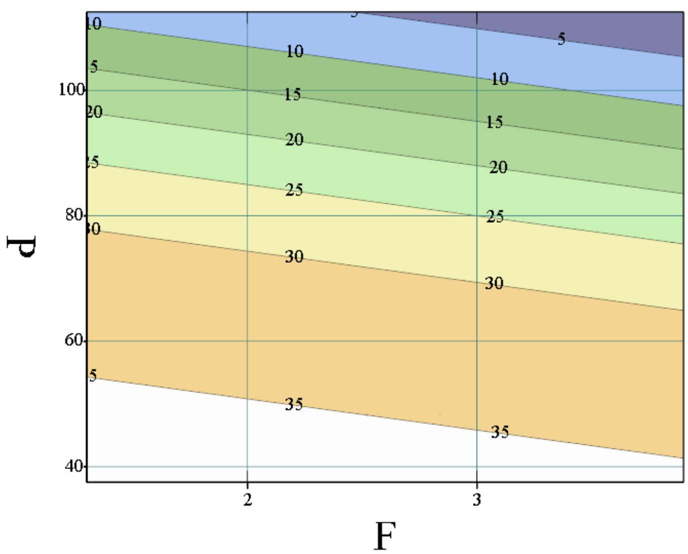
Profit /item (without service contract) ProfPro$(F´,U´,P´,W´) = 35.75$



$$\begin{pmatrix} F´ \\ P´ \end{pmatrix} = \begin{pmatrix} 2.6 \\ 75 \end{pmatrix}$$

$S(F´,U´,P´,W´) = 30.4$

 # items sold $S(F´,U´,P´,W´) = 28.5$



$$\begin{pmatrix} F´ \\ P´ \end{pmatrix} = \begin{pmatrix} 2.6 \\ 75 \end{pmatrix}$$

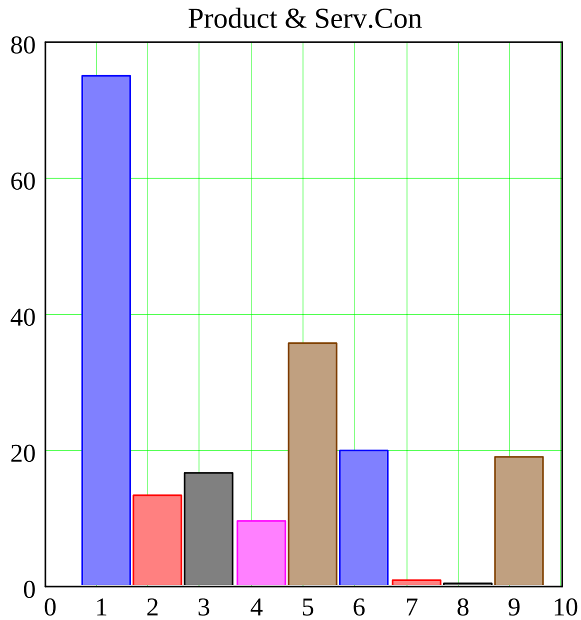
HUOM

Voi palata mihin tahansa aiempaan keltaiseen kohtaan ja muuttaa syöttöä.

6. Results

	New design	**Nominal design**
Failures /item	$F´ = 2.6$	$F_0 = 1.5$
Unav. time /failure	$U´ = 1$	$U_0 = 2$
Price (incl.warr)	$P´ = 75.00$	$P_0 = 80.00$

Warranty period	$W' = 1460$	$W_0 = 730$
Sales (items sold)	$S' = 28.5$	$S_0 = 20$
Revenue (total)	$Rev' = 2423.78$	$Rev_0 = 1800.00$
Product (+warr)	$RevPro' = 2138.63$	$RevPro_0 = 1600.00$
Serv.Con	$RevSc' = 285.15$	$RevSc_0 = 200.00$
Profit (total)	$Profs' = 1556.16$	$Profs_0 = 717.90$
Product (+warr)	$ProfPros' = 1019.35$	$ProfPros_0 = 355.33$
Serv.Con	$ProfScs' = 536.81$	$ProfScs_0 = 362.57$
Profit /item	$Prof' = 54.57$	$Prof_0 = 35.89$
Product (+warr)	$ProfPro' = 35.75$	$ProfPro_0 = 17.77$
Serv.Con	$ProfSc' = 18.83$	$ProfSc_0 = 18.13$
Costs /item (not SC)	$CostPro' = 39.25$	$CostPro_0 = 62.23$
Des&DevCost	$DeCo' = 13.18$	$DeCo_0 = 30.00$
Prod&InstCost	$PrCo' = 16.59$	$PrCo_0 = 25.00$
WarrantyCost	$WaCo' = 9.48$	$WaCo_0 = 7.23$
Serv.Con costs /item	$SeCo' = 1.17$	$SeCo_0 = 1.87$
FR-cost	$SeFr' = 0.74$	$SeFr_0 = 1.12$
PM-cost	$SePm' = 0.44$	$SePm_0 = 0.75$
$\frac{DesDevCosts}{SalePrice}$	$\frac{DeCo'}{P'} = 17.6\%$	$\frac{DeC_0}{P_0} = 37.5\%$
$\frac{ProdInstCosts}{SalePrice}$	$\frac{PrCo'}{P'} = 22.1\%$	$\frac{PrC_0}{P_0} = 31.3\%$
$\frac{WarrantyCosts}{SalePrice}$	$\frac{WaCo'}{P'} = 12.6\%$	$\frac{WaCo_0}{P_0} = 9\%$
$\frac{Profits}{Revenue}$	$\frac{Profs'}{Rev'} = 64.2\%$	$\frac{Profs_0}{Rev_0} = 39.9\%$



Product (item)

1. P´ = 75.00
2. DeCo´ = 13.18
3. PrCo´ = 16.59
4. WaCo´ = 9.48
5. ProfPro´ = 35.75

Serv.Con. /item

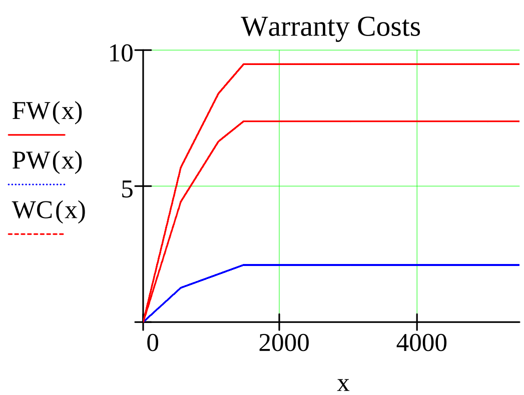
6. Psc = 20.00
7. SeFr´ = 0.74
8. SePm´ = 0.44
9. ProfSc´ = 18.83

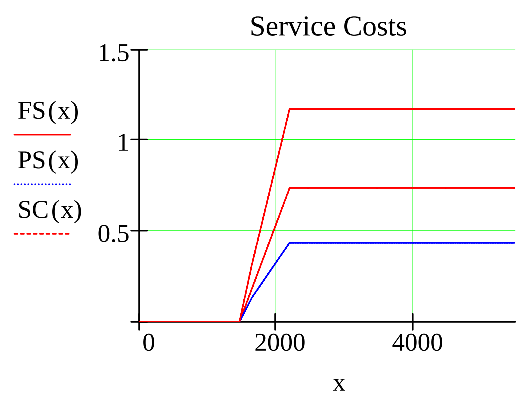
HUOM

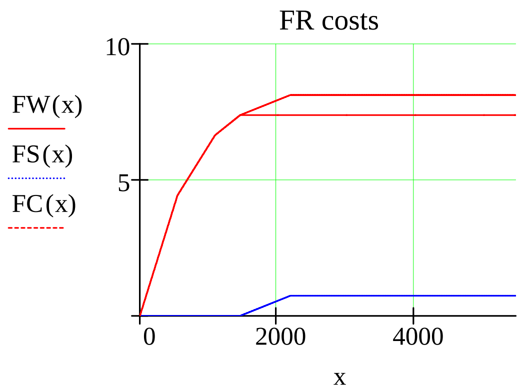
Voi palata mihin tahansa aiempaan keltaiseen kohtaan ja muuttaa syöttöä.

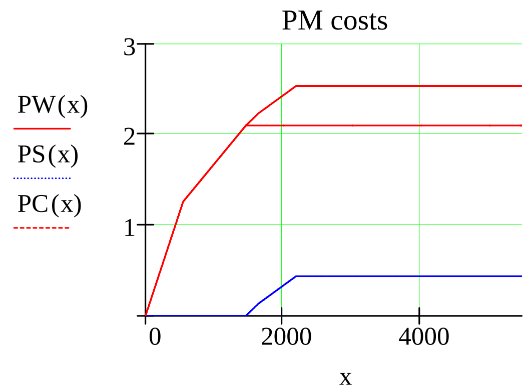
7. Manufacturer's cumulative costs and profits / item

Warranty FR-costs	FW	FR-costs	FC = FW + FS
Service FR-costs	FS	PM-costs	PC = PW + PS
Warranty PM-costs	PW	Warranty costs	WC = FW + PW
Service PM-costs	PS	Service costs	SC = FS + PS





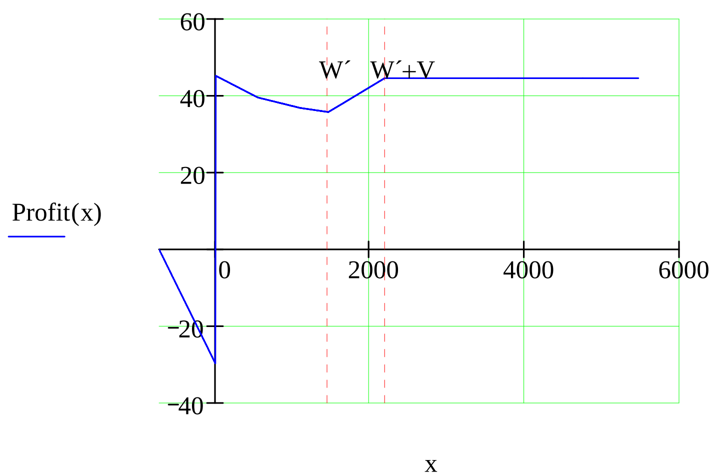




Time before sale (DeCo & PrCo) $D := 2 \cdot 365$ $x := -D, -D + 0.001 \cdot L \,..\, L$

Manufacturer's cumulative profit

$$\begin{aligned} \text{Profit}(x) := & (-D < x \le 0) \cdot (-DeCo' - PrCo') \cdot \left(\frac{x}{D} + 1\right) \ldots \\ & + (x \ge 0) \cdot (P' - DeCo' - PrCo') - WC(x) - SC(x) \ldots \\ & + Q \cdot Psc \cdot \left[(0 < x - W' \le V) \cdot \frac{x - W'}{V} + (x > W' + V)\right] \end{aligned}$$



Asiakas maksaa tuotteen *kerralla* ja huoltosopimuksen *tasaisesti* W...W+V

HUOM

Voi palata mihin tahansa aiempaan keltaiseen kohtaan ja muuttaa syöttöä.

Risk Analysis

Comments: Per-Erik.Hagmark@tut.fi

Tämän metamallin keskeiset ainekset ovat *käyttövarmuus, takuu- ja huoltosopimukset, kustannukset, hinnoittelu, myynti, riskit, profiitit*. Erityisenä vahvuutena on kustannus- ja profiitti- riskien yksityiskohtainen *stokastinen mallinnus.* Perusnäkökulma on valmistajan, mutta älykkäillä tulkinnoilla malli palvelee myös muita näkökulmia.

Valitaan tarkasteltavaksi tuoteyksilön elinjakso vähintään sen pituisena kuin se valmistajaa voi kiinnostaa takuu- ja huoltosopimuksia ajatellen. *Yllätyksettömät* kulut kuten valmistus- ja asennuskustannukset sekä ennakkohuollon kustannukset (PM) käsitellään ilman satunnaisuutta, jälkimmäisiä myös profiloituna elinjaksolle. *Yllättävät* "viat" voidaan jakaa 4 eri tyyppiin, ja jokaisen tyypin esiintymisen riippuvuus iästä mallinnetaan. Tuoteyksilön vikojen lukumäärät eri ikäväleillä ja FR(failure-related)-kustannukset mallinnetaan satunnaissuureina ja simuloidaan.

Takuu- ja huoltosopimuksille (1+3 kpl) malli tarjoaa yhtenäisen ja melko yleisen kehyksen, johon monet käytännössä esiintyvät sopimustyypit voidaan sovittaa pienellä esilaskennalla. Tämä merkitsee esimerkiksi, että valmistaja voi eksperimentoida minkälaisiin kustannusjakaumiin, profiitteihin ja siten taloudellisiin riskeihin erilaiset takuu- tai huoltosopimukset tai hinnoittelu johtavat. Tarkastelu voidaan tehdä myös sopimuskohtaisesti.

Lopuksi koko tarkastelu laajenee tuoteyksilöstä tuote-eriin, kun myös myyntimäärä mallinnetaan stokastisena. Oppimis- ja demonstraatiomielessä voi myös simuloida satunnaisten tuoteyksilöiden historiat (valmistajan tulot, menot, profiitit).

Syötöt keltaisella!

1. Pre-costs and PM costs

(constants for item)

Arvioi valmistajan kustannukset yhteensä ennen käyttöönottoa (can include design, development, production, installation, etc.).

Pre-costs /item (ry) $Pre := 10.6$ (ry = rahayksikkö) — Jos ei oteta huomioon, niin Pre = 0.

Life of item (ky) $L := 5400$ (ky = käyttömääräyksikkö) — valmistajan kannalta kiinnostava jakso 0..L

Ennakohuolto (PM) tarkoittaa tässä kaikkea sellaista kunnossapitoa, jonka tapahtumahetket ja kustannukset ovat (myyntihetkellä) melko tarkasti tiedossa.

PM costs /item 0..L (ry) $Pm := 21.5$ — siinä tapauksessa että valmistaja tekisi "kaiken"

Proportional profile for PM costs /item 0..L

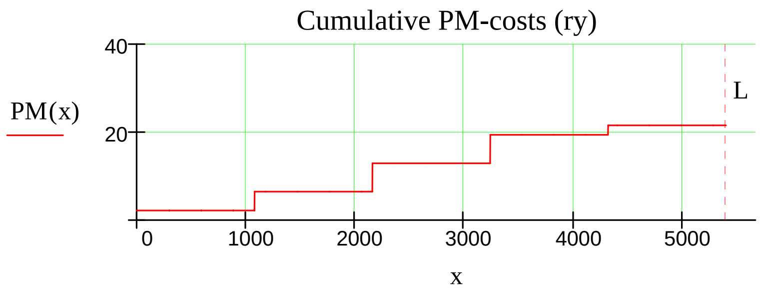
$$D := \begin{pmatrix} 0 & 0.2\cdot L & 0.4\cdot L & 0.6\cdot L & 0.8\cdot L \\ 1 & 2 & 3 & 3 & 1 \end{pmatrix}^T$$

PM-kustannusten suhteellinen jakautuminen 0..L

PM costs /item in 0..x (ry)

$$PM(x) := Pm \cdot \frac{1}{\sum D^{\langle 1 \rangle}} \cdot \sum_{i=0}^{rows(D)-1} D_{i,1} \cdot (D_{i,0} \le x)$$

yksilön PM-kustannus ikään x mennessä



2. Failures and failure related costs

(averages for item)

PM määriteltiin §1:ssa. Muun kunnossapidon aiheuttajia kutsutaan *vioksi* (olkoot nimikkeet käytännössä mitkä tahansa). Tapahtumahetkiin ja/tai kustannuksiin liittyy yllätyksellisyyttä ja epävarmuutta.

Huomioon otettavat viat ja niiden aiheuttamat kustannukset voidaan jakaa *tyyppeihin* f = 1, 2, 3, 4. Jako on vapaasti valittavissa, ja valinta kannattaa tehdä älykkäästi, erityisesti huomioiden valmistajan kustannuslaskentaa yleensä.

Arvioidaan yhden f-vian aiheuttama keskimääräinen kustannus (μ_f), f-vikojen keskimääräinen lukumäärä koko ikävälillä (F_f) sekä vikojen jakautumisen suhteelliset kumulatiiviset profiilit 0..L ($\Lambda_{\blacksquare,f}$). (Huomaa myös PM-kustannusten ja vikojen yhteys (§1)!)

Averages for f-failure	f = 1	f = 2	f = 3	f = 4
f-cost /f-failure (ry)*	$\mu_1 := 10$	$\mu_2 := 5.1$	$\mu_3 := 2.3$	$\mu_4 := 2$
f-failures /item 0..L	$F_1 := 0.45$	$F_2 := 1.2$	$F_3 := 2$	$F_4 := 3.5$

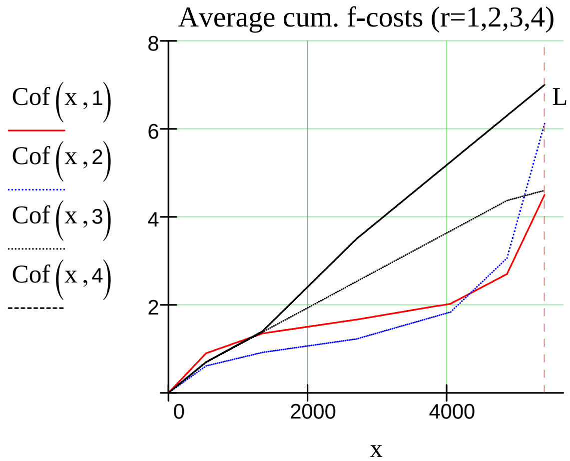
* μ-arvo on yhden vian valmistajalle aiheuttamat kustannukset (keskimäärin) *siinä tapauksessa* että valmistaja joutuisi maksamaan "kaiken".

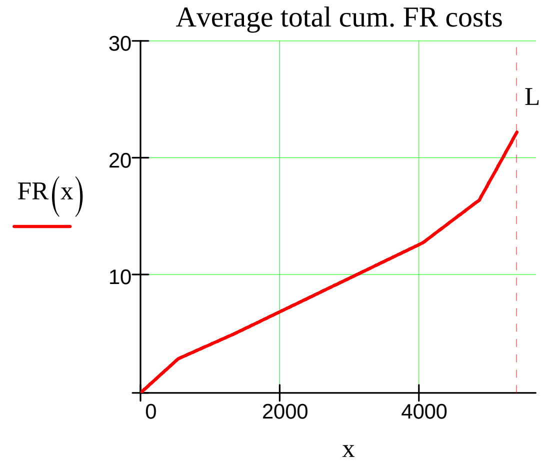
Normalized cumulative profile for #f-failures /item $0 \le \Lambda(x,f) \le 1$ $f := 1..4$ $(x = 0..L)$

Age / 1-fail. / 2-fail. / 3-fail. / 4-fail.

$$\begin{pmatrix} x_0 & x_1 & x_2 & x_3 & x_4 & x_5 & x_6 \\ \Lambda_{0,1} & \Lambda_{1,1} & \Lambda_{2,1} & \Lambda_{3,1} & \Lambda_{4,1} & \Lambda_{5,1} & \Lambda_{6,1} \\ \Lambda_{0,2} & \Lambda_{1,2} & \Lambda_{2,2} & \Lambda_{3,2} & \Lambda_{4,2} & \Lambda_{5,2} & \Lambda_{6,2} \\ \Lambda_{0,3} & \Lambda_{1,3} & \Lambda_{2,3} & \Lambda_{3,3} & \Lambda_{4,3} & \Lambda_{5,3} & \Lambda_{6,3} \\ \Lambda_{0,4} & \Lambda_{1,4} & \Lambda_{2,4} & \Lambda_{3,4} & \Lambda_{4,4} & \Lambda_{5,4} & \Lambda_{6,4} \end{pmatrix} := \begin{pmatrix} 0 & 0.1 \cdot L & 0.25 \cdot L & 0.5 \cdot L & 0.75 \cdot L & 0.9 \cdot L & L \\ 0 & 0.2 & 0.3 & 0.37 & 0.45 & 0.6 & 1 \\ 0 & 0.1 & 0.15 & 0.2 & 0.3 & 0.5 & 1 \\ 0 & 0.15 & 0.3 & 0.55 & 0.8 & 0.95 & 1 \\ 0 & 0.1 & 0.2 & 0.5 & 0.75 & 0.9 & 1 \end{pmatrix}$$

Average #f-failures /item during a..b	$\lambda(f,a,b) := F_f \cdot (\Lambda(b,f) - \Lambda(a,f)) \cdot (a < b)$	f-vikoja keskimäärin /yksilö ikävälillä a..b
Average f-costs /item 0..x (ry)	$Cof(x,f) := \mu_f \cdot \lambda(f,0,x)$	keskimääräiset kumulatiiv. f-kustannukset /yksilö 0..x
Average total FR costs /item 0..x (ry)	$FR(x) := \sum_{f=1}^{4} Cof(x,f)$	keskimääräinen FR-kustannus /yksilö 0..x (FR = failure related)





3. Stochastic modeling of failure related costs (random variables)

A. Edellä annettiin f-kustannuksen (eli f-vian aiheuttaman kustannuksen) keskiarvot μ (§2).

Nyt laajennetaan *satunnaissuureeksi.*

$$\begin{pmatrix} \mu_1 & \mu_2 & \mu_3 & \mu_4 \end{pmatrix} = \begin{pmatrix} 10 & 5.1 & 2.3 & 2 \end{pmatrix}$$

Assess **minimum** m (ry) & p**rob**(m) P.
Adjust **shape** β to get desired Q-quantile
RC or deviation σ (below).

$$\begin{pmatrix} m_1 & m_2 & m_3 & m_4 \\ P_1 & P_2 & P_3 & P_4 \\ Q_1 & Q_2 & Q_3 & Q_4 \\ \beta_1 & \beta_2 & \beta_3 & \beta_4 \end{pmatrix} := \begin{pmatrix} 5.5 & 3 & 1.2 & 0 \\ 0 & 0.15 & 0 & 0 \\ 0.85 & 0.9 & 0.95 & 0.95 \\ 2.9 & 2.7 & 2.9 & 2.88 \end{pmatrix}$$

Random f-cost (ry) RC(U,f) =
the cost caused by a random f-failure

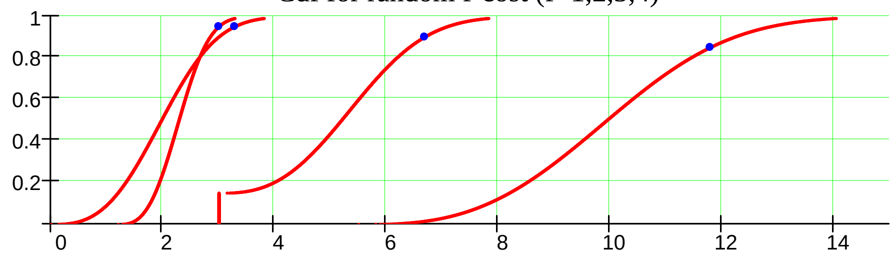
$$RC(U,f) := m_f + \frac{(U > P_f)\cdot(\mu_f - m_f)}{(1-P_f)\cdot\Gamma\left[1+(\beta_f)^{-1}\right]}\cdot\left(-\ln\left(\frac{1-U}{1-P_f}\right)\right)^{(\beta_f)^{-1}} \qquad \sigma_f := \sqrt{\int_0^1 \left(RC(u,f)-\mu_f\right)^2 du}$$

$$\begin{pmatrix} RC(Q_1,1) & RC(Q_2,2) & RC(Q_3,3) & RC(Q_4,4) \\ \sigma_1 & \sigma_2 & \sigma_3 & \sigma_4 \end{pmatrix} = \begin{pmatrix} 11.79 & 6.68 & 3 & 3.28 \\ 1.69 & 1.27 & 0.41 & 0.75 \end{pmatrix}$$

RC(rnd(1),f) =

6.006
3.931
2.38
1.675

Cdf for random f-cost (f=1,2,3,4)



B. Yksilön f-vikojen lukumäärä halutulla ikävälillä *satunnaissuureena.* Keskiarvot määriteltiin §2:ssa (λ).

#f-failures of a random item during a...b (Poisson)

$$\text{Fails}(f,a,b) := \left| \begin{array}{l} \lambda \leftarrow \lambda(f,a,b) \\ \text{qpois}(\text{rnd}(1),\lambda) \ \text{ if } \lambda > 0 \\ 0 \ \ \text{otherwise} \end{array} \right.$$

$\text{Fails}(f,0,L) =$

1
0
3
2

C. Yhdistämällä satunnaissuureet RC ja Fails saadaan *yksilön f-kustannukset ikävälillä* a...b

Total f-costs of a random item during a...b (ry)

$$\text{Cost}(f,a,b) := \left| \begin{array}{l} n \leftarrow \text{Fails}(f,a,b) \\ (n > 0)\cdot \sum_{i=1}^{n} \text{RC}(\text{rnd}(1),f) \end{array} \right.$$

$\text{Cost}(f,0,L) =$

0
0
4.12
2.6

Alustavaa riskintarkastelua

Valittujen vikatyyppien f aiheuttamat kustannukset valituilla väleillä a...b.

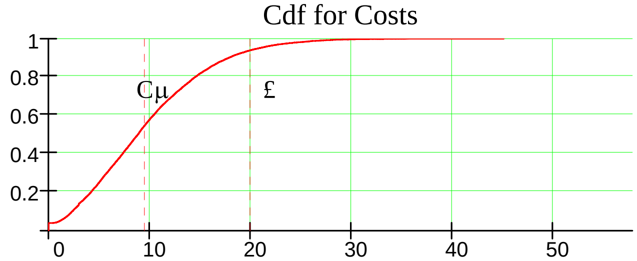
$$\begin{pmatrix} f_1 & f_2 & f_3 & f_4 \\ a_1 & a_2 & a_3 & a_4 \\ b_1 & b_2 & b_3 & b_4 \end{pmatrix} := \begin{pmatrix} 0 & 1 & 0 & 1 \\ 0 & 2000 & 0 & 2000 \\ 0 & 5400 & 0 & 5400 \end{pmatrix}$$

Risk cost

$£ := 20.00$

F9

Cdf for Costs



Prob(> £)	$P(£) = 0.061$
Mean	$C\mu = 9.644$
Stdev	$C\sigma = 6.123$
Prob(0)	$P0 = 0.039$

4. Warranty contract and Service contracts

Määritellään *takuusopimus ja huoltosopimukset valmistajan näkökulmasta.* Malli sallii että jokaiseen sopimukseen voi kuulua sekä PM (f = 0) että FR (f = 1,2,3,4).

Valmistajan vastuu mallinnetaan suoraan <u>osuuksina kustannuksista (§1-3) eri ikäväleillä</u>.

$(a_{s,f}..b_{s,f})$	interval for f-cost in s-contract	
$p_{s,f}$	manufacturer's <u>fraction</u> of f-cost in $(a_{s,f}..b_{s,f})$	
$(A_s..B_s)$	interval during which the s-contract is paid	
Cc_s	manufacturer's constant cost with s-contract	

Index symbols
Warranty   s = 0
Service   s = 1, 2, 3
PM cost   f = 0
FR cost   f = 1, 2, 3, 4

The contracts   PM   f=1   f=2   f=3   f=4   (= cost types)

Warranty (s=0)

$$\begin{pmatrix} a_{0,0} & a_{0,1} & a_{0,2} & a_{0,3} & a_{0,4} & A_0 \\ b_{0,0} & b_{0,1} & b_{0,2} & b_{0,3} & b_{0,4} & B_0 \\ p_{0,0} & p_{0,1} & p_{0,2} & p_{0,3} & p_{0,4} & Cc_0 \end{pmatrix} := \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1080 & 1080 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0.50 \end{pmatrix}$$

Service 1 (s=1)

$$\begin{pmatrix} a_{1,0} & a_{1,1} & a_{1,2} & a_{1,3} & a_{1,4} & A_1 \\ b_{1,0} & b_{1,1} & b_{1,2} & b_{1,3} & b_{1,4} & B_1 \\ p_{1,0} & p_{1,1} & p_{1,2} & p_{1,3} & p_{1,4} & Cc_1 \end{pmatrix} := \begin{pmatrix} 0 & 0 & 1080 & 0 & 0 & 0 \\ 1080 & 0 & 3240 & 0 & 0 & 3240 \\ 1 & 0 & 0.5 & 0 & 0 & 0.00 \end{pmatrix}$$

Service 2 (s=2)

$$\begin{pmatrix} a_{2,0} & a_{2,1} & a_{2,2} & a_{2,3} & a_{2,4} & A_2 \\ b_{2,0} & b_{2,1} & b_{2,2} & b_{2,3} & b_{2,4} & B_2 \\ p_{2,0} & p_{2,1} & p_{2,2} & p_{2,3} & p_{2,4} & Cc_2 \end{pmatrix} := \begin{pmatrix} 1080 & 1080 & 3240 & 0 & 0 & 0 \\ 5400 & 3240 & 5400 & 0 & 0 & 5400 \\ 0.5 & 0.2 & 0.5 & 0 & 0 & 1.50 \end{pmatrix}$$

Service 3 (s=3)

$$\begin{pmatrix} a_{3,0} & a_{3,1} & a_{3,2} & a_{3,3} & a_{3,4} & A_3 \\ b_{3,0} & b_{3,1} & b_{3,2} & b_{3,3} & b_{3,4} & B_3 \\ p_{3,0} & p_{3,1} & p_{3,2} & p_{3,3} & p_{3,4} & Cc_3 \end{pmatrix} := \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5400 & 0 & 5400 \\ 0 & 0 & 0 & 0.5 & 0 & 1.00 \end{pmatrix}$$

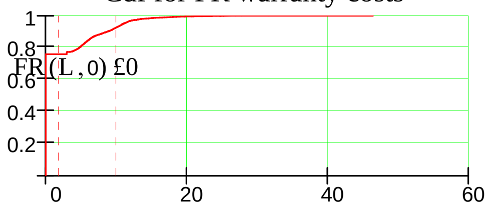
<u>5. Manufacturer's Warranty-Service (WS) costs and FR risks</u> (item)

Lasketaan valmistajan takuu- ja huoltokustannukset. FR-kustannukset saadaan täydellisinä jakaumina, joten voidaan tutkia myös riskejä.

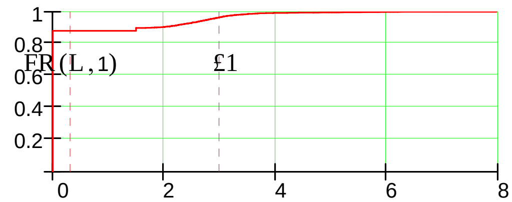
WS costs	<u>Warranty</u>	<u>Service 1</u>	<u>Service 2</u>	<u>Service 3</u>
Total	$C_0 = 2.52$	$C_1 = 6.78$	$C_2 = 11.47$	$C_3 = 3.3$
Constant	$Cc_0 = 0.5$	$Cc_1 = 0$	$Cc_2 = 1.5$	$Cc_3 = 1$
PM (const.)	$PM(L,0) = 0$	$PM(L,1) = 6.45$	$PM(L,2) = 7.53$	$PM(L,3) = 0$
FR mean	$FR(L,0) = 2.02$	$FR(L,1) = 0.33$	$FR(L,2) = 2.45$	$FR(L,3) = 2.3$
Risk FR cost	£0 := 10	£1 := 3	£2 := 7	£3 := 4

Prob(FR>£)	$\rho0(£0) = 0.074559$	$\rho1(£1) = 0.035496$	$\rho2(£2) = 0.060059$	$\rho3(£3) = 0.159963$
Prob(FR=0)	$P0 = 0.759286$	$P1 = 0.881$	$P2 = 0.387143$	$P3 = 0.128286$

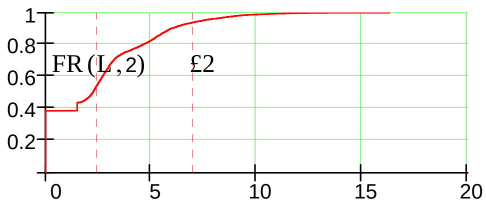
Cdf for FR warranty costs



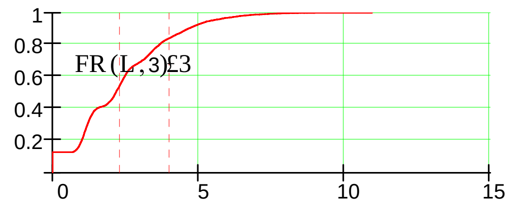
Cdf for FR Service1 costs



Cdf for FR Service2 costs



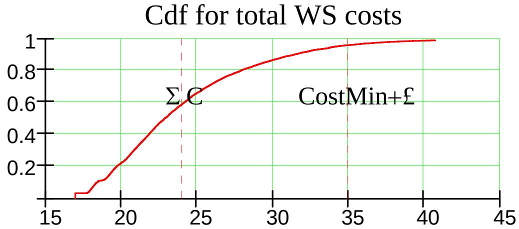
Cdf for FR Service3 costs



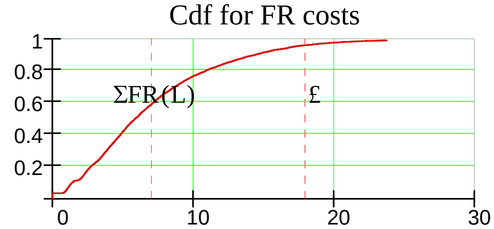
Summary of Warranty-Service costs 0...L. Yhteenveto riskitarkastelulla

Total mean	$\Sigma C = 24.065$	Minimikustannus	$CostMin = 16.975$ (kun FR = 0)
Constant	$\Sigma Cc = 3$	Minimin todennäk.	$P0 \cdot P1 \cdot P2 \cdot P3 = 0.033$
PM (const.)	$\Sigma PM(L) = 13.975$	Risk FR cost	$£ := 18$
FR mean	$\Sigma FR(L) = 7.09$	Prob(FR > £)	$\rho(£) = 0.040527$
Deviation	$sd = 5.225$		

Cdf for total WS costs



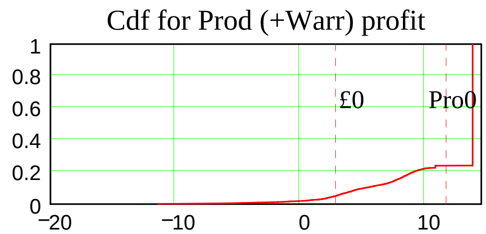
Cdf for FR costs

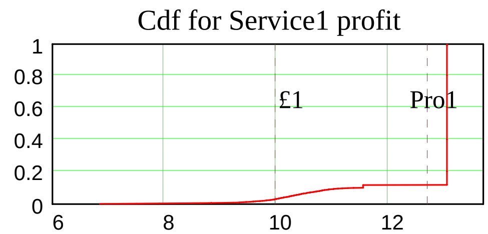


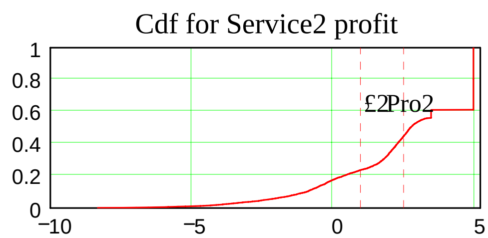
6. Pricing, manufacturer's profits and risks (item)

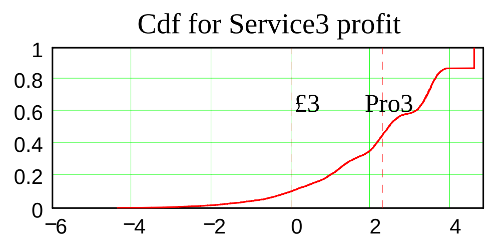
RESULTS	Product (+warr.)	Service 1	Service 2	Service 3
Cost mean	$Pre + C_0 = 13.12$	$C_1 = 6.78$	$C_2 = 11.47$	$C_3 = 3.3$
Sale price	$P_0 := 25$	$P_1 := 19.5$	$P_2 := 14$	$P_3 := 5.6$

Profit mean	Pro0 = 11.88	Pro1 = 12.72	Pro2 = 2.53	Pro3 = 2.3
Risk profit	£0 := 3	£1 := 10.	£2 := 1	£3 := 0
Prob(< £s)	ρ0(£0) = 0.053354	ρ1(£1) = 0.031772	ρ2(£2) = 0.238088	ρ3(£3) = 0.104532
Profit = max.	Pro0(1) = 13.9	Pro1(1) = 13.05	Pro2(1) = 4.97	Pro3(1) = 4.6
Prob(max.)	P0 = 0.759286	P1 = 0.881	P2 = 0.387143	P3 = 0.128286

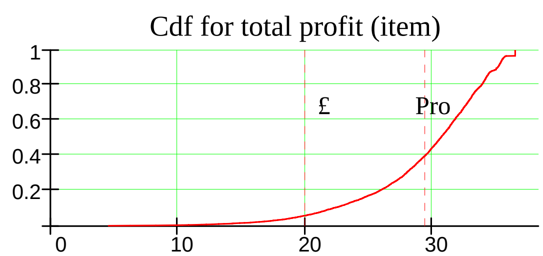








Total profit and risk analysis



Risk profit	£ := 20
Prob(< £)	ρ(£) = 0.059537
Profit mean	Pro = 29.44
Profit max.	Pro(1) = 36.53
Prob(max.)	P0·P1·P2·P3 = 0.033

7. Modeling the sale of lots

Tähän mennessä on käsitelty yksilöitä. Tarkastellaan nyt useita *'samanlaisia'* yksilöitä eli erää.
Esimerkki: Erä voi koostua kerralla tai tietyn markkinajakson aikana myytävistä yksilöistä.

Assessing lot size (# items sold)	Bad := 6	Mean := 7.5	Bad < Mean < Good
	Good := 10	Pr := 0.95	Pr = Prob(Bad...Good)

Random lot size

$$N(U) := \begin{vmatrix} Z \leftarrow \frac{n\mu}{\kappa} \cdot \text{qgamma}(U, \kappa) \\ \text{floor}(Z) + (\text{rnd}(1) < Z - \text{floor}(Z)) \end{vmatrix}$$

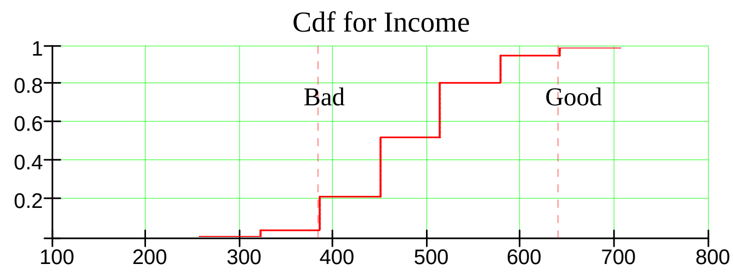
$(\kappa = 41.025)$

$N(\text{rnd}(1)) = 7$

Income figures

mean(inc) = 480.36

stdev(inc) = 79.47

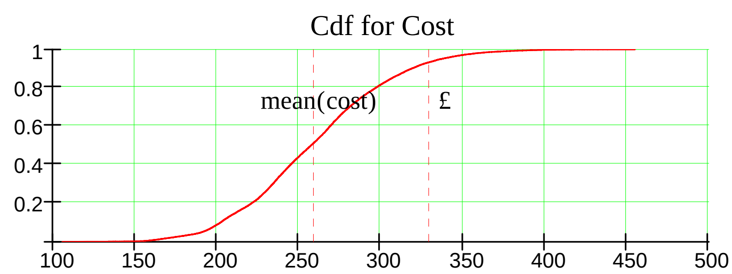


Risk cost £ := 330

Prob(>£) δco(£) = 0.065

mean(cost) = 259.25

stdev(cost) = 45.22

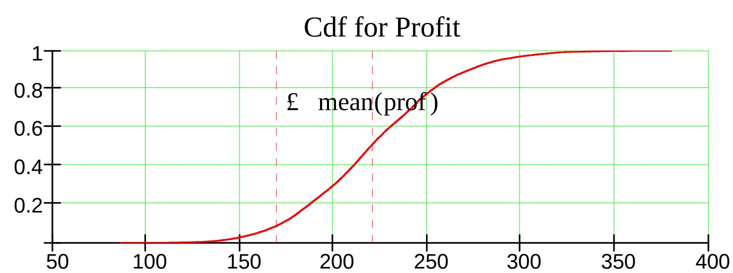


Risk profit £ := 170

Prob(<£) δpr(£) = 0.091

mean(prof) = 221.11

stdev(prof) = 39.2



F9

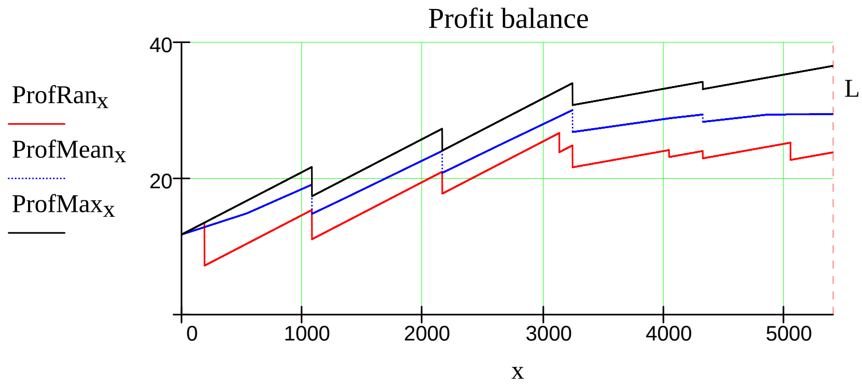
8. Demo: Failure history and profit balance of a random item

Failure history. (Click & F9 above!)

$y^T =$

"Age"	190	305	1745	1844	2152	3131	3965	4041	5047	5094	5130
"Failure type"	2	4	4	4	4	2	4	3	2	4	4
"Total FR cost"	6.318	0.73	2.084	2.613	1.014	5.643	2.488	2.051	5.071	1.481	2.056
"Manuf. FR cost"	6.318	0	0	0	0	2.821	0	1.025	2.535	0	0

Manufacturer's profit balance. Random item (red), average item (blue), lucky item (black).



Tuotteen ostohinta, PM-kustannukset ja FR-kustannukset näkyvät heti, huolto-sopimusten hinnat jatkuvasti.

Diffusion Model I

Comments: Per-Erik.Hagmark@tut.fi

Tämä on yhden tuotteen metamalli, jossa suureiden muuttuminen lasketaan diffuusioperiaatteella sekä tuoteyksilön elinaikana että markkinajakson aikana.

Perusmalleilla voidaan määritellä *eri vikatyyppien* esiintyminen ja niiden aiheuttamat kustannukset (FR), *ennakkohuollon* kustannukset (PM), *valmistus*kustannukset, *takuusopimus* ja *huoltosopimus, populaatio, satsaus mainostamiseen*, todellinen ja odotettu *myyntihinta, asiakastyytyväisyys* liittyen hintaan ja vikoihin, ym., ja näiden mahdollinen aika-riippuvuus.

Rakennetaan tietoiseksi tulemisen, *ensimmäisen oston ja uudelleenoston* ajasta riippuvat "todennäköisyydet" ottaen myös humioon kuinka mones osto on kyseessä. Säätöparametrit ja rinnakkaiset differenssiyhtälöt ohjaavat *markkinatilan ajallista muuttumista*, eli erilaisten asiakaslukumäärien (potentiaaliset ostajat, kerran ostaneet, kaksikertaa ostaneet, jne.) kehittymistä.

Tästä diffuusion tuottamasta perusdatasta malli laskee kustannusten, tulojen, profiittien ym. ajallista kehittymistä markkinajaksolla.

Mainittava piirre tämän mallin rakenteessa on sen *käännettävyys.* Markkinajakson todellisesta datasta voitaisiin kääntäen laskea säätöparametrien arvot.

Syötöt keltaisella!

1. Product's failure tendency

Useful life of item *(tu)** $L := 500$

Failure types: f = 1,2,3...
(vikatyypit täysin vapaasti valittavissa)

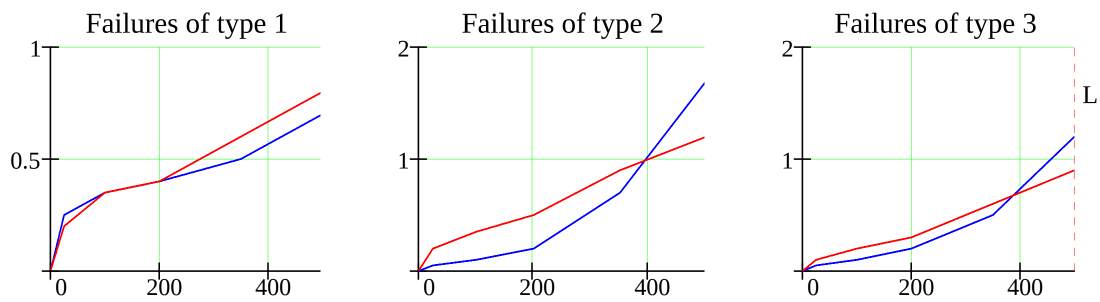
* Use such a time unit *(tu)* that a customer buys *at most once item during* t...t+1.
Example: If a customer buys maximally 1 item/day, then choose *(tu)* = day, or less!

Real average #failures (manufacturer)
$vm_{s,f}$ = #f-failures in time interval $0...\xi_s$
(Basic reliability, PM, ageing, etc.)

Tolerated average #failures (customer)
$vc_{s,f}$ = #f-failures in time interval $0...\xi_s$
(How is this assessed? Inquiries?)

$$\begin{pmatrix} \xi_1 & \xi_2 & \xi_3 & \xi_4 & \xi_5 \\ vm_{1,1} & vm_{2,1} & vm_{3,1} & vm_{4,1} & vm_{5,1} \\ vm_{1,2} & vm_{2,2} & vm_{3,2} & vm_{4,2} & vm_{5,2} \\ vm_{1,3} & vm_{2,3} & vm_{3,3} & vm_{4,3} & vm_{5,3} \\ vc_{1,1} & vc_{2,1} & vc_{3,1} & vc_{4,1} & vc_{5,1} \\ vc_{1,2} & vc_{2,2} & vc_{3,2} & vc_{4,2} & vc_{5,2} \\ vc_{1,3} & vc_{2,3} & vc_{3,3} & vc_{4,3} & vc_{5,3} \end{pmatrix} := \begin{pmatrix} 0.05\cdot L & 0.2\cdot L & 0.4\cdot L & 0.7\cdot L & L \\ 0.25 & 0.35 & 0.4 & 0.5 & 0.7 \\ 0.05 & 0.1 & 0.2 & 0.7 & 1.7 \\ 0.05 & 0.1 & 0.2 & 0.5 & 1.2 \\ 0.2 & 0.35 & 0.4 & 0.6 & 0.8 \\ 0.2 & 0.35 & 0.5 & 0.9 & 1.2 \\ 0.1 & 0.2 & 0.3 & 0.6 & 0.9 \end{pmatrix}$$

Cumulative number of failures (**blue** = *real*, **red** = tolerated, average item)



2. Costs and the warranty contract

Each product support cost to be considered shall be placed in one of the following four classes:

Preventive maintenance (PM) costs C_0 *euro /tu* (f = 0)

Failure related (FR) costs C_f *euro /f-failure* (f = 1, 2, 3...)

for subintervals $(\alpha, \beta] = (0, V_f], (V_f, W_f]$ and $(W_f, L]$, respectively. In each subinterval $(\alpha, \beta]$, manufacturer's warranty fraction varies from p_f to q_f according to the *variation coefficient* γ_f:

$$C_f \cdot \left[p_f + (q_f - p_f) \cdot \left(\frac{x - \alpha}{\beta - \alpha} \right)^{\gamma_f} \right] \qquad x \in (\alpha, \beta] \; .$$

PM-costs *euro /tu* (f = 0)

$\alpha \ldots \beta$	*Costs*	*Frac ... Frac*	*Variation*
$0 \ldots V_0$	$C1_0$	$p1_0 \ldots q1_0$	$\gamma1_0$
$V_0..W_0$	$C2_0$	$p2_0 \ldots q2_0$	$\gamma2_0$
$W_0..L$	$C3_0$	$p3_0 \ldots q3_0$	$\gamma3_0$

FR-costs *euro /f-failure* (f = 1, 2, 3)

$\alpha \ldots \beta$	*Costs*	*Frac ...Frac*	*Variation*
$0 \ldots V_f$	$C1_f$	$p1_f \ldots q1_f$	$\gamma1_f$
$V_f..W_f$	$C2_f$	$p2_f \ldots q2_f$	$\gamma2_f$
$W_f..L$	$C3_f$	$p3_f \ldots q3_f$	$\gamma3_f$

Costs and the warranty contract

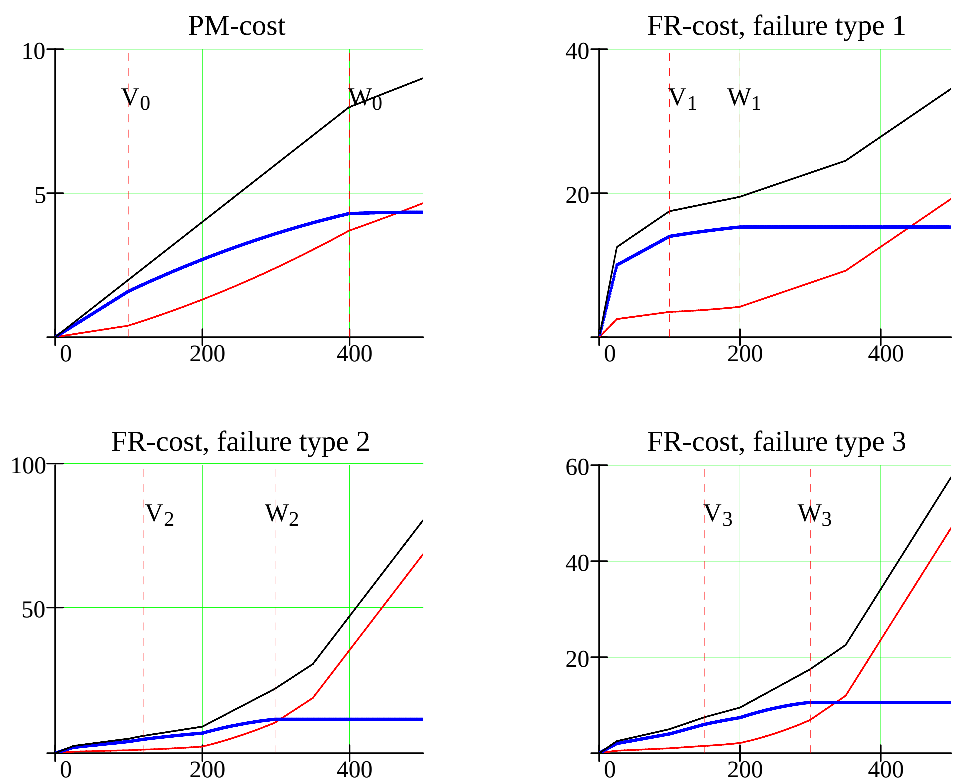
$$\begin{pmatrix} C1_0 & C1_1 & C1_2 & C1_3 \\ p1_0 & p1_1 & p1_2 & p1_3 \\ q1_0 & q1_1 & q1_2 & q1_3 \\ \gamma1_0 & \gamma1_1 & \gamma1_2 & \gamma1_3 \\ V_0 & V_1 & V_2 & V_3 \\ C2_0 & C2_1 & C2_2 & C2_3 \\ p2_0 & p2_1 & p2_2 & p2_3 \\ q2_0 & q2_1 & q2_2 & q2_3 \\ \gamma2_0 & \gamma2_1 & \gamma2_2 & \gamma2_3 \\ W_0 & W_1 & W_2 & W_3 \\ C3_0 & C3_1 & C3_2 & C3_3 \\ p3_0 & p3_1 & p3_2 & p3_3 \\ q3_0 & q3_1 & q3_2 & q3_3 \\ \gamma3_0 & \gamma3_1 & \gamma3_2 & \gamma3_3 \end{pmatrix} := \begin{pmatrix} 0.02 & 50 & 50 & 50 \\ 0.8 & 0.8 & 0.8 & 0.8 \\ 0.8 & 0.8 & 0.8 & 0.8 \\ 1 & 1 & 1 & 1 \\ 100 & 100 & 120 & 150 \\ 0.02 & 40 & 40 & 40 \\ 0.6 & 0.8 & 0.8 & 0.8 \\ 0.3 & 0.5 & 0.2 & 0.2 \\ 1 & 1 & 1 & 1 \\ 400 & 200 & 300 & 300 \\ 0.01 & 50 & 50 & 50 \\ 0.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 \end{pmatrix}$$

Examples of warranty fractions <u>Free replacement</u> warranty (FRW) $0..V_f$ => $p1_f = q1_f < 1$ (any γ).

Full responsibility (FRW) $0..V_f$ => $p1_f = q1_f = 1$ (any γ). Linear <u>pro-rata</u> warranty $V_f..W_f$ => $p2_f \neq q2_f$, $\gamma2_f = 1$ (x-dependent)

3. Cumulative costs and separate maintenance service contract

Cumulative PM and FR costs caused by average item
(**black** = total costs, **blue** = covered by warranty, **red** = not covered by warranty)



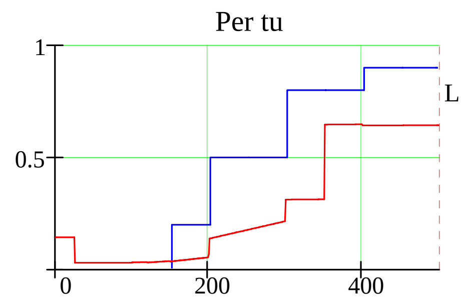
The costs not covered by the warranty (red curves) can be managed by a separately bought

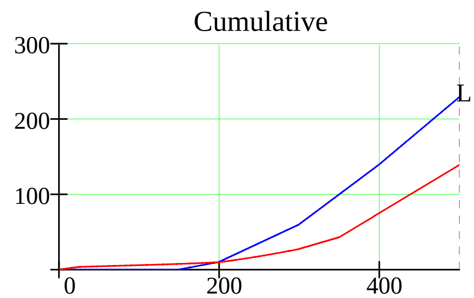
Maintenance service contract
The customer pays Ms_i
(euro/tu) from ξ_i *(tu)*

$$\begin{pmatrix} \xi_0 & \xi_1 & \xi_2 & \xi_3 & \xi_4 \\ Ms_0 & Ms_1 & Ms_2 & Ms_3 & Ms_4 \end{pmatrix} := \begin{pmatrix} 0 & 0.3 \cdot L & 0.4 \cdot L & 0.6 \cdot L & 0.8 \cdot L \\ 0 & 0.2 & 0.5 & 0.8 & 0.9 \end{pmatrix}$$

<u>Customer's PM + FR costs</u>

Blue = with maintenance service contract
Red = without maintenance service contract





4. Customers' satisfaction related to failures

Intervals

s=1: 0 ...V_f

s=2: V_f ..W_f

s=3: W_f ..L

Failure types

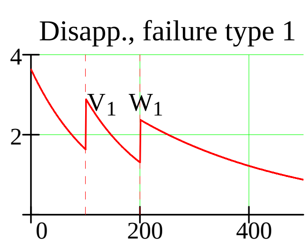
f = 1, 2, 3

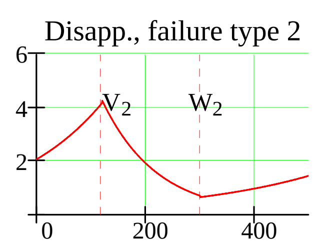
Average disappointment ds_f in interval s = 1, 2, 3
when an f-failure has occurred. Relative (e.g. costs)

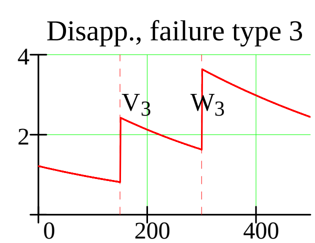
Location parameter ps_f (etumerkin vaihto vaihtaa suunnan)
Disappointment can depend on the location inside the interval.

$$\begin{matrix} f = 1 \\ f = 2 \\ f = 3 \end{matrix} \quad \begin{pmatrix} V_1 & W_1 \\ V_2 & W_2 \\ V_3 & W_3 \end{pmatrix} = \begin{pmatrix} 100 & 200 \\ 120 & 300 \\ 150 & 300 \end{pmatrix}$$

$$\begin{pmatrix} d1_1 & d2_1 & d3_1 & p1_1 & p2_1 & p3_1 \\ d1_2 & d2_2 & d3_2 & p1_2 & p2_2 & p3_2 \\ d1_3 & d2_3 & d3_3 & p1_3 & p2_3 & p3_3 \end{pmatrix} := \begin{pmatrix} 2.5 & 2 & 1.5 & 0.8 & 0.8 & 1 \\ 3 & 2 & 1 & -0.7 & 1.8 & -0.8 \\ 1 & 2 & 3 & 0.4 & 0.4 & 0.4 \end{pmatrix}$$



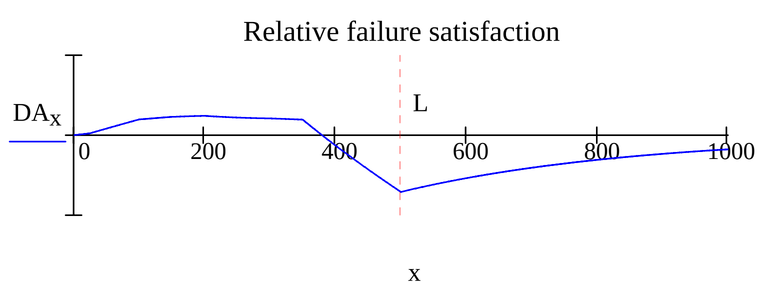




Halfing time for disappointment HaDi := 250

Relative failure satisfaction

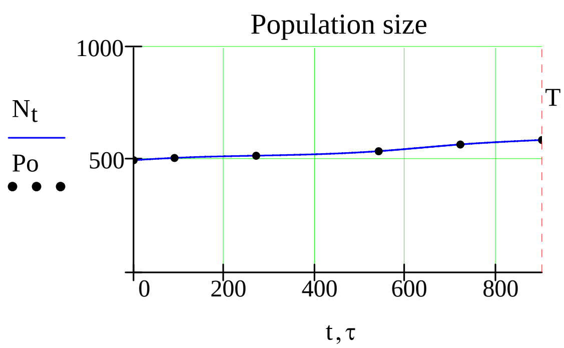
(average item)

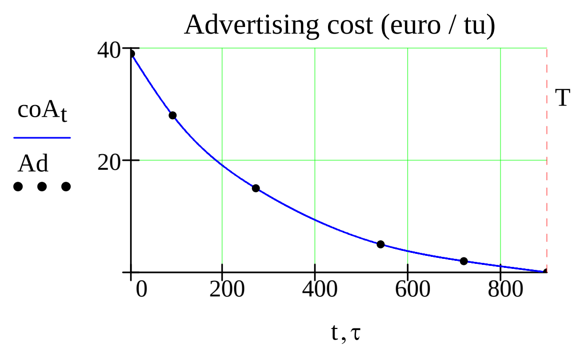


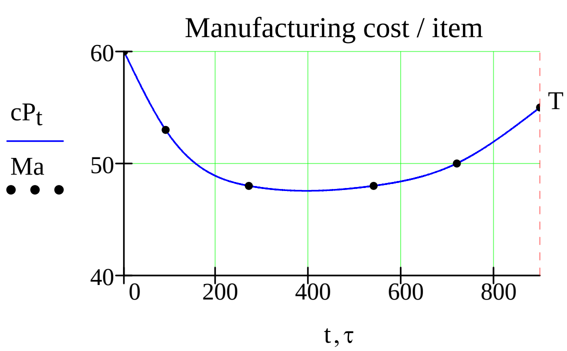
5. Input for the market period

Market period T *(tu)*	$T := 900$	T = the time of the product on market
Population size (at time moment τ_s)	Po_s	Po = #those who can buy or have buyed.
Advertising cost effort	Ad_s *euro/tu*	Ma includes agreed contributions.
Manufacturing cost	Ma_s *euro/item*	It is assumed that the real sale price and the expected sale price can be assessed.
Real sale price (manufacturer)	Pm_s *euro/item*	
Expected sale price (customers)	Pc_s *euro/item*	

$$\begin{pmatrix} \tau_0 & \tau_1 & \tau_2 & \tau_3 & \tau_4 & \tau_5 \\ Po_0 & Po_1 & Po_2 & Po_3 & Po_4 & Po_5 \\ Ad_0 & Ad_1 & Ad_2 & Ad_3 & Ad_4 & Ad_5 \\ Ma_0 & Ma_1 & Ma_2 & Ma_3 & Ma_4 & Ma_5 \\ Pm_0 & Pm_1 & Pm_2 & Pm_3 & Pm_4 & Pm_5 \\ Pc_0 & Pc_1 & Pc_2 & Pc_3 & Pc_4 & Pc_5 \end{pmatrix} := \begin{pmatrix} 0 & 0.1 \cdot T & 0.3 \cdot T & 0.6 \cdot T & 0.8 \cdot T & T \\ 500 & 510 & 520 & 540 & 570 & 590 \\ 39 & 28 & 15 & 5 & 2 & 0 \\ 60 & 53 & 48 & 48 & 50 & 55 \\ 300 & 260 & 200 & 230 & 240 & 230 \\ 300 & 270 & 240 & 220 & 220 & 220 \end{pmatrix}$$





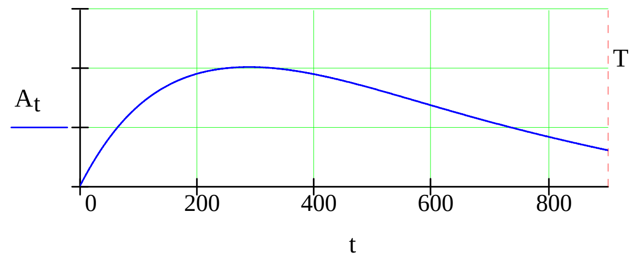


6. Profiles for awareness and purchace modeling

Halfing time for the effect of advertising $HaAd := 200$

Profile A_t Advertising effect on buying

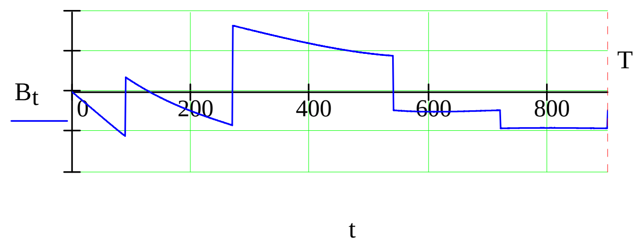
Follows from advertising effort (Ad §5).



Profile B_t Sale price satisfaction effect

The %-difference between the real and the expected price (Pm & Pc §5).

(Tyytyväisyys on verrannollinen odotetun ja todellisen hinnan suhteelliseen eroon.)



Profile C_t Failure satisfaction effect

Recall disappointment DA (§4).

Sales dS, S will be computed in §9.

$$C_t = \frac{1}{S_t} \cdot \sum_{x=0}^{t-1} dS_{t-x} \cdot DA_x$$

7. The diffusion principle

T *(tu)*	market period considered, t = 0,1,...,T
I	maximum # items the same customer can buy during 0...T
N_t	population size (at time t)
$m_{0,t}$	# those who know but have not bought
$m_{i,t}$	# those who have bought *exactly* i items $(1 \le i \le I)$
$M_{0,t}$	# those in the population who know about the product $(m_{0,t} \le M_{0,t} \le N_t)$
$M_{i,t}$	# those who have bought *at least* i items
$P_{0,t}$	the fraction of uninformed that becomes aware during (t, t+1]
$P_{i,t}$	the fraction of i-1-customers that buys during (t, t+1]
S_t	items sold
dS_t	items sold during (t, t+1]

Some connections

$M_{0,t} = \Sigma\, m^{\langle t \rangle}$ $\quad M_{I+1,t} = 0$ $\quad m_{I+1,t} = 0$ $\quad P_{I+1,t} = 0$ $\quad dS_t = S_{t+1} - S_t$ $\quad m_{I,0} = 0$

$$M_{i,t} = \sum_{j=i}^{I} m_{j,t} \qquad S_t = \sum_{j=1}^{I} \left(j \cdot m_{j,t}\right) \qquad P_{0,t} = \frac{M_{0,t+1} - M_{0,t}}{N_t - M_{0,t}}$$

Generation formulas

$$m_{0,t+1} = \left(N_t - M_{0,t}\right)\cdot P_{0,t} + m_{0,t}\cdot\left(1 - P_{1,t}\right) \qquad \text{avareness } (i = 0) \qquad (1)$$

$$m_{i,t+1} = m_{i-1,t}\cdot P_{i,t} + m_{i,t}\cdot\left(1 - P_{i+1,t}\right) \qquad i^{th} \text{ purchase } (i = 1, 2, .., I) \qquad (2)$$

Matrix formulations

$$\begin{pmatrix} m_{0,t+1} \\ m_{1,t+1} \\ m_{2,t+1} \\ .... \\ m_{I-1,t+1} \\ m_{I,t+1} \end{pmatrix} = \begin{pmatrix} m_{0,t} \\ m_{1,t} \\ m_{2,t} \\ .... \\ m_{I-1,t} \\ m_{I,t} \end{pmatrix} + \begin{pmatrix} N_t - \Sigma\, m^{\langle t \rangle} & -m_{0,t} & 0 & .... & 0 & 0 \\ 0 & m_{0,t} & -m_{1,t} & .... & 0 & 0 \\ 0 & 0 & m_{1,t} & .... & 0 & 0 \\ .... & .... & .... & .... & .... & .... \\ 0 & 0 & 0 & .... & m_{I-2,t} & -m_{I-1,t} \\ 0 & 0 & 0 & .... & 0 & m_{I-1,t} \end{pmatrix} \cdot \begin{pmatrix} P_{0,t} \\ P_{1,t} \\ P_{2,t} \\ .... \\ P_{I-1,t} \\ P_{I,t} \end{pmatrix} \qquad (3)$$

$$\begin{pmatrix} N_{t+1} \\ m_{0,t+1} \\ m_{1,t+1} \\ .... \\ m_{I-1,t+1} \\ m_{I,t+1} \end{pmatrix} = \begin{pmatrix} Q_t & 0 & 0 & .... & 0 & 0 & 0 \\ P_{0,t} & 1 - P_{0,t} - P_{1,t} & -P_{0,t} & .... & -P_{0,t} & -P_{0,t} & -P_{0,t} \\ 0 & P_{1,t} & 1 - P_{2,t} & .... & 0 & 0 & 0 \\ .... & .... & .... & .... & .... & .... & .... \\ 0 & 0 & 0 & .... & P_{I-1,t} & 1 - P_{I,t} & 0 \\ 0 & 0 & 0 & .... & 0 & P_{I,t} & 1 \end{pmatrix} \cdot \begin{pmatrix} N_t \\ m_{0,t} \\ m_{1,t} \\ .... \\ m_{I-1,t} \\ m_{I,t} \end{pmatrix} \qquad (3')$$

8. Adjustment parameters for awareness and purchaces

Adjustment parameters for a member of the population N_t to become *aware of the product*:

Advertising (A_t §6) $a_0 := 0.0000008$

A customer tells $b_0 := 0.004$

An informed non-customer tells $c_0 := 0.001$

(Säätöparametrit eivät ole suhteessa toisiinsa.)

$P_{0,t}$ = the fraction of uninformed that becomes aware of the product during (t, t+1]

$$P_{0,t} = 1 - e^{-\left(a_0\cdot A_t + b_0\cdot\frac{M_{1,t}}{N_t} + c_0\cdot\frac{m_{0,t}}{N_t}\right)} \qquad (4)$$

A_t is the advertising profile (§6). The parameter $a_0 \geq 0$ levels the contribution to $P_{0,t}$, and the parameter $a_0 \geq 0$ fixes the general level.

The fraction of customers $M_{1,t}/N_t$ defines the time dependence of the contribution to $P_{0,t}$, and the parameter $b_0 \geq 0$ fixes the general level (WOM).

The fraction of informed $m_{0,t}/N_t$ defines the time dependence of the contribution to $P_{0,t}$, and the parameter $c_0 \geq 0$ fixes the general level (WOM).

Upper bound for items bought by the same customer $I := 2$ $(i = 1,2,...,I)$

Adjustment parameters (a_i, b_i, c_i) for a customer's i^{th} *purchase* (i=1 => first purchase):

Advertising (A_t §6)
Price satisfaction (B_t §6)
Failure satisfaction (C_t §6)

$$\begin{pmatrix} a_1 & a_2 & a_3 & a_4 & a_5 & a_6 & a_7 \\ b_1 & b_2 & b_3 & b_4 & b_5 & b_6 & b_7 \\ c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 \end{pmatrix} := \begin{pmatrix} 0.000001 & 0.0000005 & 0 & 0 & 0 & 0 & 0 \\ 0.007 & 0.003 & 0 & 0 & 0 & 0 & 0 \\ 0.0000005 & 0.000001 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$P_{i,t}$ = <u>the fraction of i-1-customers that buys during</u> (t, t+1]

$$P_{i,t} = 1 - e^{-\left(a_i \cdot A_t + b_i \cdot B_t + c_i \cdot C_t \cdot \frac{M_{1,t}}{M_{0,t}}\right)} \quad (5)$$

A_t is the advertising profile (§6). The parameter $a_i \geq 0$ levels the contribution to $P_{i,t}$

B_t is the price satisfaction profile (§6). The parameter $b_i \geq 0$ levels the contribution to $P_{i,t}$

C_t is the failure satisfaction profile (§4, §6). A positive/negative C_t corresponds to a pos./neg. WOM-effect. The impact is also proportional to the ratio $M_{1,t}/M_{0,t}$, i.e. depends on how many of the informed have actually bought. The parameter $c_i \geq 0$ levels the contribution.

Matrix versions of (4) and (5):

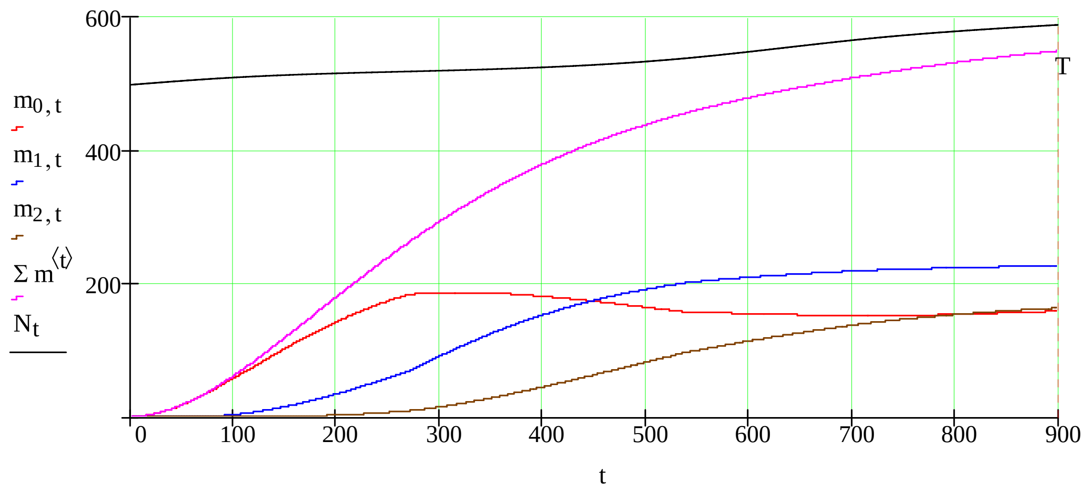
$$\begin{pmatrix} -\ln(1 - P_{0,0}) \\ -\ln(1 - P_{0,1}) \\ .... \\ -\ln(1 - P_{0,T-1}) \end{pmatrix} = \begin{bmatrix} A_0 & M_{1,0} \cdot (N_0)^{-1} & m_{0,0} \cdot (N_0)^{-1} \\ A_1 & M_{1,1} \cdot (N_1)^{-1} & m_{0,1} \cdot (N_1)^{-1} \\ .... & .... & .... \\ A_{T-1} & M_{1,T-1} \cdot (N_{T-1})^{-1} & m_{0,T-1} \cdot (N_{T-1})^{-1} \end{bmatrix} \cdot \begin{pmatrix} a_0 \\ b_0 \\ c_0 \end{pmatrix} \quad (4')$$

$$\begin{pmatrix} -\ln(1 - P_{i,0}) \\ -\ln(1 - P_{i,1}) \\ .... \\ -\ln(1 - P_{i,T-1}) \end{pmatrix} = \begin{bmatrix} A_0 & B_0 & C_0 \cdot M_{1,0} \cdot (M_{0,0})^{-1} \\ A_1 & B_1 & C_1 \cdot M_{1,1} \cdot (M_{0,1})^{-1} \\ .... & .... & .... \\ A_{T-1} & B_{T-1} & C_{T-1} \cdot M_{1,T-1} \cdot (M_{0,T-1})^{-1} \end{bmatrix} \cdot \begin{pmatrix} a_i \\ b_i \\ c_i \end{pmatrix} \quad (5')$$

9. Cumulation of purchases and customers (examples)

ASSUMPTION:
one item / purchase

 # informed at the start (t = 0) $m_{0,0} := 1$ $(m_{0,0} > 0)$



N_t Population (black)
$m_{0,t}$ The number of those who know but have not bought by time t (**red**)
$m_{i,t}$ The number of those who have bought *exactly* i items by time t (**blue**, **brown**, ...)
$\Sigma\, m^{\langle t \rangle}$ The number of those who knows by time t (= $M_{0,t}$) (**lila**)

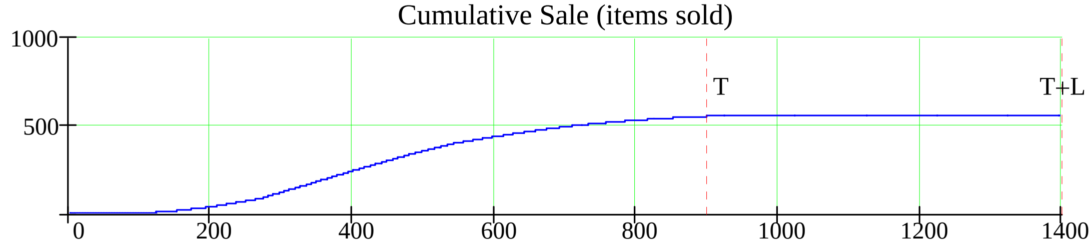
m =

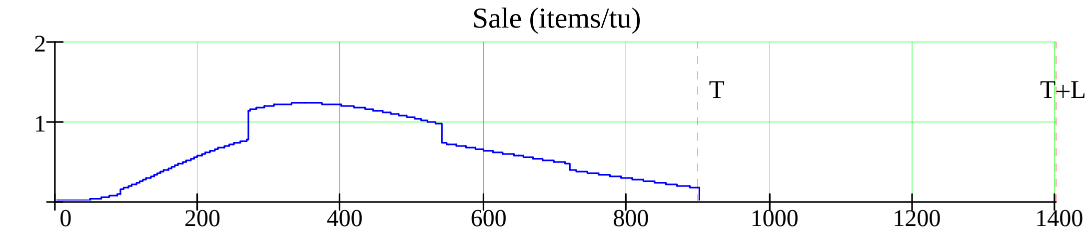
	0	1	2	3	4	5	6	7	8	
0	1	1.017	1.049	1.096	1.158	1.236	1.329	1.437	1.56	
1	0	$3.908\cdot10^{-5}$	$1.1\cdot10^{-4}$	$2.145\cdot10^{-4}$	$3.565\cdot10^{-4}$	$5.406\cdot10^{-4}$	$7.734\cdot10^{-4}$	$1.062\cdot10^{-3}$	$1.415\cdot10^{-3}$	1
2	0	0	$1.386\cdot10^{-9}$	$6.999\cdot10^{-9}$	$2.128\cdot10^{-8}$	$5.046\cdot10^{-8}$	$1.03\cdot10^{-7}$	$1.898\cdot10^{-7}$	$3.248\cdot10^{-7}$	5
3										

10. Cost accounting (examples)

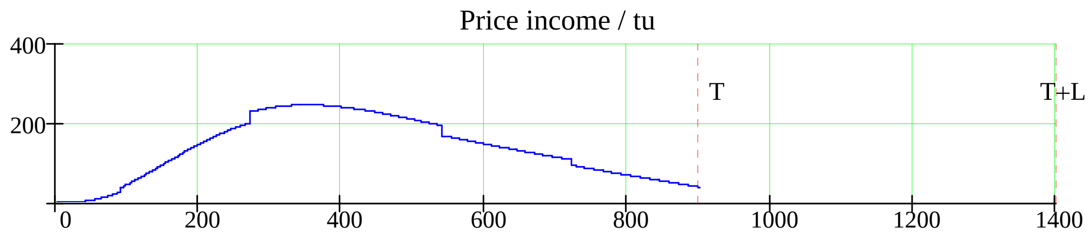
$t = 0 \ldots T + L = 1400$

Cumulative Sale (items sold)

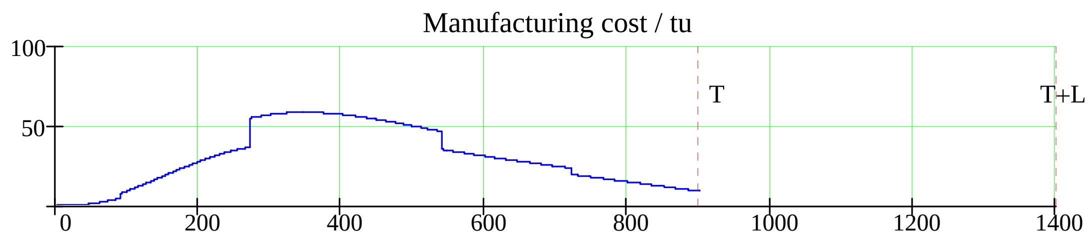




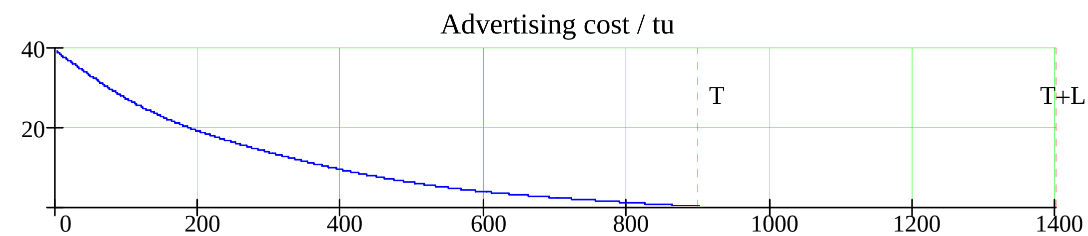
Sale (items/tu)
2
1
T
T+L
0
200
400
600
800
1000
1200
1400



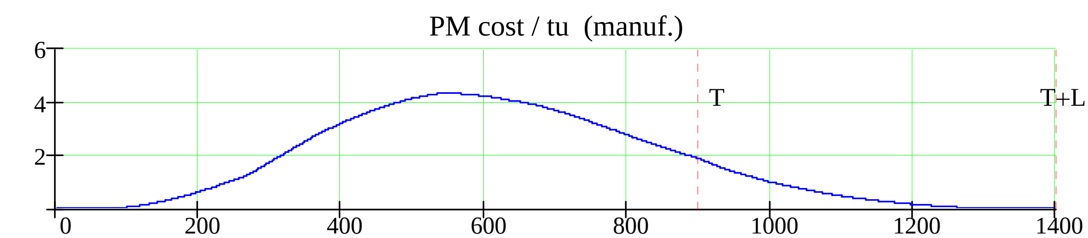
Price income / tu
400
200
T
T+L
0
200
400
600
800
1000
1200
1400



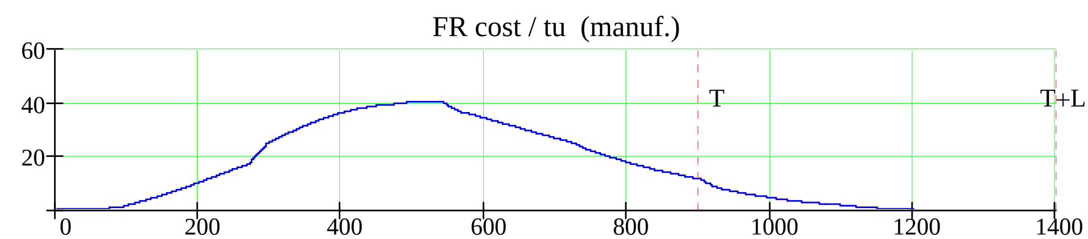
Manufacturing cost / tu
100
50
T
T+L
0
200
400
600
800
1000
1200
1400



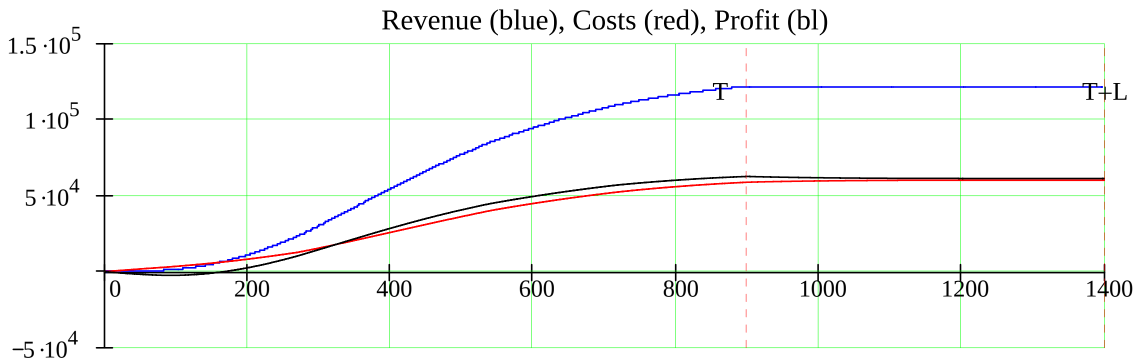
Advertising cost / tu
40
20
T
T+L
0
200
400
600
800
1000
1200
1400

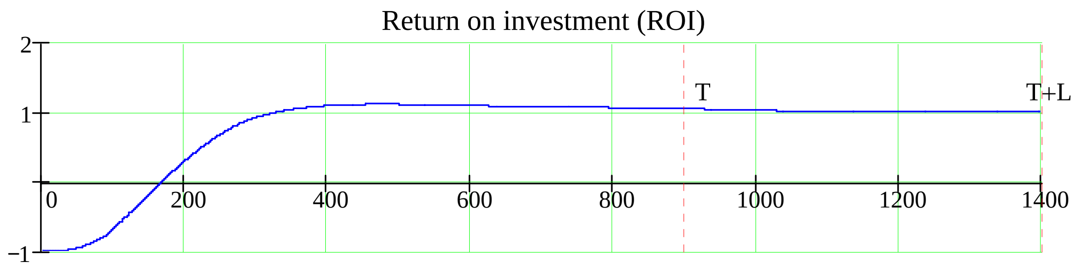


PM cost / tu (manuf.)
6
4
2
T
T+L
0
200
400
600
800
1000
1200
1400



FR cost / tu (manuf.)
60
40
20
T
T+L
0
200
400
600
800
1000
1200
1400





Final Rev_{T+L} = 121548.54   Final $Profit_{T+L}$ = 61359.44   min(Profit) = −2414.14

Final $ToCo_{T+L}$ = 60189.09   Final ROI_{T+L} = 1.019   max(Profit) = 62673.72

Average price Pr_{av} = 219.117   (interval 0... T = 900)

Customer's LCC LCC_c = 359.069   (no maintenance service contract)

Manufacturer's. LCC LCC_m = 108.503   (no maintenance service contract)

Diffusion Model II

Comments: Per-Erik.Hagmark@tut.fi

Tämä on yhden tuotteen metamalli, jossa suureiden muuttuminen lasketaan diffuusioperiaatteella sekä tuoteyksilön elinaikana että markkinajakson aikana. Malli muistuttaa edellistä (Diffusion Model I), mutta on tarkempi ja laajempi.

Määritellään edelleen *eri vikatyyppien* esiintymistä ja niiden aiheuttamat kustannukset (FR), *ennakko-huollon* kustannukset (PM), t*akuusopimus ja huoltosopimus*, *populaatio*, satsaus *mainostamiseen*, todellinen ja odotettu *myyntihinta*, *asiakastyytyväisyys* liittyen hintaan ja vikoihin, ym. sekä näiden mahdollinen aikariippuvuus. Perusmalleja on paikoittain kehitetty syötön ja/tai matemaattisen käsittelyn osalta oleellisesti.

Kokonaan uusia elementtejä ovat esimerkiksi *uudelleenoston ja asiakkuudesta luopumisen* tarkka mallinnus, asiakkaan *oman kokemuksen ja kilpailevien valmistajien* vaikutus myyntiin, sekä *epäkäytettävyyden* vaikutus tyytyväisyyteen.

Rakennetaan ostojen *ajasta riippuvat* "todennäköisyydet" ottaen myös humioon kuinka mones osto on kyseessä. Säätöparametrit ja rinnakkaiset differenssiyhtälöt ohjaavat *markkinatilan ajallista muuttumista*, eli erilaisten asiakaslukumäärien kehittymistä (potentiaaliset ostajat, kerran ostaneet, kaksikertaa ostaneet, jne.).

Lopuksi *kustannuslaskentaa*. Diffuusion tuottamasta perusdatasta malli laskee kustannusten, tulojen, profiittien ym. ajallista kehittymistä markkinajaksolla.

Syötöt keltaisella!

1. Product's failure tendency (item)

Essential lifetime of an item *(tu)* $L := 220$

The average number $v_{c,f}$ **of f-failures during the interval** $0...x_c$.

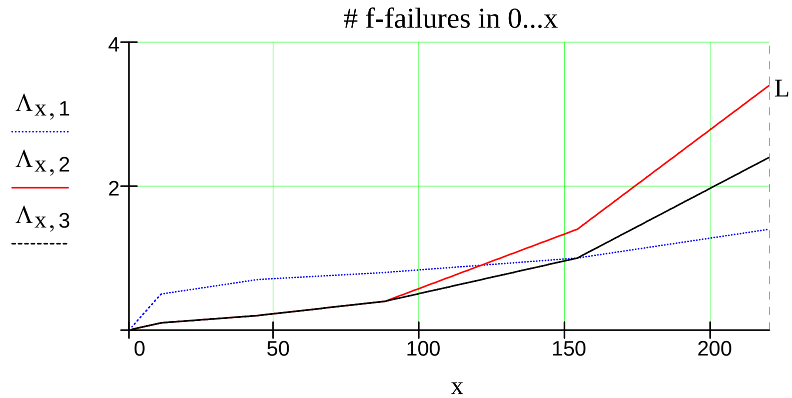
f=1, f=2, f=3

$$\begin{pmatrix} x_1 & x_2 & x_3 & x_4 & x_5 \\ v_{1,1} & v_{2,1} & v_{3,1} & v_{4,1} & v_{5,1} \\ v_{1,2} & v_{2,2} & v_{3,2} & v_{4,2} & v_{5,2} \\ v_{1,3} & v_{2,3} & v_{3,3} & v_{4,3} & v_{5,3} \end{pmatrix} := \begin{pmatrix} 0.05 \cdot L & 0.2 \cdot L & 0.4 \cdot L & 0.7 \cdot L & L \\ 0.5 & 0.7 & 0.8 & 1 & 1.4 \\ 0.1 & 0.2 & 0.4 & 1.4 & 3.4 \\ 0.1 & 0.2 & 0.4 & 1 & 2.4 \end{pmatrix}$$

Failure types: f = 1,2,3
Vikatyypit ovat täysin vapaasti määriteltävissä.

Failure tendencies $\Lambda_{x,f}$

i.e. # f-failures /item 0...x
(f = 1, 2, 3)



2. Costs and the warranty contract (item)

Every product support cost (to be considered) must be placed in one of the following four classes:

Preventive maintenance (PM) costs C_0 *euro /tu* (f = 0)

Failure related (FR) costs C_f *euro /f-failure* (f = 1,2,3, §1)

for subintervals $(\alpha, \beta] = (0, V_f\,], (V_f, W_f]$ and $(W_f\,, L]$, respectively.
In each subinterval, manufacturer's **warranty fraction** varies from p_f to q_f:

$$C_f \cdot \left[p_f + (q_f - p_f) \cdot \left(\frac{x - \alpha}{\beta - \alpha} \right) \right] \quad x \in (\alpha, \beta] \quad f = 0, 1, 2, 3.$$

Costs in 0...V	$C1_0$	$C1_1$	$C1_2$	$C1_3$		0.18	50	50	50
End point V	V_0	V_1	V_2	V_3		0.3·L	0.3·L	0.4·L	0.4·L
Fraction at 0+	pV_0	pV_1	pV_2	pV_3		0.3	0.8	0.8	0.8
Fraction at V	qV_0	qV_1	qV_2	qV_3		0.2	0.8	0.8	0.8
Costs in V...W	$C2_0$	$C2_1$	$C2_2$	$C2_3$		0.18	40	40	40
End point W	W_0	W_1	W_2	W_3	:=	0.6·L	0.6·L	0.6·L	0.7·L
Fraction at V+	pW_0	pW_1	pW_2	pW_3		0.2	0.8	0.6	0.6
Fraction at W	qW_0	qW_1	qW_2	qW_3		0.1	0.5	0.2	0.2
Costs in W...L	$C3_0$	$C3_1$	$C3_2$	$C3_3$		0.15	50	50	50
Fraction at W+	pL_0	pL_1	pL_2	pL_3		0	0	0	0
Fraction at L	qL_0	qL_1	qL_2	qL_3		0	0	0	0
	f=0	f=1	f=2	f=3					

Examples

pV = qV = 1 *FRW*-warranty on 0...V with manufacturer's full responsibility

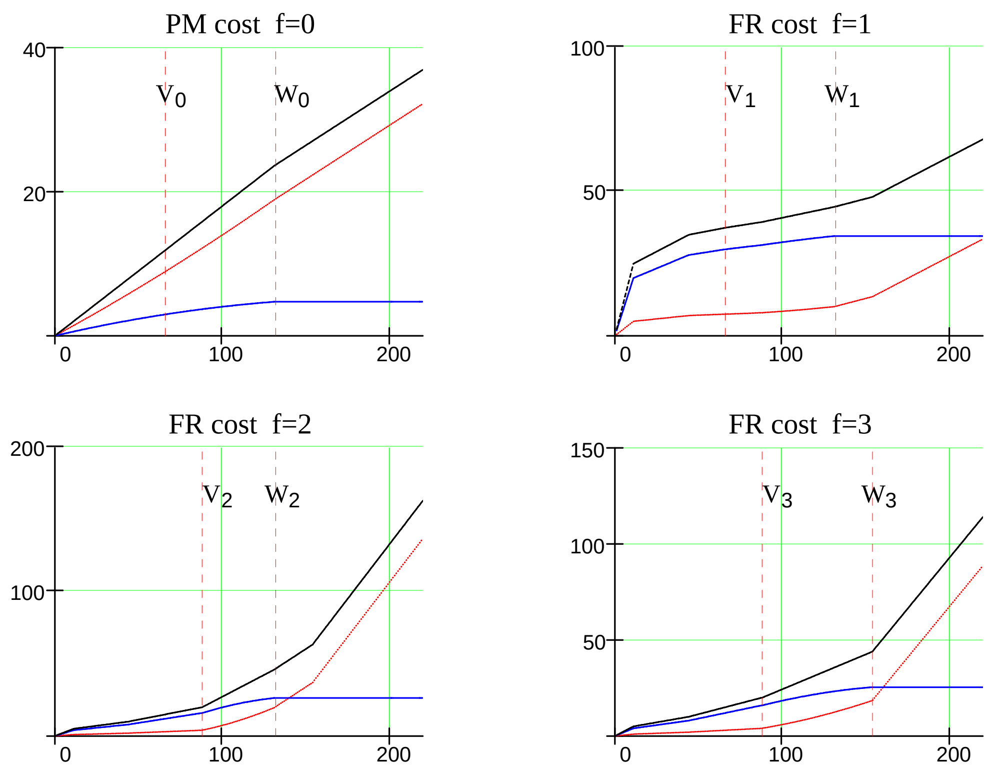
pV = qV < 1 *FRW*-warranty on 0...V with manufacturer's partial responsibility

pW ≠ qW *PRW*-warranty on V ..W, manufacturer's time dependent responsibility

<u>3. Cumulative costs and maintenance service contract</u> (item)

Cumulative PM and FR costs /item during 0...L

(manufacturer's cost = solid, customer's cost = dot, total = dash)



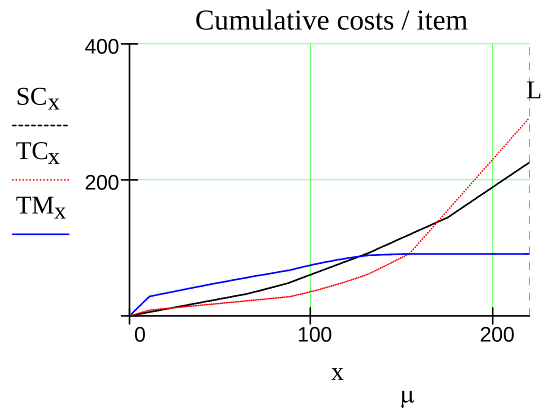
The customer pays FR costs during warranty periods 0...W_f : FaiReal = 49.321 (totally).

Maintenance Service Contract. The costs not covered by warranty (dot curves above) can be managed by a separately bought. The customer pays MS_c /tu from x_c tu .

$$\begin{pmatrix} x_0 & x_1 & x_2 & x_3 & x_4 \\ MS_0 & MS_1 & MS_2 & MS_3 & MS_4 \end{pmatrix} := \begin{pmatrix} 0 & 0.3\cdot L & 0.4\cdot L & 0.6\cdot L & 0.8\cdot L \\ 0.5 & 0.7 & 1.0 & 1.2 & 1.8 \end{pmatrix}$$

Cumulative costs (PM + FR)

SC	customer's cost *with* MSC
TC	customer's cost *without* MSC
TM	manufacturer's costs (warranty)



4. Satisfaction from average item

Interval	$0 \ldots V_f$	$V_f \ldots W_f$	$W_f \ldots L$	
Unavailability time in interval	$R_{1,f}$	$R_{2,f}$	$R_{3,f}$	f = 0, 1, 2, 3
Tolerated unavailability time	$T_{1,f}$	$T_{2,f}$	$T_{3,f}$	f = 0, 1, 2, 3
Dissatisfaction if $R = 2 \cdot T$	$D_{1,f}$	$D_{2,f}$	$D_{3,f}$	f = 0, 1, 2, 3
Tolerated # failures (average > 0)	$t_{1,f}$	$t_{2,f}$	$t_{3,f}$	f = 1, 2, 3
Dissatisfaction if # failures = $2 \cdot t$	$d_{1,f}$	$d_{2,f}$	$d_{3,f}$	f = 1, 2, 3

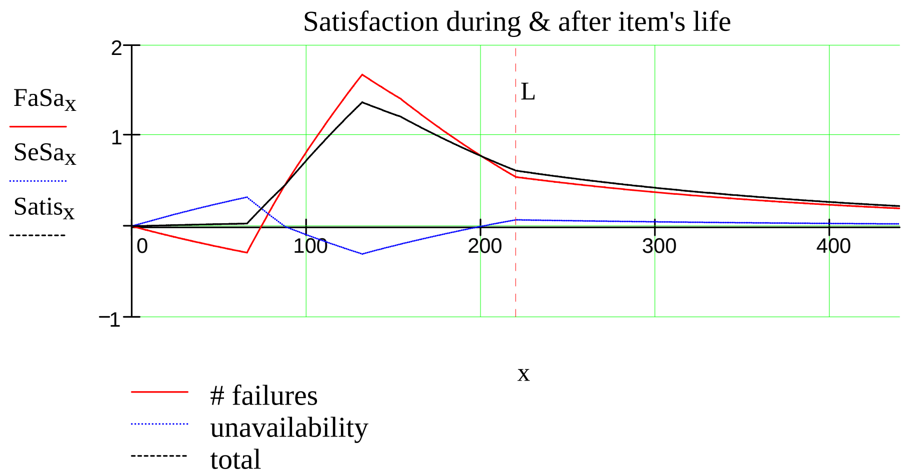
$0 \ldots V_0$	$V_0 = 66$
$V_0 \ldots W_0$	$W_0 - V_0 = 66$
$W_0 \ldots L$	$L - W_0 = 88$

$$\begin{pmatrix} R_{1,0} & T_{1,0} & D_{1,0} \\ R_{2,0} & T_{2,0} & D_{2,0} \\ R_{3,0} & T_{3,0} & D_{3,0} \end{pmatrix} := \begin{pmatrix} 5 & 7 & 1 \\ 10 & 5 & 1 \\ 7 & 7 & 1 \end{pmatrix}$$

$0 \ldots V_1$	$V_1 = 66$
$0 \ldots V_2$	$V_2 = 88$
$0 \ldots V_3$	$V_3 = 88$
$V_1 \ldots W_1$	$W_1 - V_1 = 66$
$V_2 \ldots W_2$	$W_2 - V_2 = 44$
$V_3 \ldots W_3$	$W_3 - V_3 = 66$
$W_1 \ldots L$	$L - W_1 = 88$
$W_2 \ldots L$	$L - W_2 = 88$
$W_3 \ldots L$	$L - W_3 = 66$

$$\begin{pmatrix} R_{1,1} & T_{1,1} & D_{1,1} & t_{1,1} & d_{1,1} \\ R_{1,2} & T_{1,2} & D_{1,2} & t_{1,2} & d_{1,2} \\ R_{1,3} & T_{1,3} & D_{1,3} & t_{1,3} & d_{1,3} \\ R_{2,1} & T_{2,1} & D_{2,1} & t_{2,1} & d_{2,1} \\ R_{2,2} & T_{2,2} & D_{2,2} & t_{2,2} & d_{2,2} \\ R_{2,3} & T_{2,3} & D_{2,3} & t_{2,3} & d_{2,3} \\ R_{3,1} & T_{3,1} & D_{3,1} & t_{3,1} & d_{3,1} \\ R_{3,2} & T_{3,2} & D_{3,2} & t_{3,2} & d_{3,2} \\ R_{3,3} & T_{3,3} & D_{3,3} & t_{3,3} & d_{3,3} \end{pmatrix} := \begin{pmatrix} 5 & 7 & 1 & 0.3 & 1.5 \\ 5 & 5 & 1 & 0.5 & 1 \\ 7 & 5 & 2 & 0.5 & 2 \\ 9 & 9 & 1 & 0.5 & 1 \\ 6 & 6 & 1 & 1 & 1 \\ 10 & 10 & 2 & 0.5 & 2 \\ 5 & 5 & 0.5 & 1 & 0.5 \\ 3 & 5 & 0.5 & 1 & 1 \\ 5 & 5 & 0.5 & 1 & 2 \end{pmatrix}$$

Halfing time for disappointment $HaDi := 150$ (Disappointment decreases with time.)



5. Repeat purchases and lost customers

i-customer = potential or non-lost customer that has bought exactly i times $(i \geq 0)$.

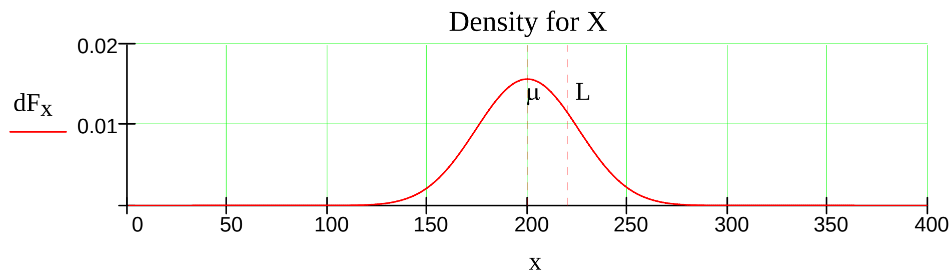
Decision. Let X *(tu)* denote *the age of a bought item* when the customer in question makes the following decision: He/she

EITHER (a) buys for the i-th time (i.e. becomes an i-customer)

OR (b) gives up the customership (i.e. becomes a lost i-1-customer)

Average for X *(tu)* $\mu := 200$

Deviation for X *(tu)* $\sigma := 25$ $(\sigma < \mu)$



Average satisfaction (§4) at the moment of decision

$$Own := \sum_x Satis_x \cdot dF_x \qquad Own = 0.8$$

Fractions for alternatives (a) or (b) (will be defined in §8). If an i-1-customer bought his/her i-1-th item during $(t-1, t]$, then he/she will make the decision during $(t+X-1, t+X]$. The corresponding "probabilities" (fractions) are $P_{i,t+X-1}$ for (a), and $1 - P_{i,t+X-1}$ for (b).

6. Input for market period

Market period (*tu* = time unit) T := 900 t = 0, 1,...T

Advertising effort at $t = \tau_s$ Ad_s *euro/tu*, media & specific

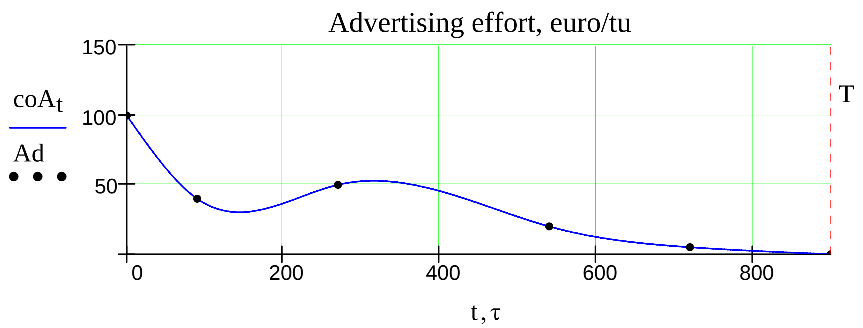
Number of competitors Co_s selling a similar product

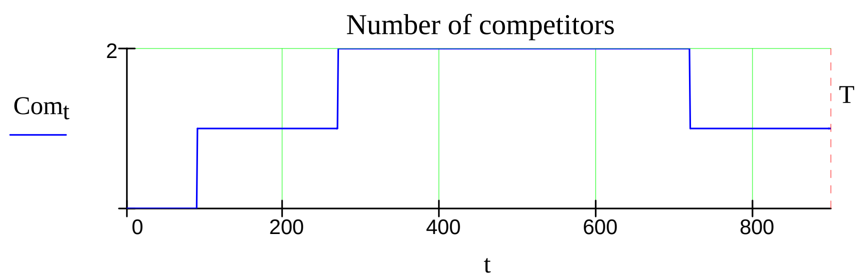
Real sale price */item* Pm_s

Expected sale price */item* Pc_s

The %-difference between Pm and Pc during 0...T provides a relative measure for price satisfaction. => §7

$$\begin{pmatrix} \tau_0 & \tau_1 & \tau_2 & \tau_3 & \tau_4 & \tau_5 \\ Ad_0 & Ad_1 & Ad_2 & Ad_3 & Ad_4 & Ad_5 \\ Co_0 & Co_1 & Co_2 & Co_3 & Co_4 & Co_5 \\ Pm_0 & Pm_1 & Pm_2 & Pm_3 & Pm_4 & Pm_5 \\ Pc_0 & Pc_1 & Pc_2 & Pc_3 & Pc_4 & Pc_5 \end{pmatrix} := \begin{pmatrix} 0 & 0.1 \cdot T & 0.3 \cdot T & 0.6 \cdot T & 0.8 \cdot T & T \\ 100 & 40 & 50 & 20 & 5 & 0 \\ 0 & 1 & 2 & 2 & 1 & 1 \\ 300 & 260 & 200 & 230 & 240 & 230 \\ 300 & 270 & 240 & 220 & 220 & 220 \end{pmatrix}$$

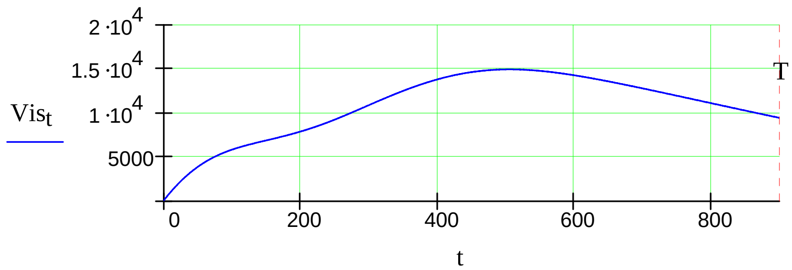




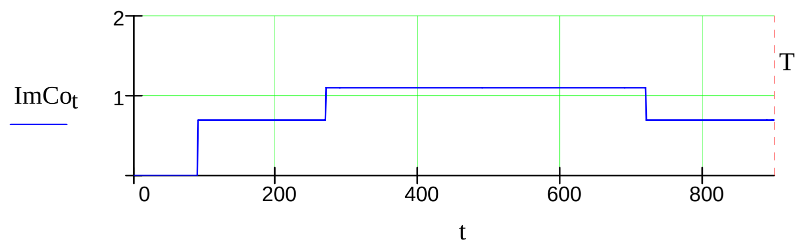
7. Profiles for market period

Halfing time for effect of advertising effort: HaAd := 400

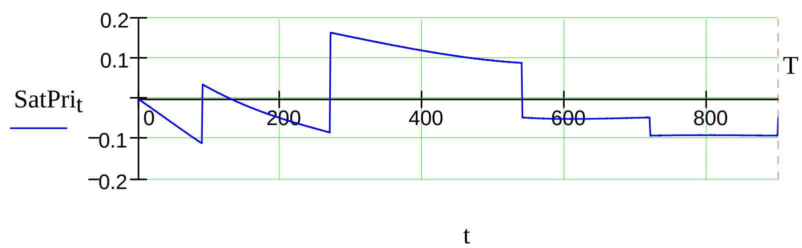
Impact of advertising.
(From Ad, §6.)



Impact of competitors.
(From Co, §6.)



Satisfaction with purchase price.
(From Pm & Pc §6.)



General satisfaction with failures and unavailability at t

$$SatPro_t = \frac{1}{Q_{t-1}} \cdot \sum_{s=1}^{t-1} dQ_s \cdot Satis_{t-s}$$

Satis was defined in §4.
SatPro will be computed in §9.
(Q_t = #purchases 0...t, §5)

8. Purchase fractions and the structure of diffusion

Adjustment parameters $(\alpha_i, \beta_i, \gamma_i, \delta_i, \varepsilon_i)$ for a customer's *i^{th} purchase* $(i = 1,2,3,4,5,6)$

Advertising
Competitors effect
Sale price satisfaction
WOM (fail. & unavail.)
Own experience

$$\begin{pmatrix} \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & \alpha_6 \\ \beta_1 & \beta_2 & \beta_3 & \beta_4 & \beta_5 & \beta_6 \\ \gamma_1 & \gamma_2 & \gamma_3 & \gamma_4 & \gamma_5 & \gamma_6 \\ \delta_1 & \delta_2 & \delta_3 & \delta_4 & \delta_5 & \delta_6 \\ \varepsilon_1 & \varepsilon_2 & \varepsilon_3 & \varepsilon_4 & \varepsilon_5 & \varepsilon_6 \end{pmatrix} := \begin{pmatrix} 0.4\cdot10^{-5} & 0.4\cdot10^{-5} & 0.4\cdot10^{-5} & 0 & 0 & 0 \\ 0.05 & 0.05 & 0.05 & 0.05 & 0.05 & 0.05 \\ 0.2 & 0.2 & 0.2 & 0.2 & 0.2 & 0.2 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.2 & 0 \\ 0 & 0.5 & 1 & 1.5 & 2 & 2 \end{pmatrix}$$

$P_{i,t}$ = the fraction of i-1-customers that buys during (t, t+1]

$$P_{i,t} = 1 - e^{-\left(\alpha_i \cdot Vis_t - \beta_i \cdot ImCo_t + \gamma_i \cdot SatPri_t + \delta_i \cdot SatPro_t \cdot \frac{M_{i,t}}{M_{i,t} + N_t} + \varepsilon_i \cdot Own\right)} \qquad (1)$$

Vis_t is the advertising profile (§7). The parameter $\alpha_i \geq 0$ adjusts the contribution to $P_{i,t}$

$ImCo_t$ is the profile for competitors' impact (§7). The parameter $\beta_i \geq 0$ adjusts the contribution to $P_{i,t}$

$SatPri_t$ is the satisfaction profile for sale price (§7). The parameter $\gamma_i \geq 0$ levels the contribution.

$SatPro_t$ is the satisfaction for failures and unavailability (§4, §7). A positive/negative $SatPro_t$ corresponds to a pos./neg. WOM-effect. The impact is also proportional to the ratio $M_{i,t}/(M_{0,t}+N_t)$, i.e. depends on big part the potential has actually bought. The parameter $\delta_i \geq 0$ levels the contribution.

Own = tyytyväisyys mahdollisen uudelleenoston hetkellä (§4, §7). The parameter $\varepsilon_i \geq 0$ levels the contribution. ($Own = 0.8$)

A matrix version of (1)

$$\begin{pmatrix} -\ln(1 - P_{i,0}) \\ -\ln(1 - P_{i,1}) \\ \cdots \\ -\ln(1 - P_{i,T-1}) \end{pmatrix} = \begin{pmatrix} Vis_0 & ImCo_0 & SatPri_0 & \frac{SatPro_0 \cdot M_{i,0}}{M_{i,0} + N_0} & Own \\ Vis_1 & ImCo_1 & SatPri_1 & \frac{SatPro_1 \cdot M_{i,1}}{M_{i,1} + N_1} & Own \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Vis_{T-1} & ImCo_{T-1} & SatPri_{T-1} & \frac{SatPro_{T-1} \cdot M_{i,T-1}}{M_{i,T-1} + N_{T-1}} & Own \end{pmatrix} \cdot \begin{pmatrix} \alpha_i \\ \beta_i \\ \gamma_i \\ \delta_i \\ \varepsilon_i \end{pmatrix} \qquad (1')$$

Some variables for the market period

N_t # 0-customers at time moment t = 0, 1, ... T, market period

$dM_{i,t}$ # those who buy for the i^{th} time (i.e. # i^{th} purchases) during (t-1, t], $i \geq 1$

$M_{i,t}$ # those who have bought at least i times (i.e. # i^{th} purchases) during (0, t]

$G_{i,t}$ # i-1-customers who became lost during (0, t].

$D_{i,t}$ # i-1-customers who make the *decision* (below) during (t-1, t].

$P_{i,t-1}$ fraction for i-1-customers' decision during (t-1, t].

dQ_t # purchases during (t-1, t]

Q_t # purchases during (0, t]

Simple relations

$N_t = N_{t-1} - dM_{1,t} \qquad M_{i,0} = dM_{i,0} = 0 \qquad (i \geq 1)$

$$dQ_t = \sum_{i=1}^{\infty} dM_{i,t} \qquad Q_t = \sum_{s=1}^{t} dQ_s \qquad M_{i,t} = \sum_{s=1}^{t} dM_{i,s}$$

Main structure of diffusion

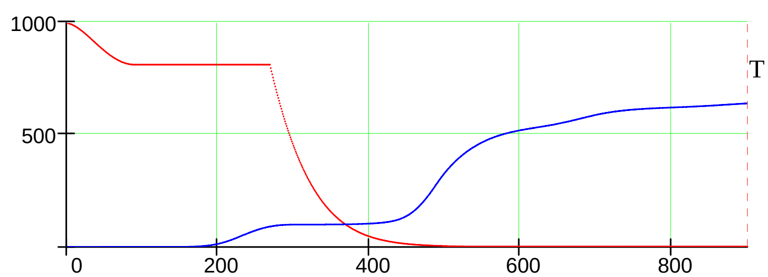
for $t \in 1,2,....$ — **Time instant t in the market period**

- $P_{1,t-1} \leftarrow \text{Formula}(1)$ — First purchase probability (i = 1)
- $dM_{1,t} \leftarrow N_{t-1} \cdot P_{1,t-1}$ — # those who buy during (t-1, t]
- $M_{1,t} \leftarrow M_{1,t-1} + dM_{1,t}$ — # those who have bought during (0, t]
- $N_t \leftarrow N_{t-1} - dM_{1,t}$ — # 0-customers at t
- for $i \in 2,3,....$ — **Repeat purchases**, i = 2, 3, ...
  - $P_{i,t-1} \leftarrow \text{Formula}(1)$ — i^{th} purchase probability
  - for $x \in 1,2,....$ — **Age x when decision** (see §5)
    - $D_{i,t+x} \leftarrow D_{i,t+x} + dM_{i-1,t} \cdot dF_x$ — $D_{i,t+x}$ = # those i-1-customers who decide in (t+x-1, t+x] (§5)
  - Next x
  - $G_{i-1,t} \leftarrow G_{i-1,t-1} + D_{i,t} \cdot (1 - P_{i,t-1})$ — # lost i-1-customers (cumulated)
  - $dM_{i,t} \leftarrow D_{i,t} \cdot P_{i,t-1}$ — # those who buy during (t-1, t]
  - $M_{i,t} \leftarrow M_{i,t-1} + dM_{i,t}$ — # those who have bought at least i times
- Next i

Next t

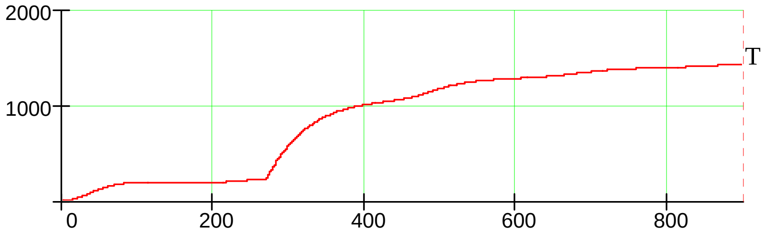
9. Cumulation of purchases and customers (examples)

0-customers at the start (t = 0): $N_0 := 1000$



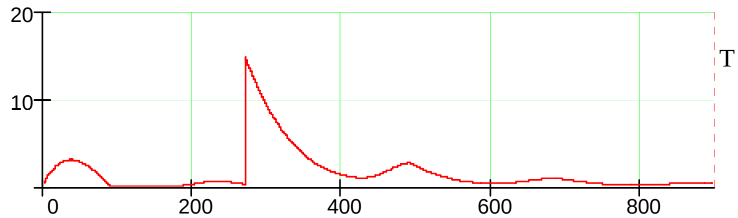
0-customers (dot) $N_T = 1.57$

Lost (solid) $\text{Lost}_T = 640.8$

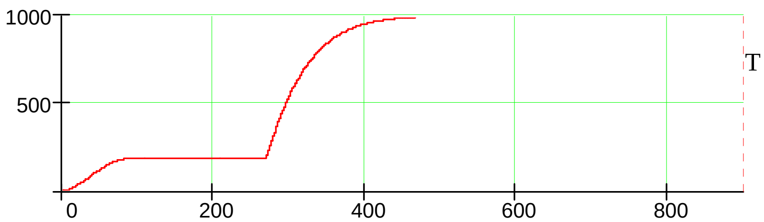


Purchases cumulated

$Q_T = 1432.53$

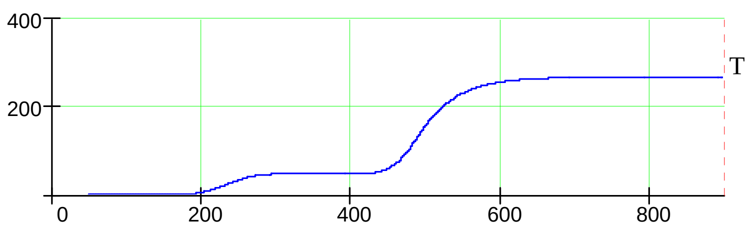


Purchases /tu



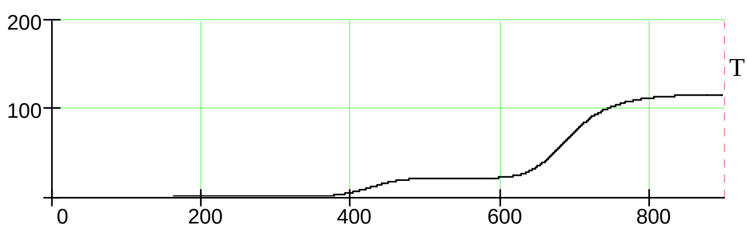
First purchases (i=1)

$M_{1,T} = 998.43$



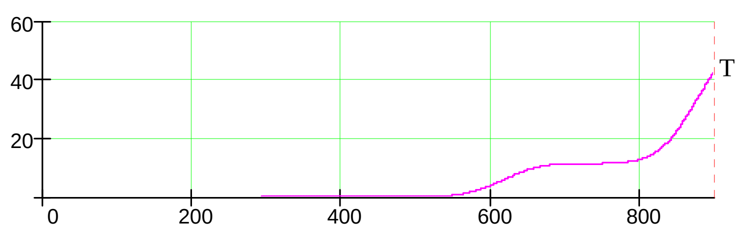
Second purchases (i=2)

$M_{2,T} = 267.29$



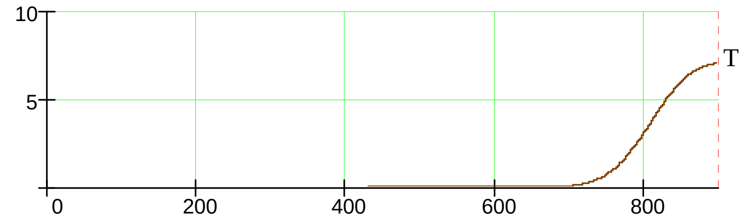
Third purchases (i=3)

$M_{3,T} = 116.03$



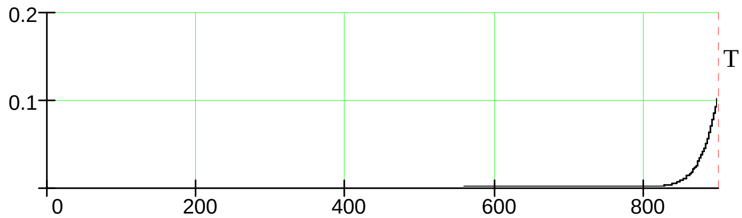
Fourth purchases (i=4)

$M_{4,T} = 43.61$



Fifth purchases (i=5)

$M_{5,T} = 7.06$



Sixth purchases (i=6)

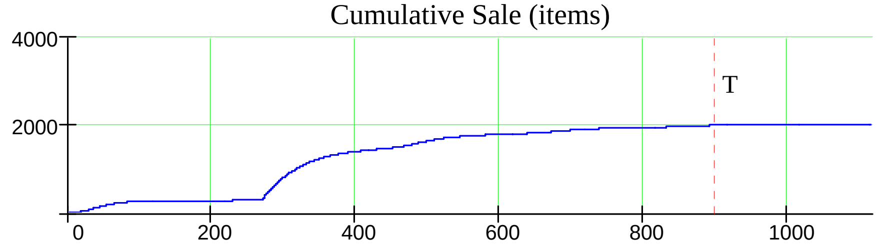
$M_{6,T} = 0.12$

10. Cost accounting (examples)

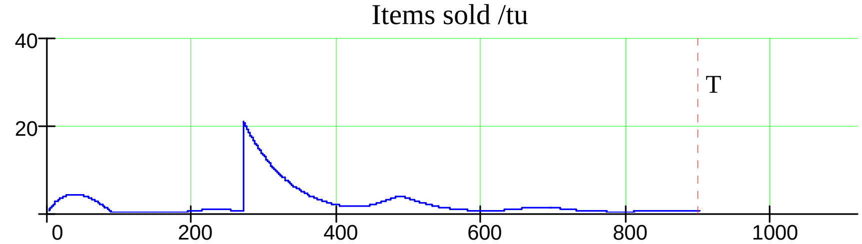
Average # items /purchase $k := 1.4$

$t = 0 \ldots T + L = 1120$

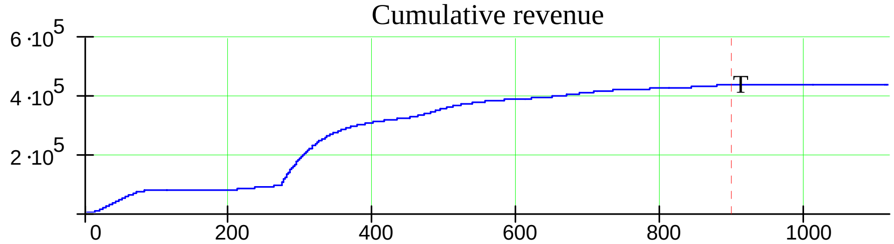
Cumulative Sale (items)



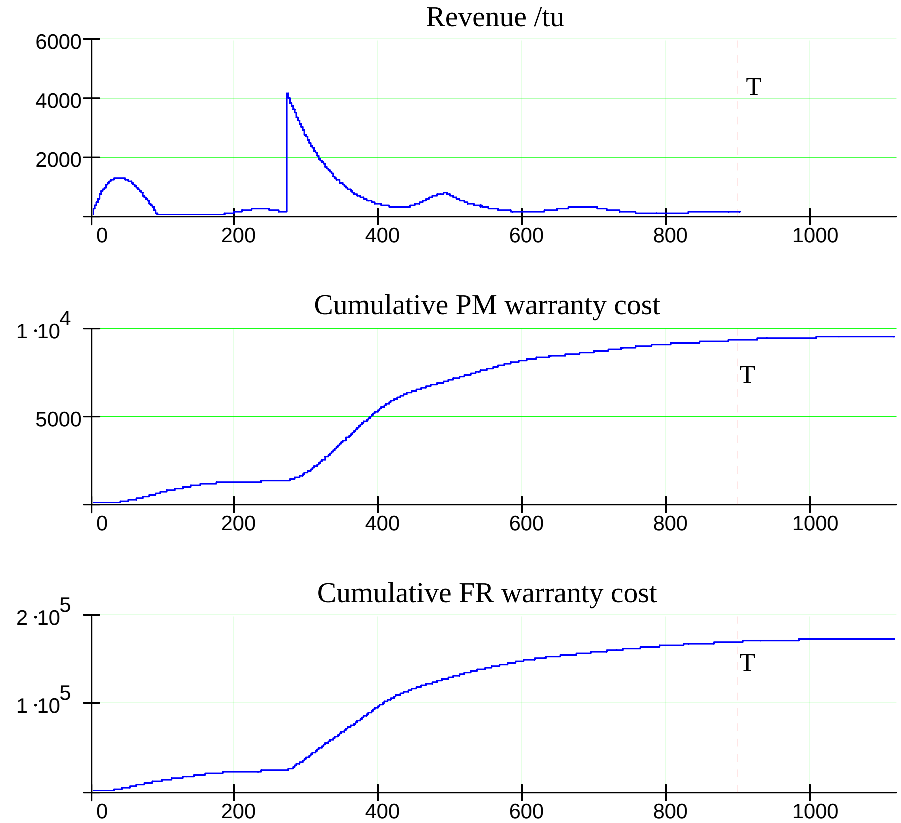
Items sold /tu



Cumulative revenue



MSC ei mukana



MSC ei mukana

Average sale price $Pr_{av} = 219.178$ during interval $0...T = 900$

Customer's LCC $LCC_c = 510.632$ if no maintenance service contract

Final Revenue $Rev_{T+L} = 439570.81$

Etc., etc.

SOME OUTPUTS

$Lost^T =$

	0	1	2	3	4	5	6
0	0	0	0	0	0	0	0

$N^T =$

	0	1	2	3	4	5	6	7	8	9	10	11
0	$1\cdot10^{3}$	999.4	998.7	997.9	996.8	995.7	994.4	993	991.5	989.9	988.1	986.3

G =

	893	894	895	896	897	898	899	900
0	0	0	0	0	0	0	0	0
1	523.219	523.219	523.219	523.219	523.219	523.219	523.219	523.219
2	95.217	95.225	95.232	95.239	95.246	95.253	95.26	95.266
3	19.077	19.265	19.451	19.636	19.819	20	20.179	20.355
4	1.895	1.897	1.898	1.9	1.902	1.904	1.905	1.907
5	0.023	0.024	0.025	0.026	0.027	0.029	0.03	0.031
6	0	0	0	0	0	0	0	0

M =

	283	284	285	286	287	288
0	0	0	0	0	0	0
1	371.030327	382.774834	394.340486	405.723317	416.922948	427.954768
2	46.308929	46.454668	46.589875	46.7149	46.8301	46.935867
3	0.00086	0.000971	0.001094	0.001232	0.001385	0.001557
4	0	$1.065575\cdot10^{-15}$	$1.355909\cdot10^{-15}$	$1.723129\cdot10^{-15}$	$2.187011\cdot10^{-15}$	$2.772271\cdot10^{-15}$
5	0	0	0	0	0	0
6	0	0	0	0	0	0

dM =

	284	285	286	287	288	289	290	291
0	0	0	0	0	0	0	0	0
1	11.745	11.566	11.383	11.2	11.032	10.851	10.682	10.51
2	0.146	0.135	0.125	0.115	0.106	0.097	0.088	0.08
3	$1.103\cdot10^{-4}$	$1.233\cdot10^{-4}$	$1.378\cdot10^{-4}$	$1.538\cdot10^{-4}$	$1.714\cdot10^{-4}$	$1.91\cdot10^{-4}$	$2.125\cdot10^{-4}$	$2.363\cdot10^{-4}$
4	0	0	0	0	0	0	0	$1.167\cdot10^{-15}$
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0

P =

	0	1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0	0	0
1	0	$5.691\cdot10^{-4}$	$7.16\cdot10^{-4}$	$8.657\cdot10^{-4}$	$1.007\cdot10^{-3}$	$1.149\cdot10^{-3}$	$1.283\cdot10^{-3}$	$1.413\cdot10^{-3}$	$1.533\cdot10^{-3}$
2	0	0.33	0.33	0.33	0.33	0.331	0.331	0.331	0.331
3	0	0.551	0.551	0.551	0.551	0.551	0.551	0.551	0.552
4	0	0.699	0.699	0.699	0.699	0.699	0.699	0.698	0.698
5	0	0.798	0.798	0.798	0.798	0.798	0.798	0.798	0.798
6	0	0.798	0.798	0.798	0.798	0.798	0.798	0.798	0.798

Data Analysis (eräs apuohjelma)

Lukumäärädatasta vikajakaumaan

Comments:
Per-Erik.Hagmark@tut.fi

Syötöt keltaisella!

Taustaoletukset

- Tarkasteltavat *laitteet* ovat samanlaisia ja toisistaan riippumattomia vikaantumisen suhteen.
- Kun laite vikaantuu, se *palautetaan* uudenveroiseksi (tavalla tai toisella).
- Laitteet voivat muodostaa *ryhmiä*, myös erikokoisia. (Tietty asiakas, yhtäaikaa myydyt, etc.)
- Saman ryhmän laitteiden *käyntiaika* kumuloituu suurin piirtein samaan tahtiin.

Vikajakauma

Haetaan tuntematonta jakaumaa F(x), missä x on laitteen käyntiaika *palautuksesta vikaan*.
(Jos palautus tarkoittaa uutta laiteyksilöä, niin kyseessä on tietenkin *uuden* laitteen vikajakauma.)

Datatyyppi 1

n_k ryhmän koko eli laitteiden lkm (k = ryhmän numero)
L_k seurattu ryhmää välillä $x = 0...L_k$ (käyntiaikaa)
M_k palautuksien lukumäärä ryhmässä välillä $0...L_k$

$$D^{\langle k\rangle} = \begin{pmatrix} n_k \\ L_k \\ M_k \end{pmatrix} \qquad D := \begin{pmatrix} 4 & 2 & 4 & 3 & 6 & 1 & 1 & 8 \\ 3 & 11 & 5 & 20 & 17 & 9 & 2 & 12 \\ 0 & 3 & 1 & 9 & 12 & 1 & 0 & 10 \end{pmatrix}$$

Vikajakauman keskiarvon ja hajonnan estimaatit (μ, σ)

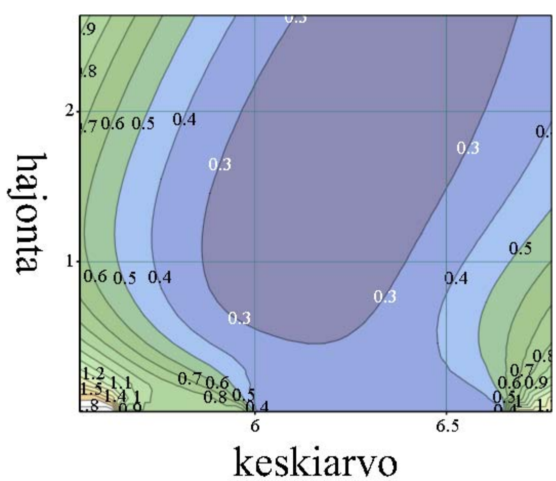
Karkea μ–vihje
$\mu = 8.849$

Alkuarvaus
$(\mu \ \ \sigma) := (8 \ \ 2)$ <= toisto F9

μσ-**kuvion %-rajaus** $\Delta\mu = \pm a \cdot \mu,\ \Delta\sigma = \pm b \cdot \sigma$ $(a \ \ b) := (0.1 \ \ 0.999)$

$$B := \text{CreateMesh}[S, \mu\cdot(1-a), \mu\cdot(1+a), \sigma\cdot(1-b), \sigma\cdot(1+b), 30, 30]$$

Optimi (S ≈ minimi)
$S(\mu, \sigma) = 0.219488$
$$\begin{pmatrix} \mu \\ \sigma \end{pmatrix} = \begin{pmatrix} 6.158605 \\ 1.320881 \end{pmatrix}$$

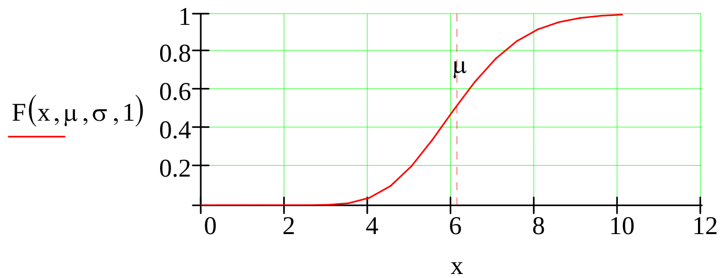


Muuttamalla alkuarvausta tai / ja toistamalla (F9) voi löytyä vielä pienempi S!

Oheinen topografiprojektio antaa tietoa ympäristöstä.

Kuvan siistiminen:
Kaksoisklikkaus ja OK.

Vikajakauman kertymäfunktio F(x) eli TN että käyntiaika vikaan ≤ x

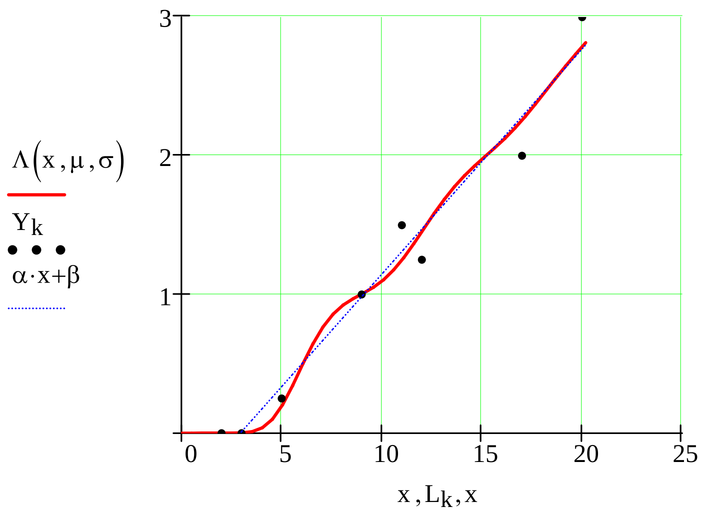


$\mu = 6.159$ keskiarvo

$\sigma = 1.321$ ja -hajonta

Renewal-fkt

Λ(x) = yhden laitteen käyntiaikavälille 0...x sattuvien palautuksien lukumäärän keskiarvo.



Asymptootti $y = \alpha \cdot x + \beta$

$$\alpha = \frac{1}{\mu} \qquad \beta = \frac{1}{2}\cdot\left(\frac{\sigma^2}{\mu^2} - 1\right)$$

$\alpha = 0.162$ $\beta = -0.477$

Yhden laitteen palautuksien lukumäärät käyntiaikaväleillä 0...L

Otoskeskiarvo Y = M/n (ks. syöttötieto). Mallin keskiarvo $y = \Lambda(L)$.

RR =

"Ryhmä"	1	2	3	4	5	6	7	8
"L"	3	11	5	20	17	9	2	12
"M"	0	3	1	9	12	1	0	10
"n"	4	2	4	3	6	1	1	8
"Y"	0	1.5	0.25	3	2	1	0	1.25
"y"	1.75×10^{-3}	1.247	0.193	2.787	2.257	1.003	7.004×10^{-6}	1.452

Datatyyppi 2

n_k	ryhmän koko eli laitteiden lkm (k = ryhmän numero)
A_k, L_k	seurattu ryhmää välillä $x = A_k ... L_k$ (käyntiaikaa)
M_k	palautuksien lukumäärä ryhmässä välillä $A_k ... L_k$

$$D^{\langle k \rangle} = \begin{pmatrix} n_k \\ A_k \\ L_k \\ M_k \end{pmatrix} \qquad D := \begin{pmatrix} 4 & 1 & 4 & 3 & 6 & 8 & 1 & 1 \\ 0 & 3 & 1 & 4 & 3 & 0 & 0 & 0 \\ 3 & 13 & 5 & 20 & 17 & 12 & 9 & 2 \\ 0 & 1 & 1 & 5 & 7 & 10 & 1 & 0 \end{pmatrix}$$

Vikajakauman keskiarvon ja hajonnan estimaatit (μ, σ)

Karkea μ–vihje $\mu = 10.863$

Alkuarvaus $(\mu \;\; \sigma) := (10 \;\; 5)$ <= toisto F9

μσ-kuvion %-rajaus $\Delta\mu = \pm a \cdot \mu$, $\Delta\sigma = \pm b \cdot \sigma$ $\quad (a \;\; b) := (0.05 \;\; 0.15)$

$$B := \text{CreateMesh}[S, \mu\cdot(1-a), \mu\cdot(1+a), \sigma\cdot(1-b), \sigma\cdot(1+b), 30, 30]$$

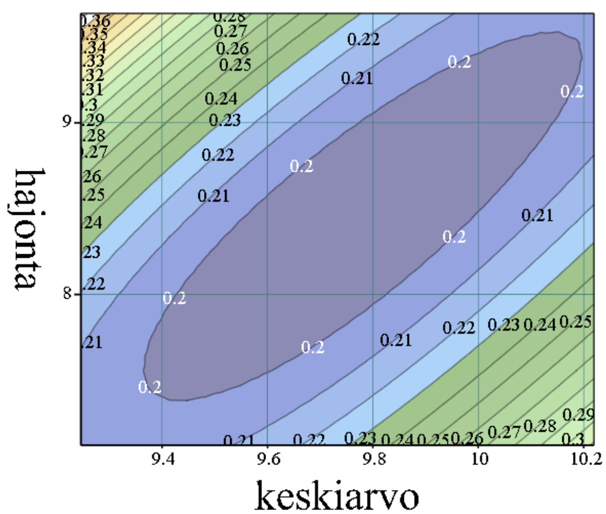
Optimi (S ≈ minimi)

$S(\mu, \sigma) = 0.192046$

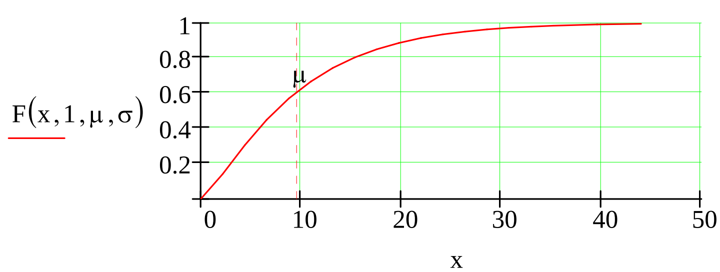
$$\begin{pmatrix} \mu \\ \sigma \end{pmatrix} = \begin{pmatrix} 9.732727 \\ 8.379457 \end{pmatrix}$$

Muuttamalla alkuarvausta tai / ja toistamalla (F9) voi löytyä vielä pienempi S!

Oheinen topografiprojektio antaa tietoa ympäristöstä. Kuvan siistiminen: Kaksoisklikkaus ja OK.



Vikajakauman kertymäfunktio F(x) eli TN että käyntiaika vikaan ≤ x

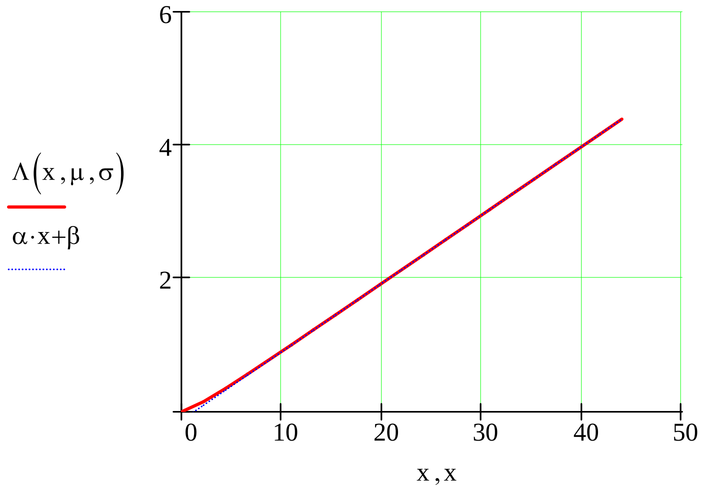


$\mu = 9.733$ keskiarvo

$\sigma = 8.379$ ja -hajonta

Renewal-fkt

$\Lambda(x)$ = yhden laitteen käyntiaikavälille 0...x sattuvien palautuksien lukumäärän keskiarvo.



Asymptootti $y = \alpha \cdot x + \beta$

$$\alpha = \frac{1}{\mu} \qquad \beta = \frac{1}{2}\cdot\left(\frac{\sigma^2}{\mu^2} - 1\right)$$

$\alpha = 0.103 \qquad \beta = -0.129$

Yhden laitteen palautuksien lukumäärät käyntiaikaväleillä A...L

Otoskeskiarvo Y = M/n (ks. syöttötieto). Mallin keskiarvo $y = \Lambda(L) - \Lambda(A)$.

RR =

"Ryhmä"	1	2	3	4	5	6	7	8
"A"	0	3	1	4	3	0	0	0
"L"	3	13	5	20	17	12	9	2
"M"	0	1	1	5	7	10	1	0
"n"	4	1	4	3	6	8	1	1
"Y"	0	1	0.25	1.667	1.167	1.25	1	0
"y"	0.219	0.99	0.352	1.615	1.399	1.107	0.803	0.132
"Y - y"	−0.219	0.01	−0.102	0.052	−0.233	0.143	0.197	−0.132

201. NewAllo

Kommentit: Per-Erik.Hagmark@tut.fi

PRNPRECISION := 10   PRNCOLWIDTH := 16

Warning! This module starts a new case.

1. Read or define entire fault tree

Read entire tree from file:

ET := READPRN("EsimTree.prn")

$$ET = \begin{pmatrix} 12 & 14 & 2 \\ 1 & 2 & 2 \\ 2 & 2 & 3 \\ 1 & 0.95 & 0.7 \\ 14 & 15 & 3 \\ 7 & 2 & 10 \\ 0 & 0 & 5 \end{pmatrix}$$

Define entire fault tree:

$$ET = \begin{pmatrix} \text{GateID} & \text{GateID} & .... \\ \text{AtLeast} & \text{AtLeast} & .... \\ \text{AtMost} & \text{AtMost} & .... \\ \text{CondProb} & \text{CondProb} & .... \\ \text{Input}_1 & \text{Input}_1 & .... \\ \text{Input}_2 & \text{Input}_2 & .... \\ .... & .... & .... \\ .... & .... & .... \end{pmatrix}$$

ET

2. Systematic numbering and initializing of files

WRITEPRN("DistAllo.prn") := D   WRITEPRN("Coeffici.prn") := Cf

WRITEPRN("AT.prn") := AT   WRITEPRN("AID.prn") := I

WRITEPRN("Puu.prn") := ET   WRITEPRN("SumParts.prn") := A

D =

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
0	2	0	0	3	0	0	5	0	0	7	0	0	10	0	0	12	0	0	14	0	0	15						

202-TopReqA

Kommentit: Per-Erik.Hagmark@tut.fi

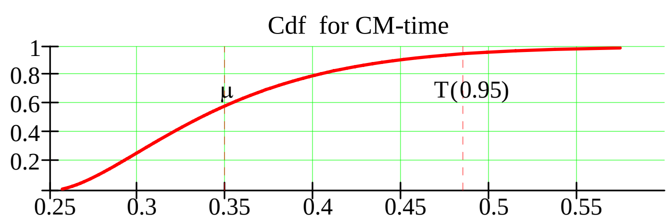
$D := (rnd(1) > 0) \cdot READPRN("DistAllo.prn")$ $\quad PRNPRECISION := 10$

$AT := (rnd(1) > 0) \cdot READPRN("AT.prn")$ $\quad PRNCOLWIDTH := 16$

1. Basic data and requirements for $TOP = 12$

$t_4 := 10 \cdot 365$	total (calendar) time $0 \ldots t_4$	$t_4 = 3650$	
$t_1 := 2 \cdot 365$	beginning period $0 \ldots t_1$	$t_1 = 730$	$0 < t_1 < t_3 < t_4$
$t_3 := 8 \cdot 365$	wear-out period $t_3 \ldots t_4$	$t_3 = 2920$	
$U_s := 0.001$	unavailability caused by SPM (scheduled PM)		Unavailability except CM
$U_u := 0.0004$	unavailability caused by UPM (unscheduled PM)		
$U_o := 0.001$	unavailability other than SPM, UPM, CM		$U_s + U_u + U_o = 0.0024$

$\mu := 0.35$	average single CM-time
$a := 0.25$	minimum single CM-time
$\sigma := 0.07$	standard deviation of single CM-time

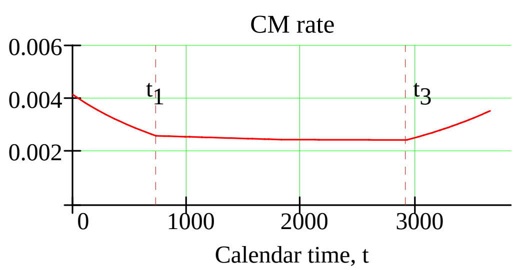


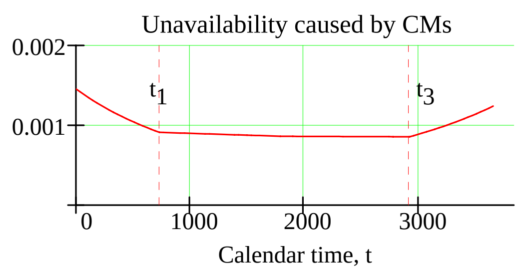
P-quantile

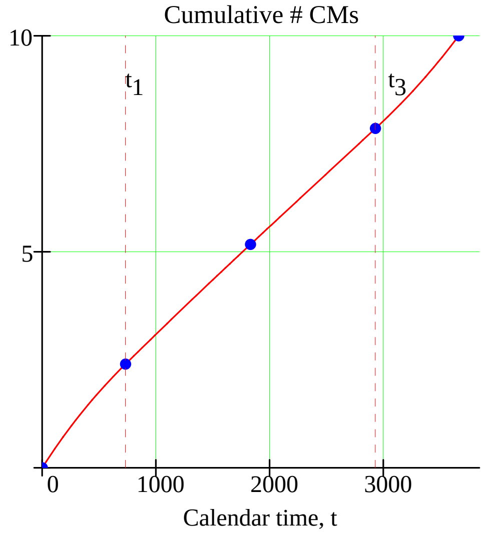
$T(0.95) = 0.486$

2. Allowed CM tendency in $0 \ldots t_4 = 3650$

$I_4 := 10$	average number of CMs in $0 \ldots t_4$	
$I_1 := 2.4$	average number of CMs in $0 \ldots t_1$	
$P := 30 \cdot \%$	more CM-tendency in $0 \ldots t_1$ than in $t_1 \ldots t_2$	$t_2 := 0.5 \cdot (t_1 + t_3)$ $\quad t_2 = 1825$
$Q := 20 \cdot \%$	more CM-tendency in $t_3 \ldots t_4$ than in $t_2 \ldots t_3$	







Running time in 0...t_4 $\quad x_4 := X(t_4)$

$x_4 = 3637.74$ $\quad t_4 = 3650$

Running time in 0...t_1 $\quad x_1 := X(t_1)$

$x_1 = 727.35$ $\quad t_1 = 730$

Number of CMs in calendar intervals

$I(t_4) - I(0) = 10$ $\qquad I(t_3) - I(t_1) = 5.453$

$I(t_1) - I(0) = 2.4$ $\qquad I(t_4) - I(t_3) = 2.147$

$I(t_4) - I(t_1) = 7.6$ $\qquad I(t_3) - I(t_2) = 2.684$

$I(t_2) - I(t_1) = 2.769$

$I(2000) - I(1000) = 2.502$

Unavailability caused by CMs

$UA(0, t_4) = 0.0009589$ $\qquad UA(t_1, t_3) = 0.0008715$

$UA(0, t_1) = 0.0011507$ $\qquad UA(t_3, t_4) = 0.0010294$

$UA(t_1, t_4) = 0.000911$ $\qquad UA(t_2, t_3) = 0.0008578$

$UA(t_1, t_2) = 0.0008851$

$UA(1000, 2000) = 0.0008756$

Checks:

$$\frac{I(t_1)\cdot(t_2 - t_1)}{t_1\cdot(I(t_2) - I(t_1))} = 1.3 \qquad (\ 1 + P = 1.3\ )$$

$$\frac{(I(t_4) - I(t_3))\cdot(t_3 - t_2)}{(t_4 - t_3)\cdot(I(t_3) - I(t_2))} = 1.2 \qquad (\ 1 + Q = 1.2\ )$$

3. Data into files (Scroll the screen!)

WRITEPRN("DistAllo.prn") := (rnd(1) > 0)·D

WRITEPRN("Tehoaika.prn") := augment(ξ, τ)

$$\text{WRITEPRN("TopReq.prn")} := (\text{rnd}(1) > 0)\cdot\begin{pmatrix} UA(0, t_1) & t_1 & 0 & 0 \\ UA(t_3, t_4) & t_3 & \mu & W \\ UA(0, t_4) & t_4 & 1 + P & 0 \\ U_s & U_u & U_o & 0 \end{pmatrix}$$

$$\begin{pmatrix} U1 & t1 & ta & td \\ U34 & t3 & \mu & W \\ U4 & t4 & s & \Delta \\ Us & Uu & Uo & Rel \end{pmatrix}$$

202-TopReqB

Kommentit: Per-Erik.Hagmark@tut.fi

$D := (rnd(1) > 0)\cdot READPRN("DistAllo.prn")$ PRNPRECISION := 10 $\delta := 0.0001$ $i := 1..400$

$AT := (rnd(1) > 0)\cdot READPRN("AT.prn")$ PRNCOLWIDTH := 16 $Z(t) := (t \ge 0)\cdot t$

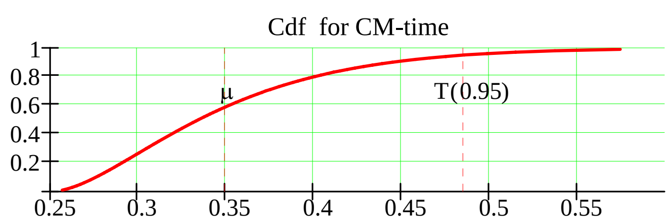
$TOP := AT_{0,cols(AT)-1}$

1. Basic data and requirements for TOP = 12

$t_4 := 10\cdot 365$	total (calendar) time $0...t_4$	$t_4 = 3650$	
$t_1 := 2\cdot 365$	beginning period $0...t_1$	$t_1 = 730$	$0 < t_1 < t_3 < t_4$
$t_3 := 8\cdot 365$	wear-out period $t_3...t_4$	$t_3 = 2920$	

$U_s := 0.001$	unavailability caused by SPM (scheduled PM)	Unavailability except CM
$U_u := 0.0004$	unavailability caused by UPM (unscheduled PM)	
$U_o := 0.001$	unavailability other than SPM, UPM, CM	$U_s + U_u + U_o = 0.0024$

$\mu := 0.35$	average single CM-time
$a := 0.25$	minimum single CM-time
$\sigma := 0.07$	standard deviation of single CM-time

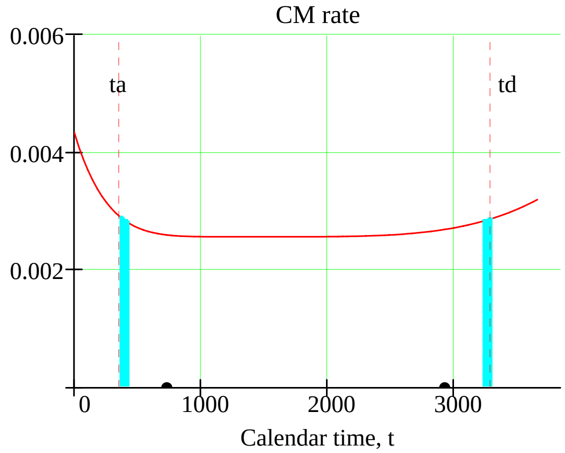


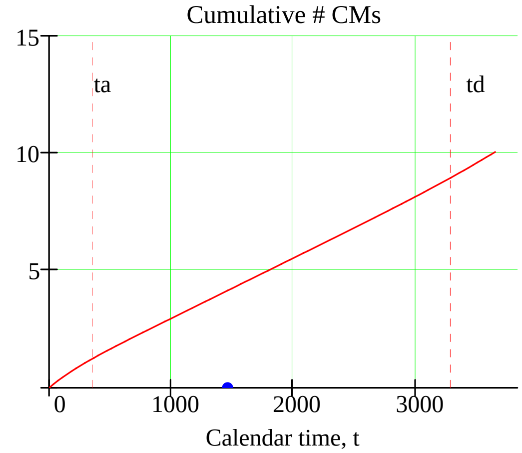
P-quantile

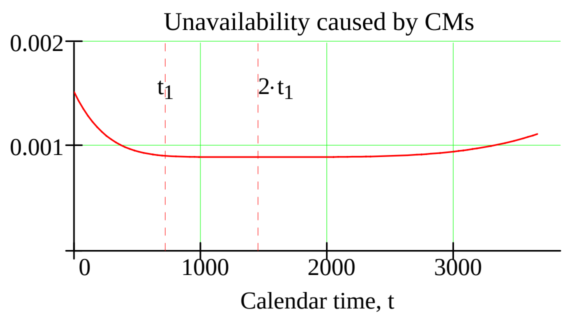
$T(0.95) = 0.486$

2. Required reliability (CM) in calendar interval $0...t_4 = 3650$

$ta := 1\cdot 365$	$td := 9\cdot 365$	main interval ta...td containing $t_1 = 730$ & $t_3 = 2920$		
$\Delta := 61$	$Rel := 0.84$	reliability (CM) in periods of length Δ during interval ta...td		
$P := 20\cdot\%$	more CMs allowed in $0...t_1$ than in $t_1...2t_1$		$\Delta < td - ta$	$\lambda 0 := \frac{-\ln(Rel)}{\Delta}$
			$ta + \Delta < 2\cdot t_1 < td - \Delta$	$\lambda 0 = 0.002858$
$\lambda := 0.9\cdot\lambda 0$	minimal CM rate at $2t_1$ $(\lambda < \lambda 0)$		$0 < ta \le t_1 < t_3 \le td \le t_4$	$\lambda = 0.002572$
$\gamma := 5$	shape after $2\cdot t_1$		$\gamma \ge 2$	







Running time in $0...t_4$ $\quad x_4 := X(t_4)$

$x_4 = 3637.723$ $\quad t_4 = 3650$

Running time in $0...t_1$ $\quad x_1 := X(t_1)$

$x_1 = 727.422$ $\quad t_1 = 730$

Number of CMs in calendar intervals

$I(t_4) - I(0) = 10.05$ $\quad I(t_4) - I(t_1) = 7.792$

$I(t_1) - I(0) = 2.258$ $\quad I(td) - I(ta) = 7.677$

$I(ta) - I(0) = 1.268$ $\quad I(t_4) - I(td) = 1.105$

$I(2000) - I(1000) = 2.573$

Unavailability caused by CMs

$UA(0, t_4) = 0.0009637$ $\quad UA(t_1, t_4) = 0.000934$

$UA(0, t_1) = 0.0010824$ $\quad UA(ta, td) = 0.0009202$

$UA(0, ta) = 0.001216$ $\quad UA(td, t_4) = 0.0010595$

$UA(1000, 2000) = 0.0009005$

Checks $\quad \dfrac{I(t_1)}{I(2 \cdot t_1) - I(t_1)} = 1.2$ $\quad e^{-(I(td) - I(td - \Delta))} = 0.84$ $\quad e^{-(I(ta + \Delta) - I(ta))} = 0.8400106$ $\quad (1 + P = 1.2\ ,\ \ Rel = 0.84\ )$

3. Data into files (Scroll the screen!)

WRITEPRN("DistAllo.prn") := (rnd(1) > 0)·D $\quad$ WRITEPRN("Tehoaika.prn") := augment(ξ, τ)

$$\text{WRITEPRN("TopReq.prn")} := (\text{rnd}(1) > 0) \cdot \begin{pmatrix} UA(0, t_1) & t_1 & ta & td \\ UA(t_3, t_4) & t_3 & \mu & W \\ UA(0, t_4) & t_4 & 1 + P & \Delta \\ U_s & U_u & U_o & Rel \end{pmatrix} \qquad \begin{pmatrix} U1 & t1 & ta & td \\ U34 & t3 & \mu & W \\ U4 & t4 & s & \Delta \\ Us & Uu & Uo & Rel \end{pmatrix}$$

202-TopReqC

Kommentit: Per-Erik.Hagmark@tut.fi

D := (rnd(1) > 0)·READPRN("DistAllo.prn") PRNPRECISION := 10

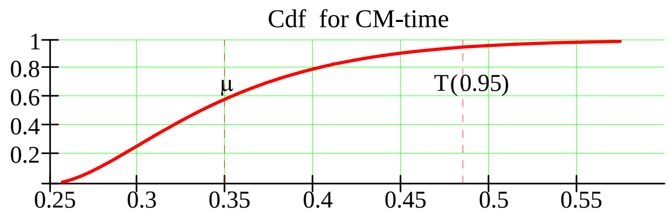
AT := (rnd(1) > 0)·READPRN("AT.prn") PRNCOLWIDTH := 16

1. Basic data and requirements for TOP = 12

$t_4 := 10 \cdot 365$	total (calendar) time $0 \ldots t_4$	$t_4 = 3650$	
$t_1 := 2 \cdot 365$	beginning period $0 \ldots t_1$	$t_1 = 730$	$0 < t_1 < t_3 < t_4$
$t_3 := 8 \cdot 365$	wear-out period $t_3 \ldots t_4$	$t_3 = 2920$	

$U_s := 0.001$	unavailability caused by SPM (scheduled PM)	Unavailability except CM
$U_u := 0.0004$	unavailability caused by UPM (unscheduled PM)	
$U_o := 0.001$	unavailability other than SPM, UPM, CM	$U_s + U_u + U_o = 0.0024$

$\mu := 0.35$	average single CM-time
$a := 0.25$	minimum single CM-time
$\sigma := 0.07$	standard deviation of single CM-time



P-quantile

$T(0.95) = 0.486$

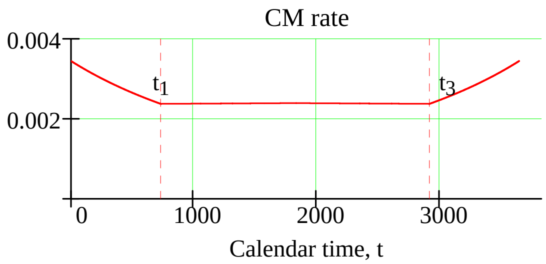
2. Allowed CM-unavailability (unavailability caused by failures)

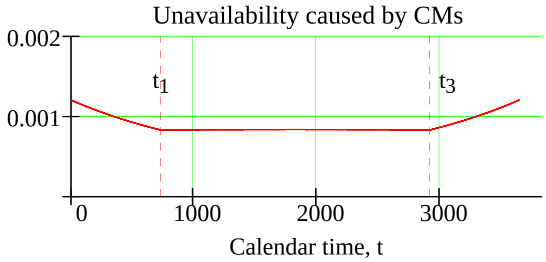
$U_4 := 0.0009$	CM-unavailability for total calendar period $0 \ldots t_4 = 3650$
$U_1 := 0.001$	CM-unavailability for the period $0 \ldots t_1 = 730$
$U_{34} := 0.001$	CM-unavailability for age-out period $t_3 \ldots t_4$, $t_3 = 2920$
$\varepsilon := 0.5$	adjustment parameter for S and S´ *)

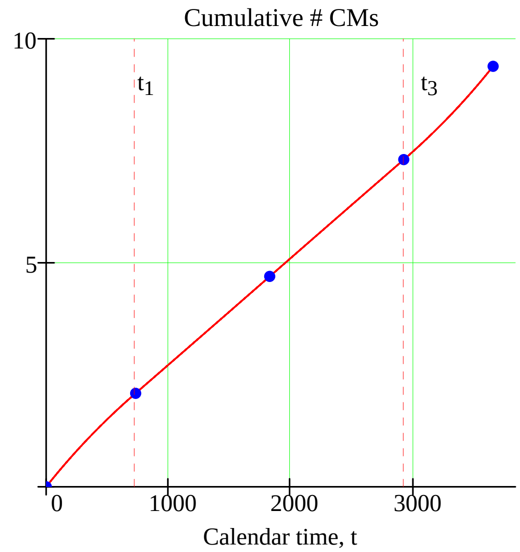
Note! $t_1 < t_3 < t_4$ $U_1 < \frac{t_4}{t_1} \cdot U_4 = 0.0045$ $U_{34} < \frac{t_4 \cdot U_4 - t_1 \cdot U_1}{t_4 - t_3} = 0.0035$ $0 < \varepsilon < 1$

*) The CM tendency in $0 \ldots t_1$ is now $S = 1.2$ times the CM tendency after t_1.

The CM tendency in $t_3 \ldots t_4$ is now $S´ = 1.2$ times the CM tendency before t_3.







Running time in $0...t_4$ $\quad x_4 := X(t_4)$ $\quad x_4 = 3637.955$ $\quad t_4 = 3650$

Running time in $0...t_1$ $\quad x_1 := X(t_1)$ $\quad x_1 = 727.486$ $\quad t_1 = 730$

Running time in $0...t_3$ $\quad x_3 := X(t_3)$ $\quad x_3 = 2910.469$ $\quad t_3 = 2920$

Number of CMs in calendar intervals

$I(t_4) - I(0) = 9.386$ $\quad I(t_3) - I(t_1) = 5.214$

$I(t_1) - I(0) = 2.086$ $\quad I(t_4) - I(t_3) = 2.086$

$I(t_4) - I(t_1) = 7.3$

$I(2000) - I(1000) = 2.384$

Unavailability caused by CMs

$UA(0, t_4) = 0.0009$ $\quad UA(t_1, t_3) = 0.0008333$

$UA(0, t_1) = 0.001$ $\quad UA(t_3, t_4) = 0.001$

$UA(t_1, t_4) = 0.000875$

$UA(1000, 2000) = 0.0008344$

3. Data into files (Scroll the screen!)

WRITEPRN("DistAllo.prn") := $(\mathrm{rnd}(1) > 0) \cdot D$

WRITEPRN("Tehoaika.prn") := $\mathrm{augment}(\xi, \tau)$

$$\mathrm{WRITEPRN}(\text{"TopReq.prn"}) := (\mathrm{rnd}(1) > 0) \cdot \begin{pmatrix} UA(0, t_1) & t_1 & 0 & 0 \\ UA(t_3, t_4) & t_3 & \mu & W \\ UA(0, t_4) & t_4 & S & 0 \\ U_s & U_u & U_o & 0 \end{pmatrix}$$

203. AlloTree

Kommentit: Per-Erik.Hagmark@tut.fi

$ET := READPRN(\text{"Puu.prn"})$ $PRNCOLWIDTH := 16$

$I := READPRN(\text{"AID.prn"})$ $AT := READPRN(\text{"AT.prn"})$ $PRNPRECISION := 10$

1. Preparation of allocation tree for CM with $TOP = 12$

Entire tree (defined in 201-NewAllo)

$$\begin{pmatrix} \text{Gate} \\ \text{AtLeast} \\ \text{AtMost} \\ \text{CondProb} \\ \text{Input}_1 \\ \text{Input}_2 \\ \text{....} \end{pmatrix} \qquad ET = \begin{pmatrix} 2 & 12 & 14 \\ 2 & 1 & 2 \\ 3 & 2 & 2 \\ 0.7 & 1 & 0.95 \\ 3 & 14 & 15 \\ 10 & 7 & 2 \\ 5 & 0 & 0 \end{pmatrix}$$

The gate to be allocated now? $Gate := 14$ $p := Pos\left[Gate, \left(ET^T\right)^{\langle 0 \rangle}\right]$

The type of $Gate = 14$ (i.e. AtLeast, AtMost, CondProb) can be redefined.

$$\begin{pmatrix} \text{Gate} \\ \text{AtLeast} \\ \text{AtMost} \\ \text{CondProb} \\ \text{Input}_1 \\ \text{Input}_2 \\ \text{....} \end{pmatrix} \qquad ET^{\langle p \rangle} = \begin{pmatrix} 14 \\ 2 \\ 2 \\ 0.95 \\ 15 \\ 2 \\ 0 \end{pmatrix}$$

Changed $ET^{\langle p \rangle}$

The allocation tree should consist of the column for the gate to be allocated now and the already allocated columns.

Allocation tree
to be considered next

$$\begin{pmatrix} \text{Gate} \\ \text{AtLeast} \\ \text{AtMost} \\ \text{CondProb} \\ \text{Input}_1 \\ \text{Input}_2 \\ \text{....} \end{pmatrix} \qquad AT = \begin{pmatrix} 14 & 12 \\ 2 & 1 \\ 2 & 2 \\ 0.95 & 1 \\ 15 & 14 \\ 2 & 7 \\ 0 & 0 \end{pmatrix}$$

WRITEPRN("Puu.prn") := ET   WRITEPRN("AID.prn") := Re(I)   WRITEPRN("AlloTree.prn") := Re(F)

WRITEPRN("AT.prn") := AT   WRITEPRN("Gate.prn") := Gate

2. Assessing and constructing allocation coefficients

Gate = 14

Instructions for matrix M (below)

Type of Gate to be allocated: $AtLeast + \sqrt{-1} \cdot AtMost$

Proportional CM-time $\mathbf{z_j}$ for inputs $\mathbf{I_j}$

$$A_B = \begin{cases} 2 & \text{if } A > B \\ 1 & \text{if } A = B \\ 0 & \text{if } A < B \end{cases}$$

CM-tendency allocation concerns two sets of factors: *Complexity* & *Importance.*

Proportional weights for the inputs

Complexity factors

A (e.g. number of parts)

B (e.g. amount of human activities)

C (e.g. amount of "state of arts")

$\mathbf{a_j, b_j, c_j}$ (I_j)

Importance factors

D (e.g. property damage)

E (e.g. environmental damage)

F (e.g. human damage)

G (e.g. business damage)

$\mathbf{d_j, e_j, f_j, g_j, h_j}$ (I_j)

Default

$$M = \begin{pmatrix} \text{Gate} & I_1 & I_2 & .. & I_n \\ AtLeast + AtMost \cdot i & z_1 & z_2 & .. & z_n \\ A_B & a_1 & a_2 & .. & a_n \\ B_C & b_1 & b_2 & .. & b_n \\ C_A & c_1 & c_2 & .. & c_n \\ D & d_1 & d_2 & .. & d_n \\ E & e_1 & e_2 & .. & e_n \\ F & f_1 & f_2 & .. & f_n \\ G & g_1 & g_2 & .. & g_n \end{pmatrix} \qquad M = \begin{pmatrix} -14 & 2 & 15 \\ 2+2i & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Change

$$M = \begin{pmatrix} \text{Gate} & I_1 & I_2 & .. & I_n \\ AtLeast + AtMost \cdot i & z_1 & z_2 & .. & z_n \\ A_B & a_1 & a_2 & .. & a_n \\ B_C & b_1 & b_2 & .. & b_n \\ C_A & c_1 & c_2 & .. & c_n \\ D & d_1 & d_2 & .. & d_n \\ E & e_1 & e_2 & .. & e_n \\ F & f_1 & f_2 & .. & f_n \\ G & g_1 & g_2 & .. & g_n \end{pmatrix}$$

M

Weighting complexity against importance? $\tau := 1$ $(0 \le \tau \le 2)$

$\tau = 0$ <=> complexity only
$\tau = 2$ <=> importance only

Weigths for complexity factors' now

$$\begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{pmatrix} 0.333 \\ 0.333 \\ 0.333 \end{pmatrix}$$

Change $A, B, C \ge 0$ $\begin{pmatrix} A \\ B \\ C \end{pmatrix}$

Inputs and their complexity (y) importance (x)

$$Cxy = \begin{pmatrix} 2 & 15 \\ 0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix}$$

Change
y & x

Cxy

Allocation coefficients for Gate = 14
Row 1: CM-tendency (w)
Row 2: CM-time (z)

$$FR = \begin{pmatrix} 2 & 15 \\ 0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix}$$

Change
w & z

FR

Cf := READPRN("Coeffici.prn")

Tiedoston päivitys

WRITEPRN("Coeffici.prn") := Re(Cf)

1.col = Gate and inputs
2.col = CM-tendency (w)
3.col = CM-time (z)

$$Cf = \begin{pmatrix} 2 & 0 & 0 & 12 & 0 & 0 & 14 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2 & 0.5 & 0.5 \\ 0 & 0 & 0 & 0 & 0 & 0 & 15 & 0.5 & 0.5 \end{pmatrix}$$

3. Restrictions and fixed parameters (TOP = 12 , Gate = 14)

Instructions for the matrix P (below)

1.row:	Input	ID-number of input	
2.row:	a=1	this part cannot be CM if TOP is running.	Otherwise a=0
3.row:	b=1	this part is not running if TOP is not running.	Otherwise b=0

4.row:	c=1	TOP will not be started if this input is still CM.	Otherwise c=0
5.row:	I > 0	the average number of CMs is fixed.	Not fixed => I = 0
6.row:	UT > 0	the average CM-time is fixed.	Not fixed => UT = 0

HUOM: Kombinaatio a=1, c=0 ei kelpaa!

Default $\begin{pmatrix} \text{Input} \\ a \\ b \\ c \\ I \\ UT \end{pmatrix}$ $P = \begin{pmatrix} 15 & 2 & 7 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Change $\begin{pmatrix} \text{Input} \\ a \\ b \\ c \\ I \\ UT \end{pmatrix}$ P

WRITEPRN("Side.prn") := P

204-AlloSim

Kommentit: Per-Erik.Hagmark@tut.fi

PRNCOLWIDTH := 16

PRNPRECISION := 10

Cf := READPRN("Coeffici.prn")

Gate := READPRN("Gate.prn")$_{0,0}$

ID := READPRN("AID.prn")

xt := READPRN("Tehoaika.prn")

ET := READPRN("Puu.prn")

TR := READPRN("TopReq.prn")

D := READPRN("DistAllo.prn")

A := READPRN("SumParts.prn")

P := READPRN("Side.prn")

F := READPRN("AlloTree.prn")

AT := READPRN("AT.prn")

1. Allocating distributions for inputs (Gate = 14) and simulation (to TOP = 12)

Allocation tree to be simulated

$$\begin{pmatrix} \text{Gate} \\ \text{AtLeast} \\ \text{AtMost} \\ \text{CondProb} \\ \text{Input}_1 \\ \text{Input}_2 \\ \text{....} \end{pmatrix} \qquad AT = \begin{pmatrix} 14 & 12 \\ 2 & 1 \\ 2 & 2 \\ 0.95 & 1 \\ 15 & 14 \\ 2 & 7 \\ 0 & 0 \end{pmatrix}$$

Level parameter for CM tendency $\alpha := 4$

Level parameter for CM time $\beta := 0.9$

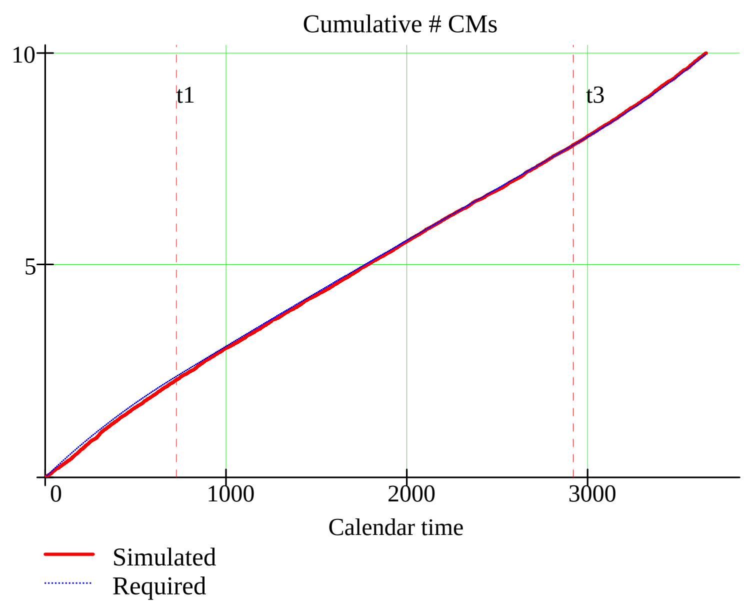
Number of copies N := 1000

Bigger α => more CM tendency
Bigger β => longer CM time
(Begin with $\alpha = 1$, $\beta = 1$.)

Simuloinnin toisto: Klikkaa N ja F9!

Allocation, simulation, etc.

Raw simulation data



WRITEPRN("DistAllo.prn") := C^T

WRITEPRN("Events.prn") := Ev

2. Numerical checking

		Simulated	Required/allowed
Average #CMs in calendar interval 0...t4 = 3650		I(t4) = 10.012028	I4 = 10
Average #CMs in calendar interval 0...t1 = 730		I(t1) = 2.31274	I1 = 2.4
Unavailability in calendar interval 0...t4 = 3650		UA(0,t4) = 0.0009743	U4 = 0.0009589
Unavailability in calendar interval 0...t1 = 730		UA(0,t1) = 0.0011253	U1 = 0.0011507
Unavailability in calendar interval t3...t4, t3 = 2920		UA(t3,t4) = 0.001049	U34 = 0.0010294
Average CM-time		μS = 0.355199	μ = 0.35
95%-quantile for CM-time		WS = 0.483288	W = 0.486056
The CM tendency in 0..t1 is s times the CM tendency after t1		sS = 1.212533	s = 1.3
Rel is the required reliability for a period of length Δ belonging to ta..td	Δ = 0 ta = 0	RelSa = 0	Rel = 0
	td = 0	RelSd = 0	Rel = 0

Notes

- No comparison is made if Required is 0.
- If resimulations change Simulated much, then choose a bigger N = 1000 (above).
- Then select such α, β (above) that Simulated is as near to Required as possible.
- When Simulated matches Required, the next allocation step can begin in *AlloTree* by defining another Gate to be allocated.

3. Dependability allocation for the life cycle

WRITEPRN("S.prn") := Re(S)

TOP and parts

1. Total running time (0)
2. Total wait for start (0.5)
3. Total CM-time (1)
4. Total wait for CM (1.5)
5. Number of CMs
6. MTTF
7. Average CM-time
8. Related 95-quantile
9. CM-unavailability

S =

0	12	15	2	7
1	3646.444459	2495.660076	2549.032072	3646.444459
2	0.401847	1.494193	1.495219	1.811113
3	3.153694	2.061348	2.060322	1.744428
4	0	1150.784383	1097.412387	0
5	10.01	6.88	6.898	4.999
6	364.280166	362.74129	369.532049	729.434779
7	0.355199	0.315	0.315	0.35
8	0.483288	0.43745	0.43745	0.486056
9	0.000864	0.000565	0.000564	0.000478

HUOM! Osa tuloksista perustuvat simulointiin.

Gates

1. total CM-time
2. number of failures

$$G = \begin{pmatrix} 0 & 14 & 12 \\ 1 & 1.4573341 & 3.1536942 \\ 2 & 5.185 & 10.01 \end{pmatrix}$$

4. Dependability allocation for selected interval

Interval: $(T0 \;\; T1) := (2 \cdot 365 \;\; 7 \cdot 365)$

$$SPV := \left(T0 + T1 \cdot \sqrt{-1} \neq 0\right) \cdot READPRN("SumParts.prn")$$

$$SPV_{0, cols(SP)-1} := 0 \qquad WRITEPRN("SumParts.prn") := stack(SPV, SP)$$

TOP and parts

0	calendar interval	T0-T1i
1	number of the part (entity)	ID
2	average # CMs	I
3	95% quantile for # CMs	Iw
4	reliability (no CMs)	R
5	CM-unavailability	U
6	average single CM-time	m

SP =

	0	1	2	3
0	730-2555i	730-2555i	730-2555i	730-2555i
1	12	15	2	7
2	4.622	4.560179	4.560179	2.28009
3	8.400035	8.315182	8.315182	4.991513
4	0.009833	0.01046	0.01046	0.102275
5	0.0009	0.000787	0.000787	0.000437
6	0.355199	0.315	0.315	0.35

HUOM! Osa tuloksista perustuvat simulointiin.

205-AlloFinal

Kommentit: Per-Erik.Hagmark@tut.fi

PRNPRECISION := 10

PRNCOLWIDTH := 16

D := READPRN("DistAllo.prn")   xt := READPRN("Tehoaika.prn")

ID := READPRN("AID.prn")   SPV := READPRN("SumParts.prn")   TR := READPRN("TopReq.prn")

1. Initial results (from TopReq and AlloSim)

Viimeinen simuloitu tapaus

0. Calendar interval (T0-T1i)
1. Part's ID-number
2. Average # CMs
3. 95% quantile for # CMs
4. Reliability (no CMs)
5. CM-unavailability
6. Average single CM-time

SP =

	0	1	2	3
0	730-2555i	730-2555i	730-2555i	730-2555i
1	12	15	2	7
2	4.622	4.560179	4.560179	2.28009
3	8.400035	8.315182	8.315182	4.991513
4	0.009833	0.01046	0.01046	0.102275
5	0.0009	0.000787	0.000787	0.000437
6	0.355199	0.315	0.315	0.35

Osa tuloksista perustuvat simulointiin, joten voi esiintyä pieniä ristiriitoja, jotka pienenevät kun simulointimääriä lisätään (AlloSim).

TOP-yksikkö   TOP = 12

Tarkasteltava kalenteriaikaväli   (T0 T1) = (730 2555)

TOP:n CM-epäkäytettävyys (AlloSim)   Uc = 0.0009

TOP:n CM-epäkäytettävyysaika $Uc\cdot(T1 - T0) = 1.641729$

TOP:n UPM-epäkäytettävyys (TopReq) $\omega\cdot Uc = 0.000375$ $\omega = 0.417$

TOP:n UPM-epäkäytettävyysaika $\omega\cdot Uc\cdot(T1 - T0) = 0.684836$

TOP:n SPM-epäkäytettävyys (TopReq)   Us = 0.001

TOP:n SPM-epäkäytettävyysaika $Us\cdot(T1 - T0) = 1.825$

TOP:n Muu epäkäytettävyys (TopReq)   Uo = 0.001

TOP:n Muu epäkäytettävyysaika $Uo\cdot(T1 - T0) = 1.825$

TOP:n koko epäkäytettävyys   U = 0.003275

TOP:n koko epäkäytettävyysaika $U\cdot(T1 - T0) = 5.976565$

Parts $BP^T = (15 \;\; 2 \;\; 7)$

Average #CMs (AlloSim) $I^T = (4.56 \;\; 4.56 \;\; 2.28)$

Average single CM-time (TopReq) $\mu^T = (0.315 \;\; 0.315 \;\; 0.35)$

2. CM cost and time allocation

$(T0 \;\; T1) = (730 \;\; 2555)$

CM-costs allowed (material + work)	$Cc := 8000$
Parts	$BP^T = (15 \;\; 2 \;\; 7)$
Työn suhteellinen hinta /ay osille	$\kappa := (1 \;\; 1.5 \;\; 0.8)^T$
Kustannussuhde 'materiaali/työ' kullekin osalle	$\alpha := \left(\frac{2}{1} \;\; \frac{1}{1.5} \;\; \frac{3}{2}\right)^T$
Työaikaa osille (ay) (AlloSim)	$\overrightarrow{(I \cdot \mu)}^T = (1.436 \;\; 1.436 \;\; 0.798)$
Työn hinta (eu/ay)	$d \cdot \kappa^T = (842.41 \;\; 1263.61 \;\; 673.93)$
Materiaalin hinta (eu/CM)	$d \cdot m^T = (530.72 \;\; 265.36 \;\; 353.81)$
CM-kustannukset osille (eu)	$kt^T + km^T = (3630.25 \;\; 3025.21 \;\; 1344.54)$
Työn kustannus (eu)	$kt^T = (1210.08 \;\; 1815.13 \;\; 537.82)$
Materiaalikustannus (eu)	$km^T = (2420.17 \;\; 1210.08 \;\; 806.72)$
CM-kustannukset yhteensä (eu)	$\Sigma\, kt + \Sigma\, km = 8000.00$ (vrt. Cc)
Työn kustannus (eu)	$\Sigma\, kt = 3563.03$
Materiaalikustannus(eu)	$\Sigma\, km = 4436.97$
Työkustannusten osuus	$X = 44.5\%$

3. UPM cost and time allocation

$(T0 \;\; T1) = (730 \;\; 2555)$

UPM-costs allowed (material + work)	$Cu := 5000$ (material + työ)
Parts	$BP^T = (15 \;\; 2 \;\; 7)$
Työajan suht. allokointikertoimet osille	$\gamma := (1 \;\; 2 \;\; 1)^T$
Työn suhteellinen hinta /ay osille	$\theta := (2 \;\; 1 \;\; 1.5)^T$
Kustannussuhde 'materiaali/työ' kullekin osalle	$\beta := \left(\frac{2}{1} \;\; \frac{1}{1} \;\; \frac{4}{3}\right)^T$
TOP:n pysähdystarve osan huollon aikana [1])	$\delta := (0.5 \;\; 0 \;\; 1)^T$
Huoltojen päällekkäisyys [2])	$z := 0$

1) $0 \le \delta_i \le 1$	Ei pysähdystä => $\delta_i = 0$. Varma pysähdys => $\delta_i = 1$.
	Jos Uu > 0 niin oltava jokin $\delta_i \cdot \gamma_i > 0$. Eli $(Uu > 0)\cdot(\delta\cdot\gamma = 0) = 0$ on oltava = 0
2) $0 \le z \le 1$	Ei ollenkaan päällekkäisyyttä => $z = 0$. Täysi päällekkäisyys => $z = 1$.
	(z :lle ehkä tehtävä esimalli.)

Työaikaa osille (ay) *) $c\cdot\gamma^T = (0.685 \;\; 1.37 \;\; 0.685)$

Työn hinta osille (eu/ay) *) $f^T = (1081.63 \;\; 540.82 \;\; 811.22)$

*) Jos TOP:ia ei tarvitse pysäyttää huollon aikana (eli kaikki $\delta = 0$), niin näitä tuloksia ei saada. (Silloin tarvitaan lisää lähtötietoa.)

UPM-kustannukset osille (eu) $ht^T + hm^T = (2222.22 \;\; 1481.48 \;\; 1296.30)$

Työkustannus (eu) $ht^T = (740.74 \;\; 740.74 \;\; 555.56)$

Materiaalikustannus (eu) $hm^T = (1481.48 \;\; 740.74 \;\; 740.74)$

UPM-kustannukset yhteensä (eu) $\Sigma\, ht + \Sigma\, hm = 5000.00$ (vrt. Cu)

Työkustannus (eu) $\Sigma\, ht = 2037.04$

Materiaalikustannus (eu) $\Sigma\, hm = 2962.96$

Työkustannusten osuus $X = 40.7\%$

4. SPM cost and time allocation

$(T0 \;\; T1) = (730 \;\; 2555)$

SPM-costs allowed (material + work) $Cs := 10000$

Parts $BP^T = (15 \;\; 2 \;\; 7)$

Työajan suht. allokointikertoimet osille $\gamma := (1 \;\; 2 \;\; 2)^T$

Työn suhteellinen hinta /ay osille $\theta := (2 \;\; 2 \;\; 1)^T$

Kustannussuhde 'materiaali/työ' kullekin osalle $\beta := \left(\frac{2}{1} \;\; \frac{1}{3} \;\; \frac{1}{1}\right)^T$

TOP:n pysähdystarve osan huollon aikana 1) $\delta := (0.6 \;\; 0 \;\; 1)^T$

Huoltojen päällekkäisyys 2) $z := 0$

1) $0 \le \delta_i \le 1$	Ei pysähdystä => $\delta_i = 0$. Varma pysähdys => $\delta_i = 1$.
	Jos Us > 0 niin oltava jokin $\delta_i \cdot \gamma_i > 0$. Eli $(Us > 0)\cdot(\delta\cdot\gamma = 0) = 0$ on oltava = 0
2) $0 \le z \le 1$	Ei ollenkaan päällekkäisyyttä => $z = 0$. Täysi päällekkäisyys => $z = 1$.
	(z :lle ehkä tehtävä esimalli.)

Työaikaa osille (ay) *) $c \cdot \gamma^T = (0.913 \quad 1.825 \quad 1.825)$

Työn hinta osille (eu/ay) *) $f^T = (1429.42 \quad 1429.42 \quad 714.71)$

*) Jos TOP:ia ei tarvitse pysäyttää huollon aikana (eli kaikki $\delta = 0$), niin näitä tuloksia ei saada.
(Silloin tarvitaan lisää lähtötietoa.)

SPM-kustannukset osille (eu) $ht^T + hm^T = (3913.04 \quad 3478.26 \quad 2608.70)$

Työkustannus (eu) $ht^T = (1304.35 \quad 2608.70 \quad 1304.35)$

Materiaalikustannus (eu) $hm^T = (2608.70 \quad 869.57 \quad 1304.35)$

SPM-kustannukset yhteensä (eu) $\Sigma\, ht + \Sigma\, hm = 10000.00$ (vrt. Cs)

Työkustannus (eu) $\Sigma\, ht = 5217.39$

Materiaalikustannus (eu) $\Sigma\, hm = 4782.61$

Työkustannusten osuus $X = 52.2\%$

Osapaikan elinikaarikustannusmalli

1. Mallin yleiset määrittelyt

1.1. Yleistä

Tässä dokumentissa esitellään Bred -projektin yhteydessä kehitetty osapaikan elinkaarikustannusmalli, joka on tarkoitettu ei-korjattavan laitteen (jatkossa osa) satunnaisesta vikaantumisesta ja määräaikaishuolloista johtuvien kustannusten arviointiin. Menetelmää voi soveltaa kaikkiin sellaisiin osiin, joiden lopullinen särkyminen voidaan mallintaa yhtenä tai kahtena peräkkäisenä, riippumattomana stokastisena tapahtumana. Ensimmäinen tapahtuma liittyy vian havaitsemiseen, ja seuraava liittyy vian kasvuun aina lopulliseen särkymiseen asti. Tarkasteltava osa on koko järjestelmän (jatkossa prosessi) kannalta kriittinen siinä mielessä, että osan vikaantuminen johtaa aina prosessin pysähtymiseen ja sitä kautta keskeytyskustannuksiin.
Keskeytyskustannukset voivat riippua siitä ajankohdasta, johon vika sattuu kalenterivuoden aikana. Keskeytyskustannusten aikariippuvuutta kutsutaan tässä prosessin kustannusprofiiliksi.

Prosessi pysäytetään suunniteltua huoltoa (PM, Preventive Maintenance) varten säännöllisesti. Huoltoväli voi olla esim. 5 vuotta, jolloin osa vaihdetaan uuteen olkoot se vialla tai ehjä. Osa voi kuitenkin vikaantua (vika havaitaan) suunniteltujen huoltojen välillä satunnaisesti. Tähän liittyy kaksi vaihtoehtoa: 1. osa vikaantuu lopullisesti ennen huoltoa, jolloin joudutaan tekemään vikakorjaus (CM, Corrective Maintenance). 2. osan lopulliseen särkymiseen kuluva aika on niin pitkä, että suunniteltu huolto ennätetään järjestää (UPM, Unexpected Preventive Maintenance).

Vikakorjaukseen liittyy aina huollon järjestämisestä johtuva odotusaikan ja vastaava keskeytyskustannus. Jos vika havaitaan lähellä suunniteltua PM:ää, niin prosessia voidaan haluta käyttää tavallista UPM:ää suuremmalla vikaantumisriskillä PM:ään asti.

Tämä dokumentti sisältää sekä kehitetyn mallin kuvauksen että laskentaesimerkin, jota viedään eteenpäin kuvauksen rinnalla. Laskentaesimerkin parametrien arvot ovat peräisin eräästä mallinkehityksen yhteydessä käytetystä esimerkkiprosessista, jossa tarkastelun kohteena oli vierintälaakeri.

1.2. Laskennassa käytetty aika

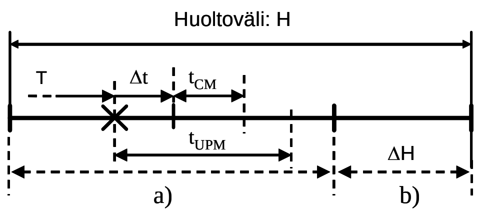
Perusyksikkö on tunti [h], luettavuuden parantamiseksi käytetään myös tunnin monikertoja so. vuorokausi [day] = 24 [h] ja vuosi [year] = 365 [day] = 8760 [h]. Vastaavat muuttujat on nimetty seuraavasti:

Tunti	$h := 1$	[h]		
Vuorokausi	$day := 24$	[h]	$day = 24\,h$	
Kalenterivuosi	$year := 8760$	[h]	$year = 365\,day$	$year = 8760\,h$

1.3. Osan vikaantuminen

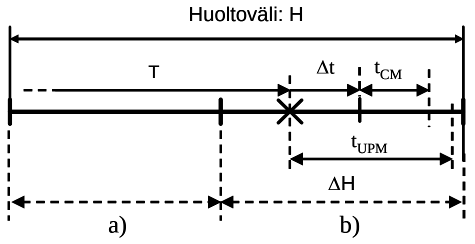
Osan elinkaari jaetaan kahteen vaiheeseen: Vikaantumisaika, *service life* (T), joka alkaa edellisestä osan käyttöönotosta ja päättyy vian havaitsemiseen hetkellä T tai suunniteltuun huoltoon hetkellä H (PM) . Toinen vaihe eli vian kasvu, *remaining life* (Δt), päättyy joko suunniteltuun huoltoon hetkellä T+ t_{UPM} (UPM) tai osan särkymiseen hetkellä T+ Δt (CM). Osan sanotaan olevan vialla, kun vika on havaittavissa, tässä se tarkoittaa, että vikahetki on T. Osan kesto tarkoittaa aikaa käyttöönotosta sen lopulliseen murtumiseen hetkellä T+ Δt.

Molempien tapahtumien (T, Δt) mallina käytetään tässä Weibull-jakumaa, joka on yleisesti mm. laakerien yhteydessä käytetty malli. (Birnbaum-Saunders -jakauma, jonka taustalla on särön kasvuun liittyvä oletus, saattaisi olla myös perusteltu malli).



1.4. Osan kunnossapitostrategia

Kunnossapitostrategian perusperiaatteita:
<u>Vika havaitaan aikavälillä a:</u>
Osa vaihdetaan hetkellä ..T+ t_{UPM} (UPM). Jos osa särkyy lopullisesti ennen hetkeä ..T+ t_{UPM}, niin seuraa vikakorjaus (CM) hetkellä ..T+ Δt + t_{CM}. t_{CM} on korjauksen odotusaika
<u>Vika havaitaan aikavälillä b:</u>
Osa vaihdetaan huoltovälin H lopussa (PM).
Särkymisestä hetkellä ..T+ Δt < H seuraa vikakorjaus (CM) hetkellä ..T+ Δt + t_{CM}.



Osa (ehjä tai rikki) vaihdetaan aina huoltovälin H lopussa (PM). ..T on vian havaitsemisajankohta mitattuna huoltovälin H alusta ja t_{CM} = max[(varaosan toimitusaika – Δt), huollon järjestämisaika].

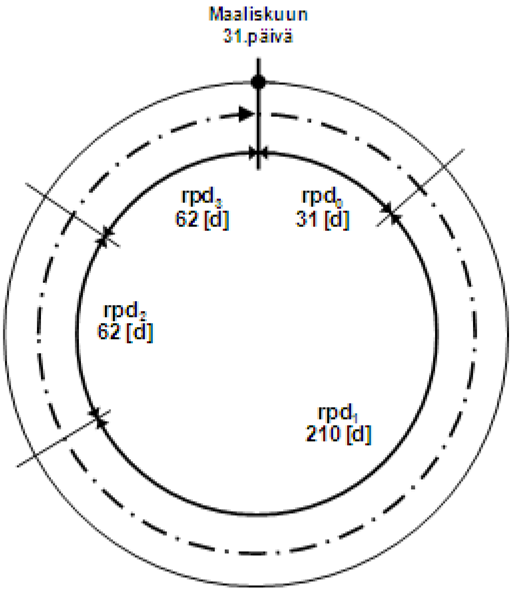
1.5. Prosessin (osan) käyttö- ja kustannusprofiili

Käyttöprofiili kuvaa prosessin keskimääräistä käyttömäärää (käyttötunteja) kalenterivuoden eri ajanjaksoina. Kustannusprofiili kuvaa vastaaviin jaksoihin liittyviä keskeytyskustannuksia.

Esimerkkiprosessimme käy yhteensä 6000 h vuodessa. Käyttöprofiili on seuraava:
Vuosi on jaettu neljään jaksoon, jotka on tässä numeroitu 0-3. Käyttöjaksojen kestot ovat likimääräisiä ja ne tarkentuvat parametrien kiinnityksen yhteydessä alempana.

Käyttöjakso 0: Käyntiaika 500h, viasta johtuva keskeytyskustannus 22k€/h
Käyttöjakso 1: Käyntiaika 3500h, viasta johtuva keskeytyskustannus 44k€/h
Käyttöjakso 2: Käyntiaika 1000h, viasta johtuva keskeytyskustannus 30k€/h
Käyttöjakso 3: Käyntiaika 1000h, viasta johtuva keskeytyskustannus 30k€/h

Kuva 1. Prosessin (osan) käyttöprofiili. Kuvassa on esitetty kalenterivuosi, joka alkaa 31. päivä maaliskuuta. Käyttöjaksot (rpd) on numeroitu 0...3.



1.6. Osan elinkaaren malli

Edellisen mukaan osan elinkaari on kahden Weibull -jakautuneen satunnaissuureen summa:

$$X = Q_W(\blacksquare, \mu s, \beta s) + Q_W(\blacksquare, \mu r, \beta r)$$

Edellinen termi kuvaa normaalia käyttöaikaa ja jälkimmäinen vian kasvua, mitattuna osan käyttömääränä (esim. käyttötunteina). Mallien parametreinä ovat keskiarvo μ ja muotoparametri β.

Osan käyttö voi olla jaksollista, jolloin vuorokautisia käyttötunteja on vähemmän kuin 24. Koska vikaantumiseen liittyvät kustannukset kytkeytyvät prosessin kustannusprofiiliin, joka puolestaan perustuu kalenteriin, niin jaksollinen käyttö on muunnettava vastaavaksi jatkuvaksi käytöksi. Muunnos tapahtuu kertoimella, joka saadaan jakamalla vuorokausi (24 [h]) vuorokautisella käyttötuntimäärällä (todellisilla käyttötunneilla).

Oletetaan, että <u>käyntiaika vuorokaudessa</u> on $otv := 16$ [h], tällöin muunnoskerroin on

$$K := \frac{day}{otv} \qquad K = 1.5$$

Osan kesto (kalenteriaikaa) on siten

$$U = K \cdot X = K \cdot Q_W(\blacksquare, \mu s, \beta s) + K \cdot Q_W(\blacksquare, \mu r, \beta r)$$

2. Käyttöprofiiliin liittyvät parametrit

Käyntiaika vuorokaudessa [h] $otv = 16\,h$

Kokonaiskäyntiaika [h] $Oyear := 365 \cdot otv$ $Oyear = 5840\,h$

Käyttöjakso 0: $rpd_0 := 31$ [day]

Käyttöjakso 1: $rpd_1 := 210$ [day]

Käyttöjakso 2: $rpd_2 := 62$ [day]

Käyttöjakso 3: $rpd_3 := 62$ [day]

$$j := 1..3 \qquad \Sigma PT_j := \sum_{i=0}^{j} rpd_i$$

Käyntiajat sijoittuvat kalenteriin alkaen maaliskuun 31. päivä (käyttöjakso 0).

2.1. Epäkäytettävyyskustannukset

Käyttöjakso 0: Vian epäytettävyyskustannus $rpc_0 := 22 \cdot 10^3$ [€/h]

Käyttöjakso 1: Vian epäytettävyyskustannus $rpc_1 := 44 \cdot 10^3$ [€/h]

Käyttöjakso 2: Vian epäytettävyyskustannus $rpc_2 := 30 \cdot 10^3$ [€/h]

Käyttöjakso 3: Vian epäytettävyyskustannus $rpc_3 := 30 \cdot 10^3$ [€/h]

2.2. Korjauksen odotuskustannukset

Odotuskustannus kussakin käyttöjaksossa riippuu tapauksesta (tässä = epäkäytettävyyskustannus)

Käyttöjakso 0: Korjauksen odotuskustannus $DDc_0 := 22 \cdot 10^3$ [€/h]

Käyttöjakso 1: Korjauksen odotuskustannus $DDc_1 := 44 \cdot 10^3$ [€/h]

Käyttöjakso 2: Korjauksen odotuskustannus $DDc_2 := 30 \cdot 10^3$ [€/h]

Käyttöjakso 3: Korjauksen odotuskustannus $DDc_3 := 30 \cdot 10^3$ [€/h]

2.3. Korjaukseen liittyvät kiinteät kustannukset

Osan hinta [€]: $Bp := 30000$

Työkalujen vuokra [€]: $Th := 50000$

Asennustyö [€]: $Aw := 350000$

Korjaamon vuokra [€]: $Dh := 500000$

$Dfc := Bp + Th + Aw + Dh$

Kiinteät kust. yhteensä[€]: $Dfc = 930000$

PM kustannus ilman korjaamon vuokraa [€] $Pm := Dfc - Dh$ $Pm = 430000$

Korjausaika

Jokainen osan vaihto (UPM tai PM) johtaa korjaukseen korjaamolla. Korjausajan kesto on esimerkkitapauksessa keskimäärin 5 vuorokautta eli 120 tuntia (varsinainen korjausaika).

Korjausaika: $DOT := 5 \cdot day$ $DOT = 120$ [h]

Kullekin korjaustyypille (PM/UPM) voidaan valita oma korjausaika (oletuksena sama kaikille):

$DOT_{UPM} := DOT$

$DOT_{PM} := DOT$

2.4. Korjaamolle pääsyn odotusaika

UPM korjauksen odotusaika muodostuu pääosin korjaamon aikataulusta ja varaosien toimitusajasta:
- Logistiikka määrää minimiajan korjauksen järjestämiselle (tässä 3 vkoa).
- Varaosien toimitusaika riippuu siitä onko varaosaa saatavilla, jos ei, niin saattaa olla hyvinkin pitkä)

Korjaamon järjestämisaika $DDt := 3 \cdot 7 \cdot day$

Varaosien toimitusaika $SPt := 1 \cdot 7 \cdot day$

Lyhin mahdollinen UPM:n järjestämiseen tarvittava aika t_{UPMmin}

$t_{UPMmin} := \max(DDt, SPt)$ $t_{UPMmin} = 504$

Toteutuva UPM:n järjestämiseen varattu aika t_{UPM} määräytyy dynaamisesti simuloinnin yhteydessä jäljempänä.

2.5. Erityisen kiireellinen korjaus (hätäkorjaus)

Erillistä hätäkorjausta ei ole sisällytetty malliin. Hätäkorjaukseen liittyy osan rikkoutumiseen ja normaalista UPM:stä poikkeavaan korjausjärjestelyyn. Kustannuslaskennassa tämä voidaan huomioida erillisellä lisäkustannuskertoimella, jonka arvoksi on tässä valittu 1.

Hätäkorjauksen lisäkustannuskerroin: $E := 1$

Kullekin käyttöjaksolle määritellään oma kertoimensa (oletuksena sama kaikille):

Käyttöjakso 0: $E_0 := E$

Käyttöjakso 1: $E_1 := E$

Käyttöjakso 2: $E_2 := E$

Käyttöjakso 3: $E_3 := E$

3. Simulointimalli

3.1.Weibull-jakauman perusyhtälöt

Vikaantumisajan jakauman mallina käytetään edellisen mukaisesti Weibull-jakaumaa. Weibull-jakauman tiheysfunktio (pdf), kertymäfunktio F(x) (cdf) ja kvantiilifunktio (ppf, percent point function) $Q(u) = F^{-1}(u)$ ovat:

$$\alpha(\mu,\beta) := \left(\frac{\Gamma\left(1+\frac{1}{\beta}\right)}{\mu}\right)^{\beta}$$

Tiheysfunktio $$f_W(x,\mu,\beta) := \alpha(\mu,\beta)\cdot\beta\cdot x^{\beta-1}\cdot e^{-\alpha(\mu,\beta)\cdot x^{\beta}}$$

Kertymäfunktio $$F_W(x,\mu,\beta) := \left(1 - e^{-\alpha(\mu,\beta)\cdot x^{\beta}}\right)$$

Kvantiilifunktio $$Q_W(u,\mu,\beta) := \frac{\mu}{\Gamma\left(1+\frac{1}{\beta}\right)}\cdot(-\ln(1-u))^{\frac{1}{\beta}}$$

3.2. Vikaantumisajan (T) jakauman parametrit (service life distribution)

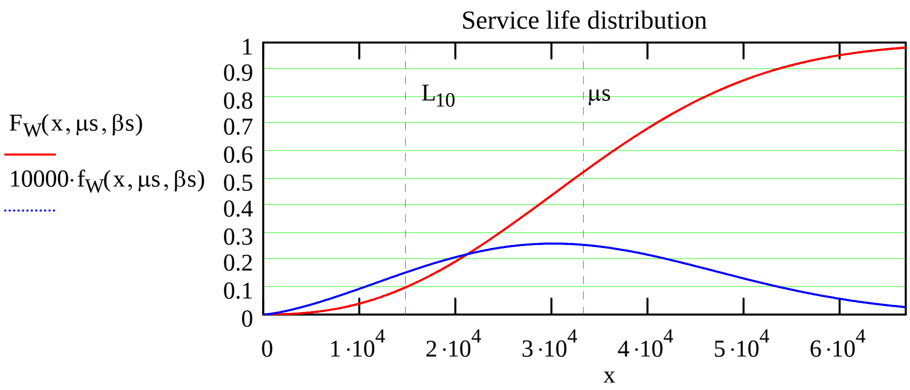
Tutkittavalle osalle on kerätty vikaantumisajan dataa tietyistä käyttökohteista, joissa ko. osan katsotaan olevan käytössä lähes samalla rasituksella (osien käyttötapa on sama). Tästä datasta on laskettu osan keston L_{10} ja Weibull-jakauman muotoparametrin β arvot.

$L_{10} := 14800$ [h] $L_{10} = 14800$

$\beta s := 2.41$

Kvantiilifunktion yhtälöstä ratkaistaan jakauman keskiarvo μ

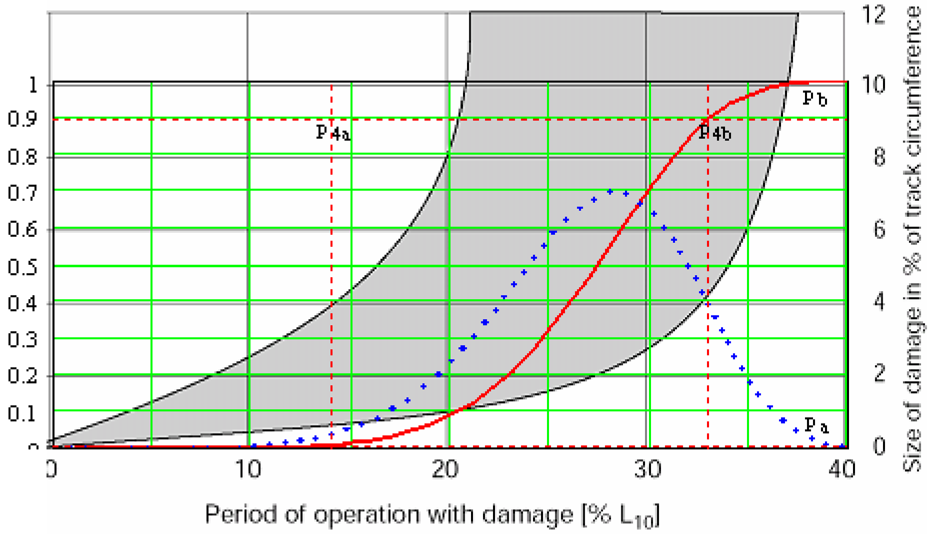
$$\mu s := \Gamma\left(1 + \frac{1}{\beta s}\right)\cdot L_{10}\cdot(-\ln(1 - 0.1))^{-\frac{1}{\beta s}} \qquad \mu s = 33381 \qquad x := 0, 100 .. 3\cdot\mu s$$



3.3. Jäljellä olevan elinajan (Δt) jakauma (remaining life distribution)

Jäljellä olevan elinajan malli on kehitetty soveltaen FAG:n julkaisussaan Publ No. WL 82 102/2 ESi: Rolling Bearing Damage. Singapore, FAG South East Asia PTE LTD esittämää alla olevan kuvan käyrästöä.

Publ No. WL 82 102/2 ESi: Rolling Bearing Damage. Singapore, FAG South East Asia PTE LTD. 71 s.



FAG:n käyrästön päälle on sovitettu jäljellä olevan elinajan jakauma. Vian kasvun mallina käytetään kaksiparametrista Weibull-jakaumaa; parametrit estimoidaan valitsemalla min (= a-kvantiili, p = 0.01) ja max (= b-kvantiili, p = 0.9).

Vierintälaakeri vioittuu käyttökelvottomaksi, kun sen vierintäpinnasta on vioittunut n. 4-10%. Tämän jälkeen vian kasvu kohti lopullista murtumista on erittäin nopeaa. Oletetaan tässä, että lopullinen murtuma tapahtuu, kun vierintäpinnasta on vioittunut 4% (FAG).

a-kvantiili: 1% todennäköisyydellä osa vioittuu ennen käyttömäärää $p_{4a} \cdot L_{10}$. p_{4a} on yllä olevasta kuvasta saatu vikaantuneen laakerin käyttöaika [%L_{10}], kun vierintäpinnasta on vioittunut 4%.

b-kvantiili: 90% todennäköisyydellä osa vioittuu ennen käyttömäärää $p_{4b} \cdot L_{10}$. p_{4b} on yllä olevasta kuvasta saatu vikaantuneen laakerin käyttöaika [%L_{10}], kun vierintäpinnasta on vioittunut 33%.

$L_{10} = 14800$	$p_{4a} := 14\%$	$p_{4b} := 33\%$	$\left(p_{10a} := 21\%,\ p_{10b} := 37\% \right)$	
Minimi (a-kvantiili)	$q_a := p_{4a} \cdot L_{10}$	$q_a = 2072$	$p_a := 0.01$	
Maksimi (b-kvantiili)	$q_b := p_{4b} \cdot L_{10}$	$q_b = 4884$	$p_b := 0.9$	

Minimin ja maksimin laskennassa käytettyjen parametrien arvot on saatu FAG:n kuvasta. Kuvassa esitetään vioittuneen vierintäradan %-osuus koko vierintäradasta vikaantumisen tunnistamisen jälkeisen käytön funktiona (vika tunnistetaan, kun n. 0.1% koko vierintäradasta on vioittunut).

3.3.1 βr-parametrin määritys

Sijoitetaan kvantiilifunktion yhtälöön edellä määritellyt parametriparit p_a, $p_{4a} \cdot L_{10}$ ja p_b, $p_{4b} \cdot L_{10}$, niin saadaan yhtälöryhmä

$$p_{4a} \cdot L_{10} = \frac{\mu}{\Gamma\left(1 + \frac{1}{\beta}\right)} \cdot \left(-\ln\left(1 - p_a\right)\right)^{\frac{1}{\beta r}}$$

$$p_{4b} \cdot L_{10} = \frac{\mu}{\Gamma\left(1 + \frac{1}{\beta}\right)} \cdot \left(-\ln\left(1 - p_b\right)\right)^{\frac{1}{\beta r}}$$

, josta ratkaistaan βr

$$\beta r := \frac{\ln\left(\frac{\ln\left(1 - p_b\right)}{\ln\left(1 - p_a\right)}\right)}{\ln\left(\frac{p_{4b}}{p_{4a}}\right)} \qquad \beta r = 6.338$$

3.3.2. μr-parametrin määritys

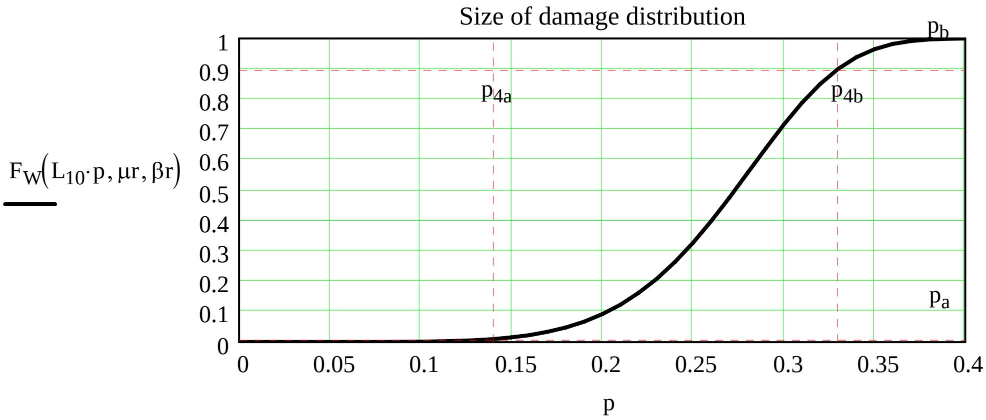
Sijoitetaan kvantiilifunktion yhtälöön edellä määritellyt parametriparit p_a, $p_{4a} \cdot L_{10}$ tai p_b, $p_{4b} \cdot L_{10}$, josta ratkaistaan μr

$$\mu r := \Gamma\left(1 + \frac{1}{\beta r}\right) \cdot p_{4a} \cdot L_{10} \cdot \left(-\ln\left(1 - p_a\right)\right)^{-\frac{1}{\beta r}}$$

$L_{10} = 14800$ $\mu r = 3984$

$p_{4a} = 14\%$ $p_{4a} \cdot L_{10} = 2072$

$p_{4b} = 33\%$ $p_{4b} \cdot L_{10} = 4884$ $p := 0, 0.01 .. 0.4$ $u := 0 .. 1$



4. Satunnaisten vikojen ja huoltojen yhdistetty simulointi

$\mu s = 33381$ $\beta s = 2.41$ $F1_W(x) := F_W(x, \mu s, \beta s)$

$\mu r = 3984$ $\beta r = 6.3$ $Fk_W(x) := F_W(x, \mu r, \beta r)$ $fk_W(x) := f_W(x, \mu r, \beta r)$ $Qk_W(u) := Q_W(u, \mu r, \beta r)$

Aika-akselina kalenteriaika: $F1_{Wk}(x) := F_W\left(\frac{x}{K}, \mu s, \beta s\right)$ $Fk_{Wk}(x) := F_W\left(\frac{x}{K}, \mu r, \beta r\right)$ $fk_{Wk}(x) := \frac{1}{K} \cdot f_W\left(\frac{x}{K}, \mu r, \beta r\right)$

4.1. Valitaan huoltoväli H ja huoltomarginaali ΔH:

H: $H := \frac{20}{5} \cdot year$

ΔH**:** $\Delta H := 0.1 \cdot year$

Huoltoväliä ja huoltomarginaalia varioimalla voidaan etsiä minimikustannukset (tässä ei ole automaattista minimin etsintää).

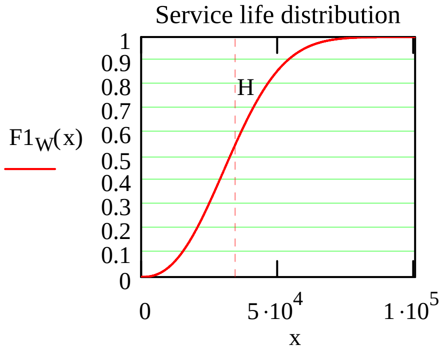
UPM:n vaatima minimiaika (aikaväli vian havaitsemisesta korjauksen aloitukseen)

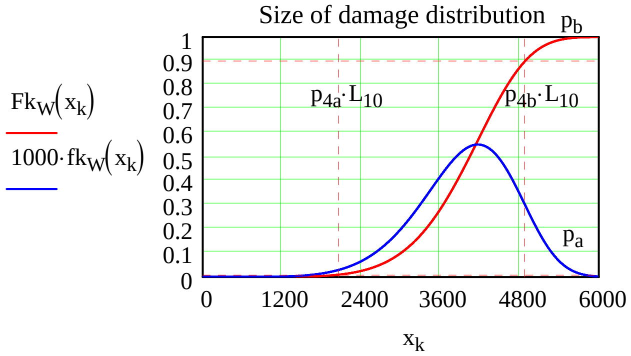
$\mathbf{t_{UPMmin}}$: $t_{UPMmin} = 504$

Todennäköisyys, että vian havaitsemisen jälkeen aikavälillä 0... $t_{UPMmin} = 504$ osa särkyy on $Fk_{Wk}(t_{UPMmin}) = 0.00000009889$.

Aika-akselina käyttötunnit (käyttömäärä):

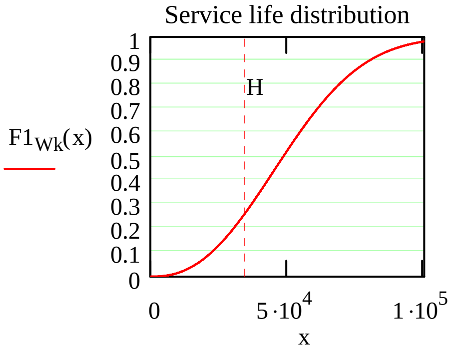
$x_k := 0 .. 1.5 \cdot \mu r$

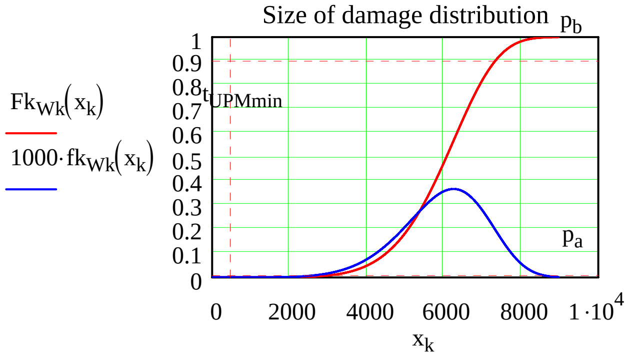




Aika-akselina kalenteriaika:

$x_k := 0 .. 1.5 \cdot K \cdot \mu r$





Todennäköisyys, että huoltovälillä H = $\frac{H}{year} = 4$ vuotta, havaitaan vähintään yksi vika, on $F1_{Wk}(H) = 0.271$.

4.2. Valitaan riskitaso Rmin

Riskitaso Rmin = osan vikaantumisajan (remaining life) vähimmäisluotettavuus: $Rmin := 0.83$

Varioimalla riskitasoa, voidaan etsiä minimikustannus (huoltoväli H ja huoltomargiaali ΔH on kiinnitetty).

Todennäköisyydellä $Rmin = 0.83$ osa kestää vähintään $K \cdot Qk_W(1 - Rmin) = 4927$ tuntia vian havaitsemisen jälkeen (remaining life).

$$\frac{K \cdot Qk_W(1 - Rmin)}{day} = 205 \quad \text{[day]}$$

****

5. Laskentaan liittyvät funktiot

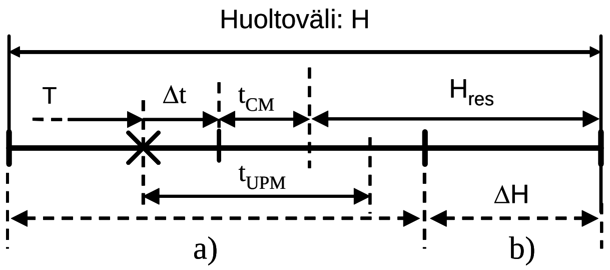
Funktio $MR(T_{min}, t_{UPMmin})$ palauttaa arvonaan odottamattoman ennakkohuollon ajankohdan t_{UPM} laskettuna vian havaitsemishetkestä (T).

▶ Funktio MR(Tmin,tUPMmin)

Funktio $CMR(M9, T, \Delta t, t_{CM})$ palauttaa vektorin, joka ilmoittaa missä rpd:ssä CM suoritettiin.

▶ Funktio (CMR(M9,T,dt,tCM)

Funktio $TT(H, H_{res}, M9)$ palauttaa arvonaan vektorin, jonka alkio 0 on uusimisien (CM, PM tai UPM) välinen aika ja alkio 1 on seuraava huoltoväli H_{res}. Seuraava huoltoväli vaihtelee huoltomarginaaliparametrien määrittelemällä tavalla (kts. kuva), riippuen CM:n ja UPM:n sijoittumisesta huoltovälille H.
- H on perushuoltoväli.
- H_{res} on huoltomarginaaliparametrien määräämä seuraava huoltoväli (jäljellä oleva huoltoväli).
- M9 on kumuloitunut käyttömäärä.



Funktio $TT(H, H_{res}, M9)$ laskee vikaantumis-/huoltoajan sekä em. huoltomarginaalien avulla päättelee seuraavan laskentakierroksen (seuraava vikaantumis-/huoltoaika) tarvitseman huoltovälin H_{res} arvon.

▶ Funktio TT(H,Hres,M9)

Seuraavalla demolla pyritään valaisemaan vikahetken T, prosessin käyttöprofiilin sekä parametrien t_{UPMmin} ja Rmin välisiä suhteita. Vapaa parametri on T_{min}. Muiden parametrien arvot on määritelty edellä. Niitä voidaan varioida, mutta niiden arvot on muistettava palauttaa alkuperäisiksi!

▶ DEMO: T, tUPMmin ja Rmin suhteet

Funktio $TTT(N, H)$ muodostaa peräkkäisiä satunnaisia vikaantumis-/huoltoaikoja kutsumalla funktiota $TT(H, H_{res}, M9)$ toistuvasti.

▶ Funktio TTT(N,H)

Funktio $nh(t, xx, s)$ palauttaa hetkeen t mennessä kertyneiden tapahtumien lukumäärän (tai aikajaksojen summan). Argumentiksi xx annetaan funktion $TTT(N, H)$ palauttama matriisi ja parametri s. s on sarakenumero, joka määrä, minkä $TTT(N, H0)$:n palauttaman sarakkeen arvoja kysytään.

▶ Funktio nh(t,xx,s)

6. Tapahtumien simulointi

Simuloidaan M kpl $TTT(N,H)$ -otoksia.

Uusimisien lukumäärä: $N := 12$

Koska etukäteen ei tiedetä, kuinka monta uusimista tulee tapahtumaan tarkastelujakson T aikana, on N:n arvo valittava riittävän suureksi tai on haettava kokeilemalla sellainen arvo, että laskenta menee läpi. (Jos yhdessäkin otoksessa on liian vähän uusimisia, ts. korjaus-vika-korjaus -prosessin kesto on < T, niin laskenta ei mene läpi!

Huoltoväli (4.1): $H = 35040$ $H = 4\,\text{year}$

Otosten lukumäärä: $M := 10000$ $i := 0 .. M - 1$ $nt_i := TTT(N,H)$

****

Tarkastelujakso (kalenteriaikaa): $T := 19.99 \cdot \text{year}$ $T = \blacksquare$

Suunniteltujen huoltojen (PM) lkm.

Suunnitellut huollot (PM) yhteensä:

PM: $\Lambda_{PM}(t) := \Lambda_{PM0}(t) + \Lambda_{PM1}(t) + \Lambda_{PM2}(t) + \Lambda_{PM3}(t) + \Lambda_{PM4}(t)$ $\Lambda_{PM}(T) = \blacksquare$

Odottamattomien huoltojen (UPM) lkm.

Odottamattomat huollot (UPM) yhteensä:

UPM: $\Lambda_{UPM}(t) := \frac{1}{M} \cdot \sum_{i=0}^{M-1} nh\left(t, nt_i, 12\right)$ $\Lambda_{UPM}(T) = 0.9673$

Huoltoja yhteensä (PM + UPM):

UPM + PM: $\Lambda_{Ren}(t) := \Lambda_{UPM}(t) + \Lambda_{PM}(t)$ $\Lambda_{Ren}(T) = 4.967$

Särkymisien lkm. yhteensä (alue a + b):

CM (alue a + b): $\Lambda_{CM}(t) := \Lambda_{CMa}(t) + \left(\Lambda_{CMbr}(t) + \Lambda_{CMbt}(t)\right)$ $\Lambda_{CM}(T) = 0.0311$

7. Huoltojen odotusajat

Keskimääräinen odotusaika CM:ää kohti [h] **(HUOM. odotusaika sijoittuu pääsääntöisesti edelliseen sektoriin)**

Odotusajat kussakin rpd sektorissa (alue a):

CM (a; rpd_0):

$$DDa0(t) := \frac{1}{M \cdot \Lambda_{CMa0}(t) + 10^{-10}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 33) \qquad DDa0(T) = 187.15$$

CM (a; rpd_1):

$$DDa1(t) := \frac{1}{M \cdot \Lambda_{CMa1}(t) + 10^{-10}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 34) \qquad DDa1(T) = 504$$

CM (a; rpd_2):

$$DDa2(t) := \frac{1}{M \cdot \Lambda_{CMa2}(t) + 10^{-10}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 35) \qquad DDa2(T) = 245.75$$

CM (a; rpd_3):

$$DDa3(t) := \frac{1}{M \cdot \Lambda_{CMa3}(t) + 10^{-10}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 36) \qquad DDa3(T) = 504$$

Odotusajat kussakin käyttöjaksossa (alue a/b):

CM (rpd_0) (alue a/b, t_{UPM}>H):

$$DDb0(t) := \frac{1}{M \cdot \Lambda_{CMb0}(t) + 10^{-15}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 29) \qquad DDb0(T) = 0$$

CM (rpd_1) (alue a/b, t_{UPM}>H):

$$DDb1(t) := \frac{1}{M \cdot \Lambda_{CMb1}(t) + 10^{-15}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 30) \qquad DDb1(T) = 0$$

CM (rpd_2) (alue a/b, t_{UPM}>H):

$$DDb2(t) := \frac{1}{M \cdot \Lambda_{CMb2}(t) + 10^{-15}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 31) \qquad DDb2(T) = 504$$

CM (rpd_3) (alue a/b, t_{UPM}>H):

$$DDb3(t) := \frac{1}{M \cdot \Lambda_{CMb3}(t) + 10^{-15}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 32) \qquad DDb3(T) = 504$$

Odotusajat alueella b:

Suuri riski

PM (alue b, riski):

$$DD0b(t) := \frac{1}{M \cdot \Lambda_{PM4}(t) + 10^{-10}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 24) \qquad DD0b(T) = 0$$

CM (alue b, riski):

$$DD4b(t) := \frac{1}{M \cdot \Lambda_{CMbr}(t) + 10^{-10}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 28) \qquad DD4b(T) = 0$$

Normaali riski

PM (alue b, t_{UPM}>H):

$$DD1b(t) := \frac{1}{M \cdot \Lambda_{PM3}(t) + 10^{-10}} \cdot \sum_{i=0}^{M-1} nh(t, nt_i, 25) \qquad DD1b(T) = 225$$

8. Kustannuslaskenta

Kustannukset kaikille vika- ja korjaustyypeille (€).

Kustannus = odotusaika*(menetetty)myyntitulo + korjaamoaika*(menetetty)revenu + kiinteä kustannus

Korjaamoon liittyvät kiinteät kustannukset muodostuvat seuraavista osista: Laakerikustannus, työkalujen vuokra, asennustyö ja korjaamovuokra.

Kiinteät kustannukset yhteensä.: $Dfc = 930000$ € Korjaamoaika: $DOT_{UPM} = 120$ [h] $T = 19.99$ year

8.1. Odottamattomat huollot (UPM)

UPM kustannukset yhteensä:

$COUPM(t) := CO_{UPM0}(t) + CO_{UPM1}(t) + CO_{UPM2}(t) + CO_{UPM3}(t)$ $COUPM(T) = 4.02 \times 10^{6}$

8.2. Satunnaiset viat (CM)

CM kustannukset yhteensä

$COCM(t) := CMCO_{a}(t) + CMCO_{b}(T) + CMCO_{br}(T)$ $COCM(T) = 148635$

8.3. Korjaamoviivekustannukset

Kustannus = Lukumäärä * (menetetty)myyntitulo * keskimääräinen odotusaika
Odotusaika sattuu pääsääntöisesti UPM:ää edeltävään käyttöjaksoon (voi periaatteessa olla niin pitkä, että koskettaa kahta tai useampaa sektoria (joilla on eri kustannus) samanaikaisesti, mutta sitä ei tässä huomioida.

Korjaamoviivekustannukset yhteensä:

$CODD(t) := CO_{CMDa}(t) + CO_{CMDab}(t) + CO_{PM3}(t) + CO_{PM4}(t) + CO_{CMbr}(t)$ $CODD(T) = 379584$

****

Kustannukset yhteensä (UPM:t + korjaamoviiveet + CM:t):

$CO_{Ren}(t) := COUPM(t) + CODD(t) + COCM(t)$ $CO_{Ren}(T) = 4550735.8$

****

APPENDIX 4

CASE-STUDIES: COMPANIES PRESENTATIONS

Total number of pages in Appendix 61

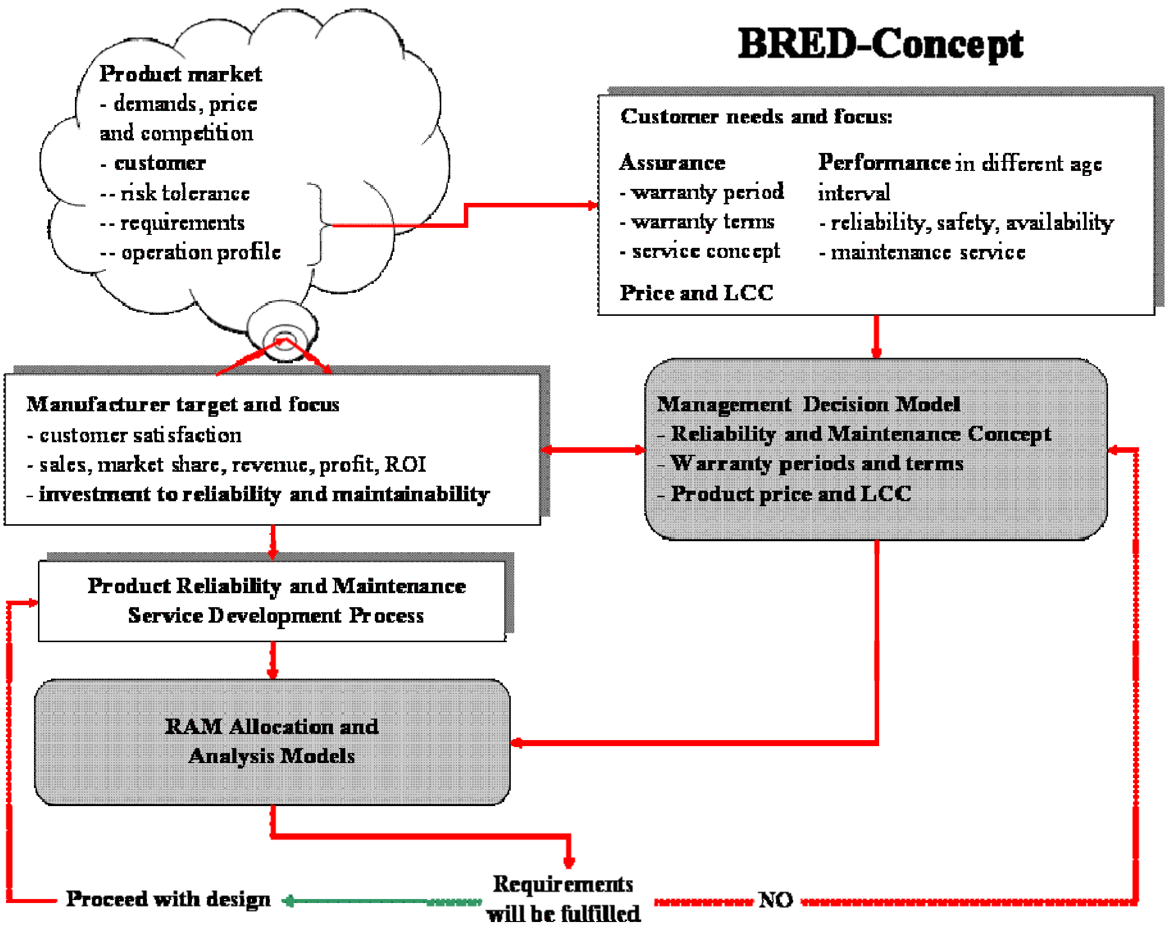
BRED-projektiin osallistuvien yrityksien esityksiä case-projekteista

- Kone
- Wärtsilä
- CarcoMacGregor

Table of contents

1 PURPOSE OF THIS DOCUMENT

This document highlights integrated business and technical product reliability design (BRED) project work at KONE during 2006 - 2008. The objective of BRED research project is to develop a management decision model that brings the reliability consideration and the economical and business expectations into the process of product design. Picture 1 illustrates BRED concept (Source Professor Seppo Virtanen).



Picture 1. High level presentation of BRED concept. With the model it is easier to identify the interaction and links between the customer satisfaction, the manufacturer business targets, product reliability and maintenance service performance.

2 SCOPE

This document describes the core activities relating to KONE BRED projects done by the Service Development and Reliability Laboratory departments. However this document does not cover in detail findings and results of work carried out as there is a need for external communication. More detailed documentation is available for KONE purposes.

The scope of KONE Projects was to improve maintainability and reliability engineering capabilities towards customer value driven and total quality management directions. Scope included Service Equipment Business related reliability metrics as Call Out Rate and availability. In addition pricing and risk analysis of maintenance contracts were drafted during project. Warranty target setting for New Equipment Business was excluded from the scope. However methods and structure suits well for warranty data management as well.

High data quality plays an important role in data management when data is turned into information and further to fact based decisions. Two Master's Thesis were carried out. Improvement actions relating to field data collection were the part of a BRED-project related Master's Thesis (Product dependability follow-up based on field data). A second MSc. thesis was conducted concerning the translation of customers' perceptions into product reliability requirements. This thesis is not an actual part of the BRED-project, but however it has a strong connection to its topics and therefore briefly presented in this document.

Other projects and activities were based on existing theories relating to failure logic analyzing and allocation of reliability requirements. Thus main effort of the project is put into the development of applications, documentation, implementation and training.

3 DEFINITIONS

COR	Call Out Rate
DFR	Design for Reliability
FTA	Fault Tree Analysis
KTO	KONE Technology Organization
LCC	Life Cycle Cost
NEB	New equipment Business
TCO	Total Cost of Ownership
PCM	Product Change Management
PD Project	Product Development Project
PDM	Product Development Matrix

RCM	Reliability Centered Maintenance
ROI	Return on Investment
SEB	Service Equipment Business

4 GENERAL

KONE delivers a performance edge to it's customers by creating the best user experience with innovative people flow solutions. High quality People Flow Solutions enable people to move smoothly, safely, comfortably and efficiently during whole life cycle. Reliable products maximize the performance of buildings of customers. Thus KONE has committed towards continuous quality improvement.

Elevator system is architecture of 12 subsystems achieving specified performance. In addition to customer-based performance requirements elevator system needs to meet its environmental (sustainability), safety and quality requirements. Quality of an elevator has great impact to customer satisfaction. As reliability is time-oriented aspect of quality its requirements are targeted in calendar time or usage rate. Not only customer satisfaction but also business profitability can be secured when reliability targets are well considered.

Elevator design work follows concurrent product development model and there are several key factors to deal and trade off. These factors include performance (speed, nominal load), features (machine-roomless), material cost, time to market and reliability. Design team needs to emphasize these factors optimally so that successful products can be launched into the market. Trade offing and finding correct "recipe" is very important when company is providing maintenance services and service repairs. Life cycle cost approach help finding correct balance between multiple design needs.

Without commonly agreed terminology and decision making models personal opinions may have too strong influence. In addition correct time and timing are important. The beginning of the product development is the right moment to raise LCC issues because critical design decisions are made then. It is not very fruitful to raise and communicate LCC if design is relative mature. Reliability has important role in LCC and in total cost of ownership (TCO) when service business is on landscape. Reliability Centered Maintenance RCM is commonly known approach in industries having high need for safety and profitability based on operational performance. Therefore reliability related targets must be well considered and agreed during early phase of product development.

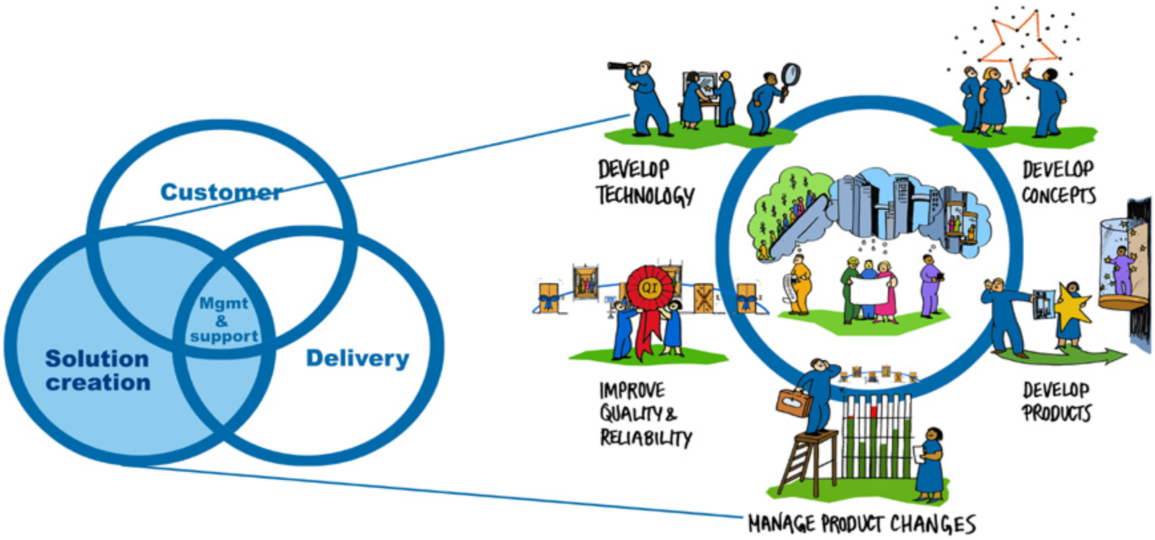
Reliability definition includes three important aspects, *probability* of operating without failure within given *time* under certain *conditions*. E.g. It can be allowed that system may have one technical failure annually (with low severity) during its 15 years useful life period under typical residential use. As it can be seen reliability target setting includes top management level strategic issues and thus top management is the correct forum to decide reliability targets for an elevator, escalator or any other system.

Service business profitability, sustainability, global competition and continues need to improve customer satisfaction are the drivers for quality improvement. System level targets are normally set based on the understanding the current level of reliability and philosophy of continuous improvement is used. This is valid especially in design projects, which are using existing design solutions and only some part of new equipment is re-designed. However making continuous improvement with linear approach has major gaps in case of revolutionary product development projects providing People Flow solutions as benchmark data does not exist. In order to support target setting discussions and decision every business needs good methods and tools for LCC and TCO evaluations. How top management can set reliability targets then? In addition to customer value and competitors offering acceptable level of cost of unreliability must be understood. This acceptable level depends on many factors including service contract pricing originating based on market condition.

KONE BRED cases created, communicated and implemented will support well further development and implementation of more complex methods towards better estimation of KONE TCO.

4.1 Background

Reliability Laboratory is responsible for KONE Way's Solution Creation process's improve quality and reliability activities, see picture 2.



Picture 2. KONE Way includes three core processes supported with management processes. KONE Technology Organization KTO is responsible for the solution creation process and it includes five sub processes. KTO Quality and Reliability including the Reliability Laboratory is the organization driving continuous quality and reliability improvements. Reliability Laboratory's mission is *to ensure product reliability and quality throughout the life cycle of the product.*

The main idea of Design for Reliability DFR is to improve and ensure that design meets its reliability goals without extensive over designing leading to increase of material costs. DFR also shortens time to market as it includes tools allowing part of the verification work to be carried out during early stages of product development and this minimizes risk for time and effort consuming test-fix-test cycles.

Service Development is part of Concurrent Engineering and supports PD project to make sure product is easy to maintain and fulfilling service business needs.

When system level targets are specified and allocated to component level then Product Development projects with the help of "Service Development" and "KTO Quality and Reliability" are able to calculate Return of Investment based on LCC and Reliability Centered Maintenance approach.

4.2 Goals of the BRED Projects

KONE BRED project and activities done besides have following goals:

1. Harmonize the quality and reliability metric terminology within KONE
2. Collect, investigate and utilize existing up-to date Call Out Rate COR data more efficiently
3. Data utilization and improve present capabilities to distribute and communicate reliability figures during early PD project phases.
4. LCC and PD Project target setting related people communication, process and tool development and improvements.
5. Study Fault tree based method to support Maintenance Need Analysis and Design FMEA etc tools.

5 PROJECT CASES

Following three BRED projects and one Master thesis having link to BRED project goals are briefly summarized in following sections.

5.1 Product Dependability Follow-up based on Field Data

The first KONE BRED project case was a Master's Thesis that examined products' perceived dependability follow-up and reliability centred maintenance planning. Thesis was performed in the Service Development department with strong co-operation with the Reliability Laboratory.

The basic purpose of the thesis was to examine the dependability of the products that are already in field. The objects of interests were failures as well as performed repair and maintenance actions. Plenty of field data has been saved into the management and maintenance systems of KONE. The evaluation of the current field data and possibility to utilise the data in maintenance planning and DFR were researched.

The aim of the thesis was divided into five main stages:

1. Locate field data sources and analyse current data
2. Find a method to model the lifetime of component based on the field data
3. Optimise a maintenance strategy for a critical component
4. Identify opportunities to improve products' dependability follow-up process
5. Gather up opportunities for product reliability and availability growth

A starting point for a follow-up was the back reported field data from maintenance actions, which included for example the reason and target of the work as well as the performed actions on site. The current level of field data was evaluated and methods to extract data were examined. The material for this study was collected from four frontline units, starting from year 2003. At the beginning, the extracted field data was analysed in general level. In addition, comparisons between countries were performed to understand the content and reliability of data.

The major part of the thesis consisted of a dependability case study that was done for a elevator component. The performed field data analyses have identified that the particular component failure is one of the most frequently reported call-out root cause in MonoSpace elevators. KONE aims to minimize call-outs by performing appropriate maintenance, which is an important financial issue, and increases customer satisfaction. In the first phase of the case study, a reliability function was modelled for the component. The Kaplan-Meier estimation method was utilised for modelling. The used calculation formulas were developed by cooperating with the reliability engineering experts of Tampere University of Technology. After that, the cost factors of corrective and preventive maintenance were evaluated for the component. Then, by utilising the modeled reliability function and ELMAS and RAMoptim software the most suitable maintenance strategy was optimised. To understand cost factors, the dependability simulation was performed for different time scenarios as typical customer warranty period, a typical maintenance contract period and whole elevator's lifetime.

In the second phase of the case study a fault tree analysis was performed. The aim was to simulate the root causes of the component's failures. The fault tree model was tested and it was found to be functional in failure analysis. A similar fault tree model could also be used in product design phase. It provides a possibility to compare the effects of different parts on the dependability of the designed product, as is shown in InnoTrack BRED-case.

Thesis' conclusions outlined demands and advantages for more systematic dependability follow-up process. The main demands include the further development of back reporting procedures and follow-up tools. In this way maintenance processes can be developed. Since the beginning of the BRED-project KONE has taken a great step forward around this topic. Possibilities to improve product dependability can be achieved by increasing the number of preventive component replacements and the further development of remote monitoring utilization. The experiences collected from the methods of the thesis and the reliability software used in preventive maintenance optimization and DFR were promising.

The more detailed results of the case study of this MSc. thesis were published globally by Springer in "Proceedings of the 3rd World Congress on Engineering Asset Management and Intelligent Maintenance Systems Conference (WCEAM-IMS 2008)".

5.2 Call out rate target setting and feasibility check improvement

The Fault Tree Analyze FTA based model was applied in a benefit of improving existing methods to specify and allocate system level reliability requirements. Modeling and allocation was done for two cases, existing MonoSpace COR and for a new innovation. The results of applications developed can be used to as an input for quality improvement based project start-ups.

Application is based on the statistical customer focused TOP-DOWN approach. The main benefit of top-down approach is that it can be adopted with the present level of data and when more in detail data is available accuracy of the analysis can be improved. These will point out potential components for cost efficient call out reduction without forgetting failure effects noticed by the final users (customer value).

5.2.1 Field Data Allocation for existing Call Out Rate data

First COR target setting and feasibility check improvement case was tried with elevator doors because of available technical understanding about root causes in addition to high quality COR data originating from product dependability follow-up based on field data Master’s Thesis. Then developed model and application was applied to cover whole existing MonoSpace.

The primary purpose of the elevator doors is guarantee passenger safety both inside car and at the landings. Car door and landing doors are usually separated when reliability analysis are done as there is only one car door in a single elevator. The number of landing doors depends on the number of landings elevator is serving. In addition landing door subsystem is fairly simple when compared to car door as there are no electronic components and all electrical components are fairly simple. As one elevator system has several doors elevator system reliability will suffer if each doors have design related defects that cannot be corrected easily in field conditions.

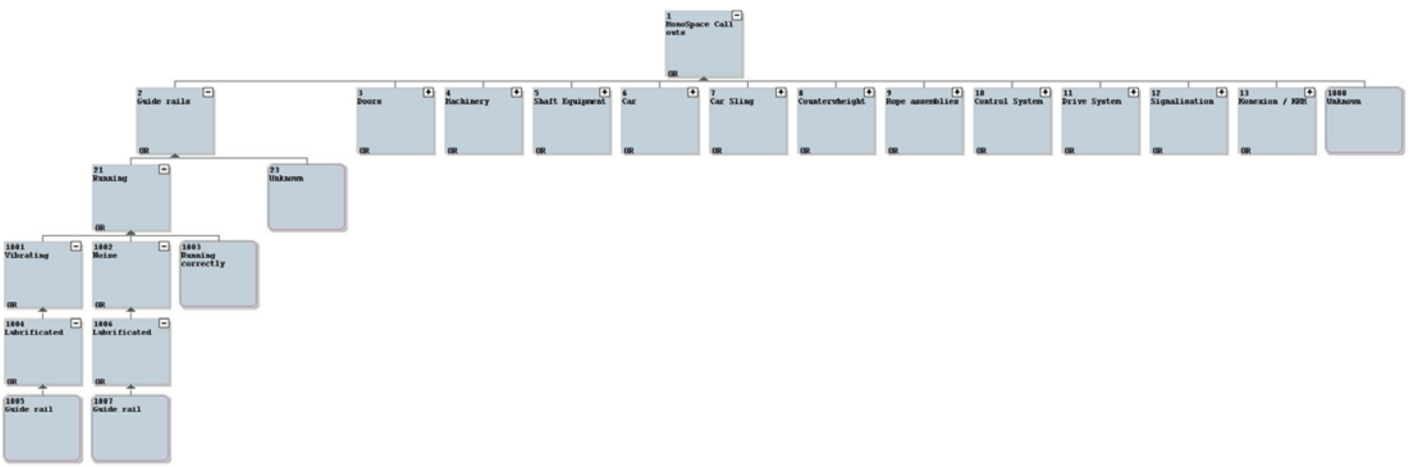
An operation of elevator door system is one of the most important factors for customer satisfaction. If doors are not closing properly whole elevator system is not able to operate. Also “soft failures” like noise and vibration are causing easily customer dissatisfaction and further unscheduled site visits and cost for KONE service business. Therefore designing of any door related systems of components must fulfill tight reliability requirements nothing to speak about safety functions of the doors.

Call out rate for the door was calculated by dividing number of annual site visits with the number of lifts in service. Data includes several root causes and some with no relationship to design quality non-parametric calculation method was used and assumption was made that failure rate is constant (exponentially distributed). Allocation included following five logical levels.

1. Primary customer effect, a) Elevator operating / b) Elevator not operating
2. Secondary customer effect, e.g. a1)noise / b1)standing at floor
3. Business effect, e.g. replacement, cleaning, repair etc
4. Primary component cause level, landing door / car door
5. Secondary component cause level, e.g. Landing door lock / car door operator

Once door trial case was done modeling was expanded to cover whole existing MonoSpace system and its Call Out data. Engineering judgment was used when making modeling in order to limit amount of gates.

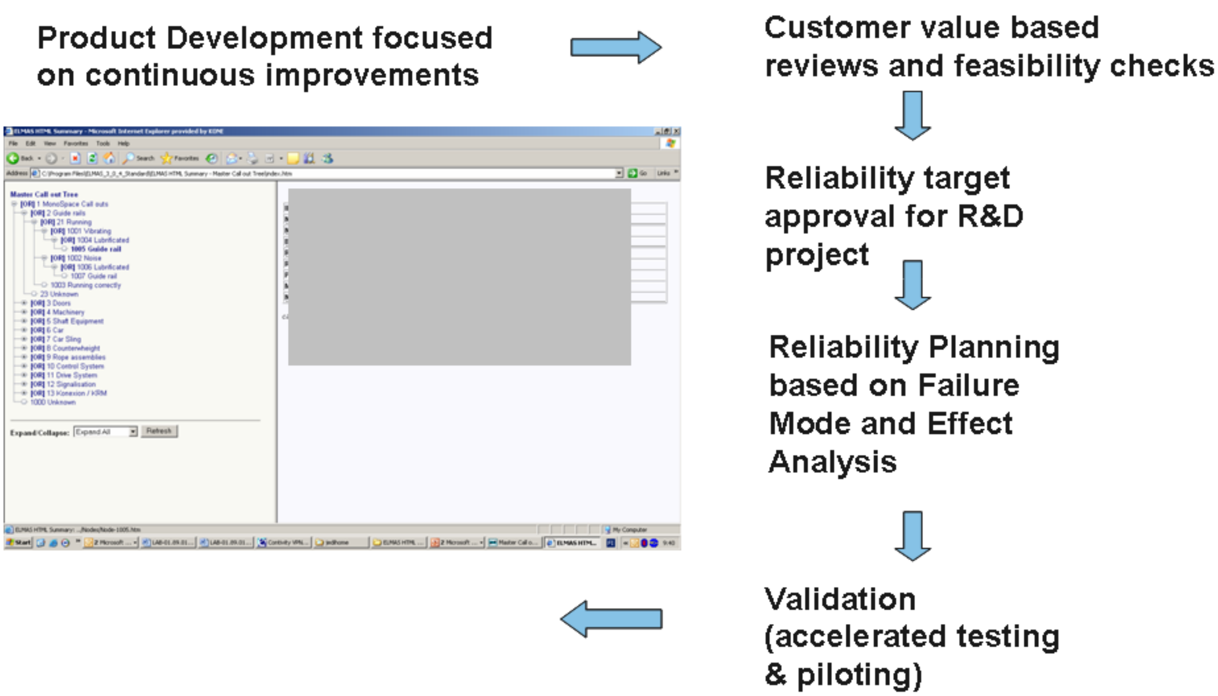
Picture 3 shows an example of one elevator system's subsystem, guide rails in COR tree.



Picture 3. Guide rail allocated. Based on the data and further modeling guide rail related call outs are causing ride comfort related customer dissatisfaction. Elevator is still under operation but noise and vibration levels have exceeded level of customer acceptance. In both customer effects fault has been corrected by adding oil to guide rails and guide shoes.

After modeling tree and making high level allocation dividing 100% between gates and their sub trees accordingly with Elmas sw data was transferred manually to RAMAlloc sw. This sw was used to simulate constant failure rates for root causes. Once Failure rates were simulated they were manually transferred back to Elmas. The Elmas simulation was used and once carried out HTML based data structure was generated as this data format is easy to distribute using MS Sharepoint among people not having need for Elmas sw.

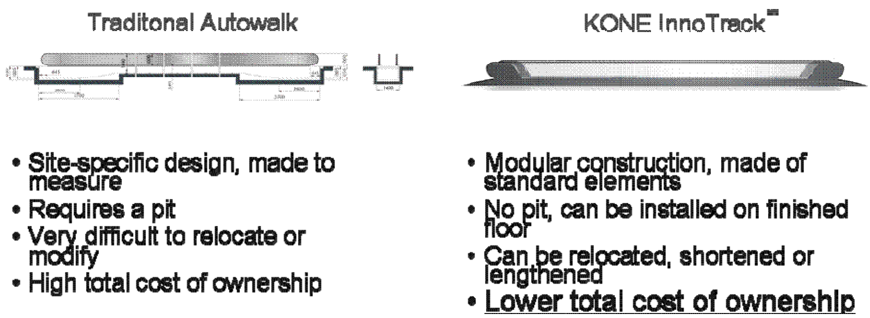
Scope of the work didn't cover maintenance cost related items at this stage. However this work will continue so that LCC can be better evaluated and lowered as needed based on customer and service business needs. Picture 4 shows conceptual level idea of the Design for Reliability process. Process shown has a capability for customer value improvements and reliability engineering excellence based on reliability budgeting against set targets.



Picture 4. Picture summarize Design for Reliability process proving continuous improvement and allowing organizational learning based on success stories and Lessons Learned captured.

5.2.2 Specification and allocation of InnoTrack's availability and maintenance cost requirements

Second KONE BRED project relating to DFR and its target setting improvements was done along with InnoTrack project. InnoTrack is an innovative autowalk application which minimizes constructional space requirements. This and other Innotrack features bring added value for customers, see picture 5.

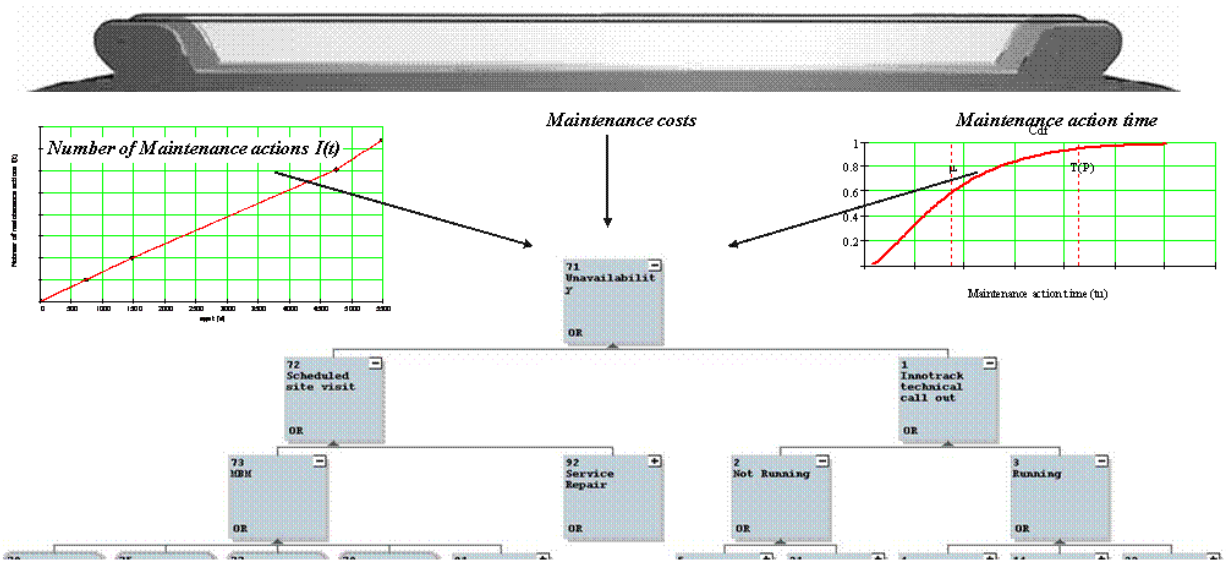


Picture 5. Picture highlights customer value that InnoTrack provides compared to existing solutions.

These were the key characteristic concerning Total Cost of Ownership in InnoTrack case:

- Reliability and Availability
- Life cycle cost: Based on installed equipment, maintenance cost, spare parts, energy consumption over a period of 20 years
- Maintenance intervals
- Preventive replacement of different parts
- Spare part list and prices

In order to make PD Project's work easier modeling and system level allocation was done based on availability, COR requirements and service business monetary requirements. Picture 6 illustrates high level allocation.



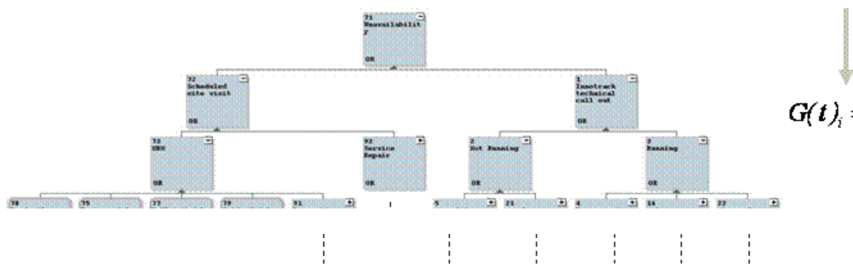
Picture 6. Targeted availability and maintenance costs were allocated using to gates, scheduled site visits and Call outs. Modeling was done till appropriate design level.

The primary purpose of this case was to divide customer based system level availability requirement to subsystem and further to key component level. This information is used for reliability verification purposes including reliability related discussions with suppliers. Allocation provides also good input for further Reliability Centered Maintenance studies (optimization of maintenance).

As quantitative field data is not available and design is at its early stages many engineering judgments are done supported with formulas shown in the picture 7. Both Elmas sw and RamAlloc were used according same practices presented above. First hand information and component level design targets are able to review in a feasibility check and when more data is available. Additional data comes from mathematical feasibility calculations (like bearing), Life data Analysis (accelerated testing) and from component suppliers. Scope of the allocation is limited to design quality (design's inherent reliability). Therefore it is assumed that both manufacturing and installation (service) quality do not decrease availability.

$$A(t) = \left(1 + MTTM \cdot \frac{d}{dt} I(t) \right)^{-1} \quad R(t) = e^{-I(t)}$$

Availability and Reliability allocation | *Maintenance time allocation*



$$I_i(t) = \alpha \cdot w_i \cdot I(t)$$
$$w_i = f(x_i, y_i, \tau)$$

$$G(t)_i = G(t)^{\beta \cdot z_i}$$

$$x_i \uparrow \Rightarrow w_i \downarrow \Rightarrow R_i, A_i \uparrow$$

$$y_i \uparrow \Rightarrow w_i \uparrow \Rightarrow R_i, A_i \downarrow$$

x_i represents an object's importance from customer's perspective
y_i represents an object's complexity from technical stand point
τ weights importance against complexity
α gate specific level parameter for maintenance action tendency
z_i represents an object's repair complexity from technical stand point, and reflects directly the ratios between the maintenance action times of the design entities
β gate specific level parameter for maintenance action time

Picture 7. Both importance from customer's perspective and object's complexity were considered while making engineer judgment based allocation.

Based on the specification and allocation of InnoTrack's availability and maintenance cost requirements following simplified example of the BRED-model application for prizing and risk analysis of maintenance contracts was carried out:

- Basic entities for pricing InnoTrack's service contracts
- Randomness in maintenance action related costs
- Service contracts
- Manufacturer's service costs and risks
- Pricing, manufacturer's profits and risks
- Cumulative incomes, costs and profits
- Sale assessments and profits during market period

Work done during this KONE BRED project enables further in detail Reliability Centered Maintenance work within InnoTrack's concurrent engineering Product Development project.
Project findings and results can be applied to other KONE projects as well.

5.3 KONE Product's Quality and Reliability metrics harmonization

A part of KONE BRED project was a revise for existing quality and reliability metrics so that they better support cross functional organization needs. The purpose of this work was to set common quantitative metrics and define responsibilities for continuous quality improvement during product's life cycle. The updated document describes product's quality and reliability metrics during product's life cycle (e.g. Early Failure Rate EFR and Call Out Rate COR).

Important part of this work was making full chain quality management responsibilities clearer especially concerning target setting. This goal was achieved so that marketing and offering teams are responsible for give input on customer requirements also regarding quality and reliability and top quality management is responsible for reviewing and approving reliability targets.

5.4 Customer Value-Driven Design for Reliability in Product Development

The scope of the thesis was defined into the following three research questions:

1. How can the customer's perception of reliability be captured and translated into product reliability requirements?
2. How are KONE offerings delivering customer value through product reliability?
3. How could/should the customer view be taken into consideration in product development?

The thesis scope was limited to considering the Call Out Rate metric and product failures causing call outs. It was investigated if the effect of failure causing a call out makes a difference to the customer. It can be dictated that various needs are subjected to an elevator from various types of customers, and therefore there may be high differences in relative criticality of different faults.

Research question number one was tackled with case study consisting of customer interviews. A number of customers were approached with a three-step session. The first step was an open-ended interview where the customer gave feedback on his perceptions of elevator reliability and also spoke about their concerns. The second step was a structured method based on the Conjoint Analysis technique. In the method customers were presented with different scenarios describing the operation of an imaginary elevator within one year. From the method customers relative preferences toward the high-level types of elevator faults were able to be dictated among other issues. In the third step of the interview session the customer was presented a number of different elevator malfunctions (identified by studying KONE maintenance records), that the customer arranged into a rank-order by their criticality. The purpose of this last method was to add detail into customer preferences captured with the Conjoint Analysis technique. As the outcome of the case study the customer-perceived criticalities were estimated for different types of elevator faults, supported by other customer comments.

Research question number two was tackled by studying call out back reporting related to the case study elevators. Elevator faults were divided into the same division by effect of failure to customer, as what was probed from the customer. Therefore the failure rate for each type of failure was estimated. For each type of failure it was analyzed what elevator component sub-systems were causing them, and through this analysis the division of failures by elevator component was also estimated. The gathered data, including the customer-perceived priorities, was summarized into an adaptation of a QFD matrix. As the result of QFD application, the outcomes of the method were the design priorities, where the efforts for reliability improvement in the technical realm would yield the most customer value. Research question number three was mostly answered by making conclusions based on the case study and field data study described above. More findings into product development process needs were identified by discussing how the results of the thesis could be implemented to an actual product development project. Finally, by studying the current process, process proposals were given.

TUOTTEEN LUOTETTAVUUDEN JA TURVALLISUUDEN SUUNNITTELU

CASE: WÄRTSILÄN POLTTOKENNOJÄRJESTELMÄT

BRED loppuseminaari 12.12.2008

Kim Åström
Senior Expert, System Development

WÄRTSILÄ

SISÄLLYS

- Wärtsilän polttokennohanke
  - Tausta
  - Kehityksen tilanne
  - Näkymät
- Luotettavuusanalyysit
  - Menetelmät
  - Mallit
  - Kokemukset & tulokset
- Turvallisuus
  - Menetelmät
  - Tulokset

WÄRTSILÄ

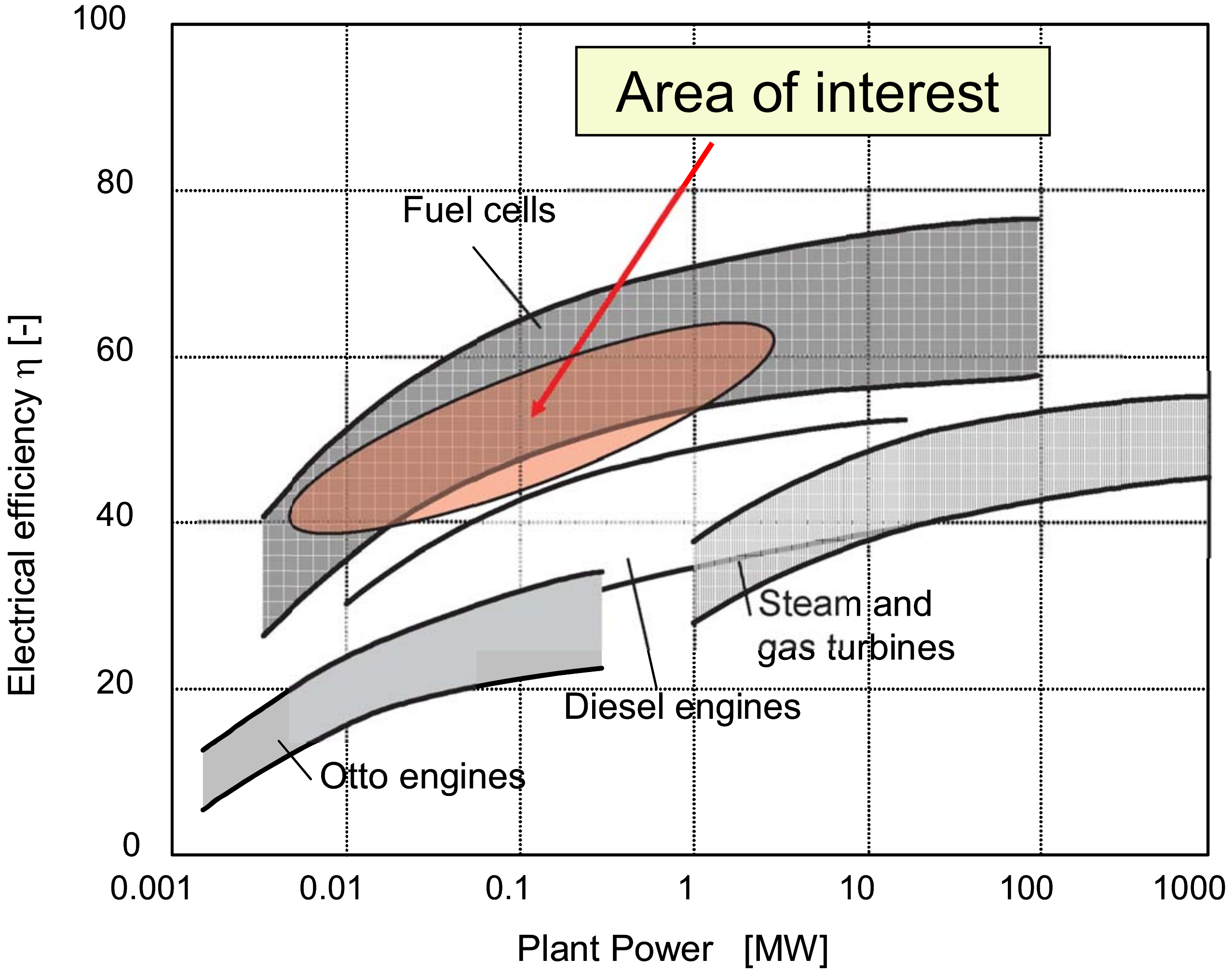
Wärtsilä Fuel Cell Program

- Wärtsilä's fuel cell R&D program is to develop and commercialize SOFC based power units for distributed power generation and for marine auxiliary power.
- We focus on design and engineering of fuel cell systems. System integration and application know-how are key areas where Wärtsilä's expertise is utilized.
- Wärtsilä has successfully demonstrated the WFC20 α-prototype and will demonstrate pre-commercial units in the 20 kW power class in 2008-2009.
- Larger commercial products in the 50 - 250 kW power range are planned to follow by 2010.

WÄRTSILÄ

Polttokennot – Miksi?

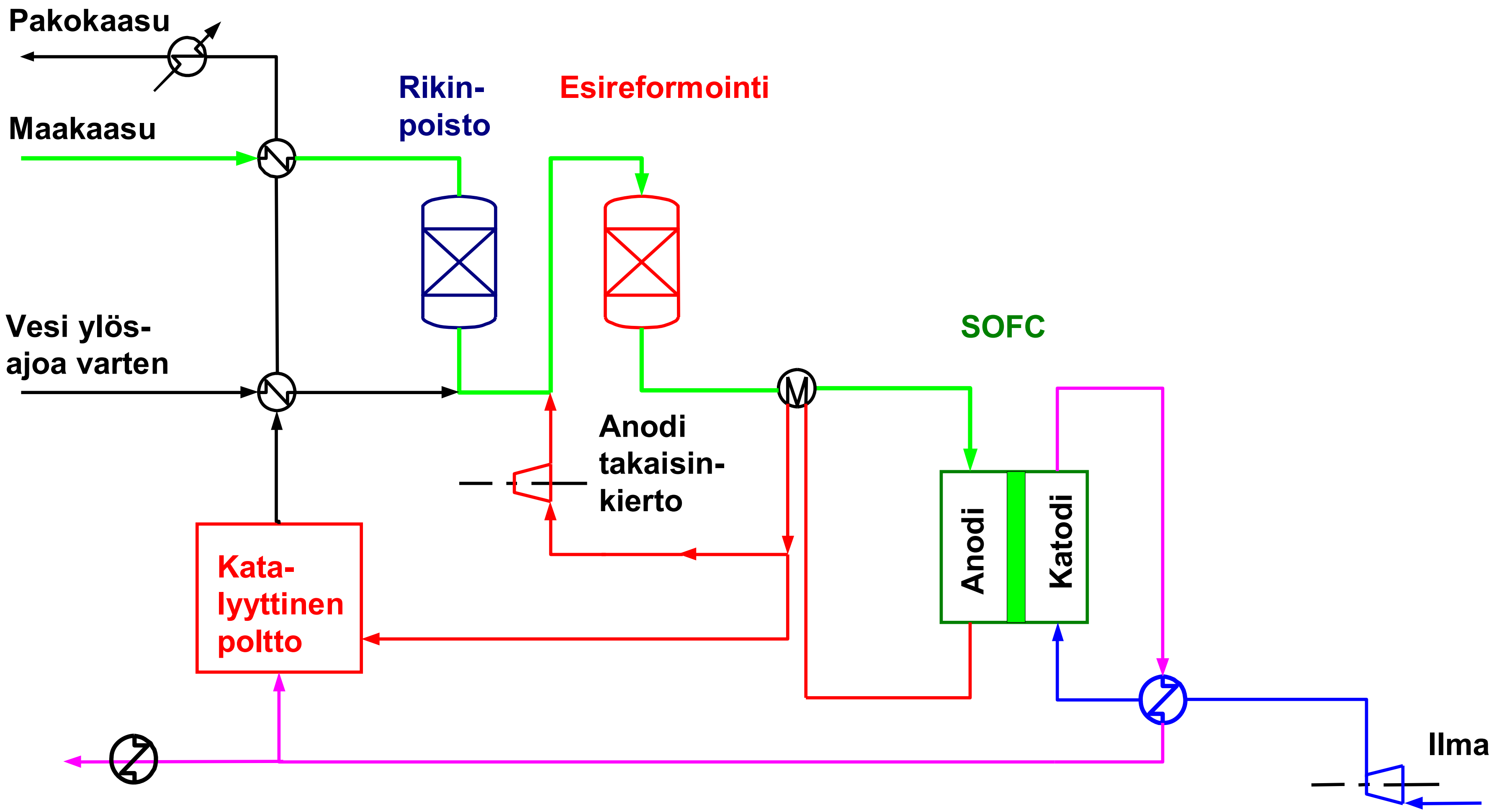
Polttokennojärjestelmän hyötysuhde



Source : W. Vielstich, *Handbook of Fuel cells – Fundamentals Technology and Applications*, Volume 1, Chapter 4, p. 29. Wiley (2004), ISBN: 0-471-49926-9

POLTTOKENNOPROSESSI

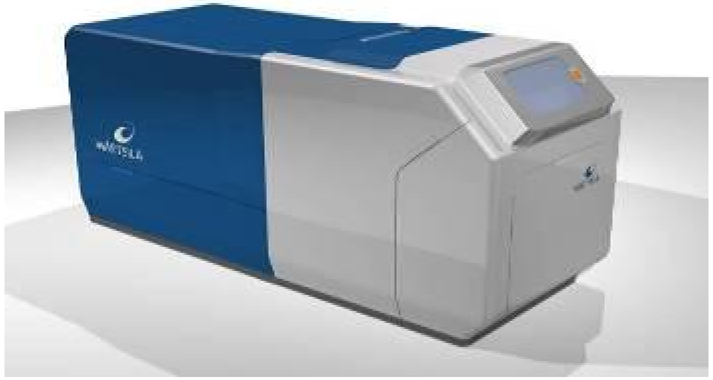
- ***Maakaasukäyttöinen SOFC konsepti***



WÄRTSILÄ

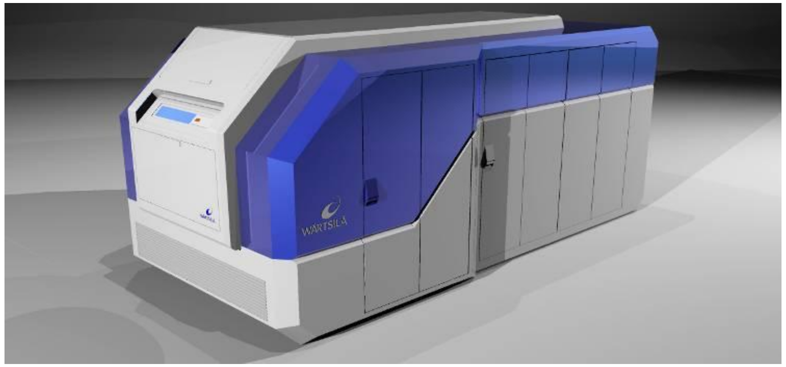
Wärtsilä Fuel Cell Program

SOFC 1 - 5 kW test system
NG, 2004, > 7000 h in operation



WFC20, WFC50
20 – 50 kW,
NG, methanol, Bio gas
ηe > 45 %
2007 - 2010

WFC20 α-prototype
20 kW, NG, > 1000 h
η_e > 42 %   2006 - 2007



WFC250
250 kWe,
NG, methanol, bio gas
η_e ~50 %

WÄRTSILÄ

WFC 20 α-Prototype, operation experiences

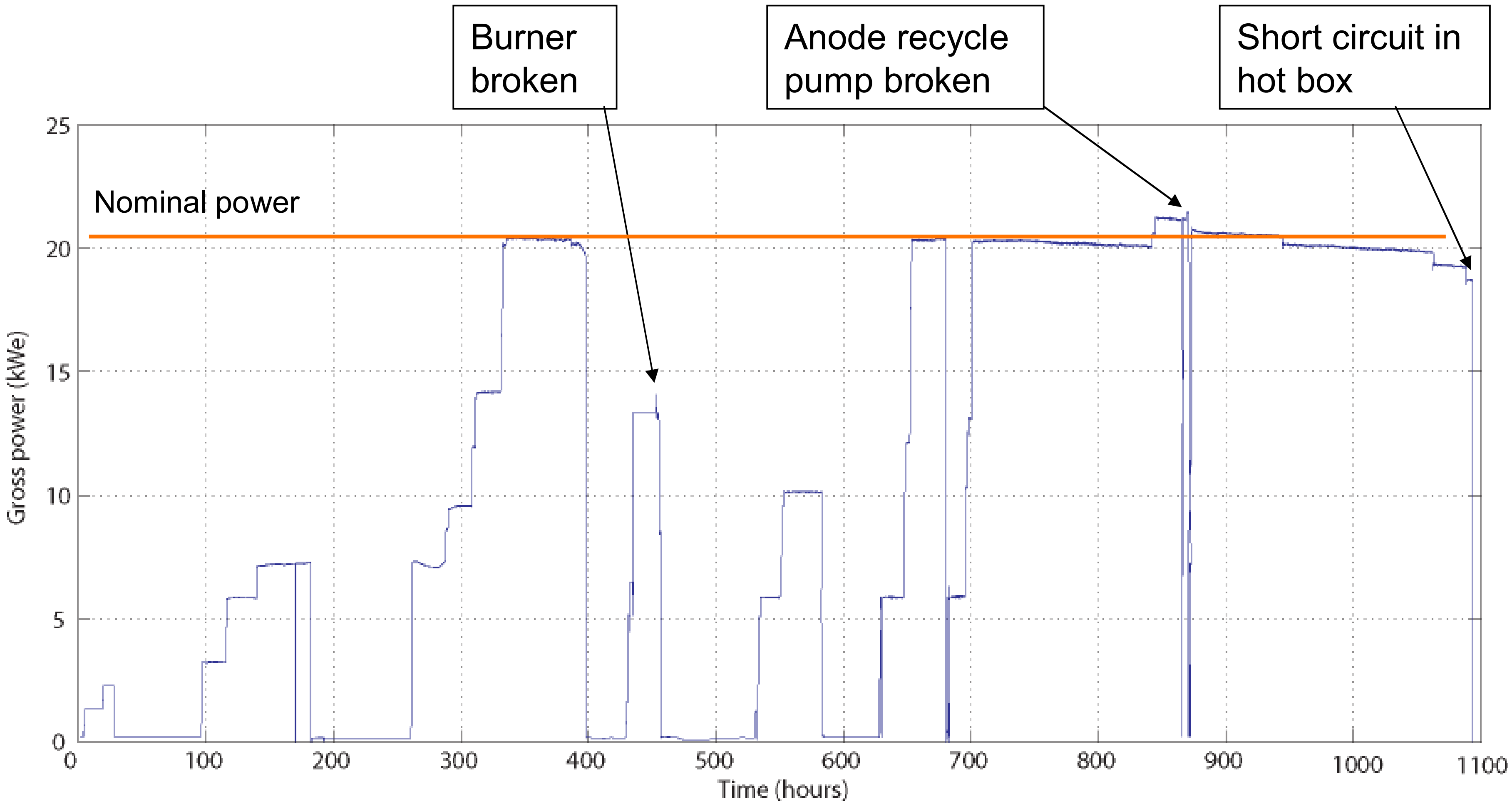
WFC20 Prototype was started on October 23rd, 2007

- The largest planar SOFC unit in world -

- System has been operated for 1096 hours of which 800 h under load
- Stable unattended operation achieved
- Nominal power reached
    - maximum gross power has been 21.5 kW and net power 17 kW.
- Stack efficiency 50.4 % (dc) with low FU provides good basis for achieving the targeted 42 % electrical efficiency
- Gross electrical energy output 12 MWh

WÄRTSILÄ

Alpha gross electric power output during 1096h



WÄRTSILÄ

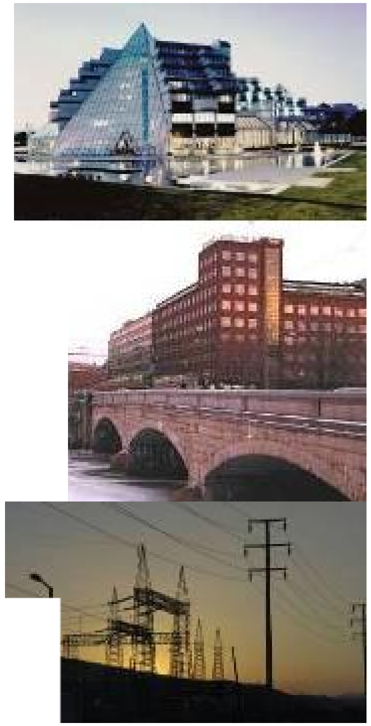
Applications & Customers

Short route ferries, car carriers, cruiser

Biogas from Landfills,
Waste water and farms

Telecom/data centers, Hospitals, Banks

Hotels, malls, offices, industries



WÄRTSILÄ

LUOTETTAVUUSANALYYSI

Järjestelmän luotettavuusanalyysityö aloitettiin vuonna 2005

Lähtökohdat:

- Luotettavuus ja elinikä keskeisiä tuotteen kilpailukyvyn kannalta
- Monimutkainen järjestelmä => tarvitaan systemaattisia menetelmiä kokonaisuuden hahmottamiseksi
- Riittävä luotettavuus/käytettävyys edellytys jo protovaiheessa

Alustavat tavoitteet:

- Menetelmien kartoitus ja valinta
- Menetelmien käyttöönotto
- Järjestelmäkomponenttien luotettavuuden kartoitus
- Alustavien luotettavuusennusteiden määrittäminen
- Alustavat vaatimukset komponenttien luotettavuudelle

WÄRTSILÄ

LUOTETTAVUUSANALYYSIN LÄHESTYMISTAPOJA

- **Tilastollinen (laskennallinen) lähestymistapa**
  - Luotettavuuden ennustaminen
  - Riskien kvantisointi
  - Luotettavuusvaatimusten määrittäminen (allokointi)

  Edellyttää luotettavuusdataa

  - tilastoitu tieto
  - rasituskestoanalyysit
  - testaus
  - **omat oletukset**

- **Kvalitatiivinen lähestymistapa**
  - Vikalogiikan hahmottaminen (syy-seuraussuhteet)
    - FMEA (Failure Mode and Effect Analysis)
    - HAZOP (Hazard and Operability Analysis)

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KÄYTETTY LÄHESTYMISTAPA

- **Laadittiin FMEA kaikille järjestelmän keskeisille komponenteille**
  - Komponettien vikaantumismekanismit ja näiden seuraukset
  - Vikojen havaittavuus
  - Kriittiset tapahtumaketjut
- **FMEA:n pohjalta laadittiin vikapuu**
  - Fokus vioissa joista voi seurata järjestelmän alasajo
- **Vikapuun pohjalta simuloitiin järjestelmän vikakäyttäytymistä dynaamisessa mallissa**
  - Pohjana karkeat arviot komponenttien vikajakaumista
- **Varsinaiset polttokennot käsiteltiin erikseen**

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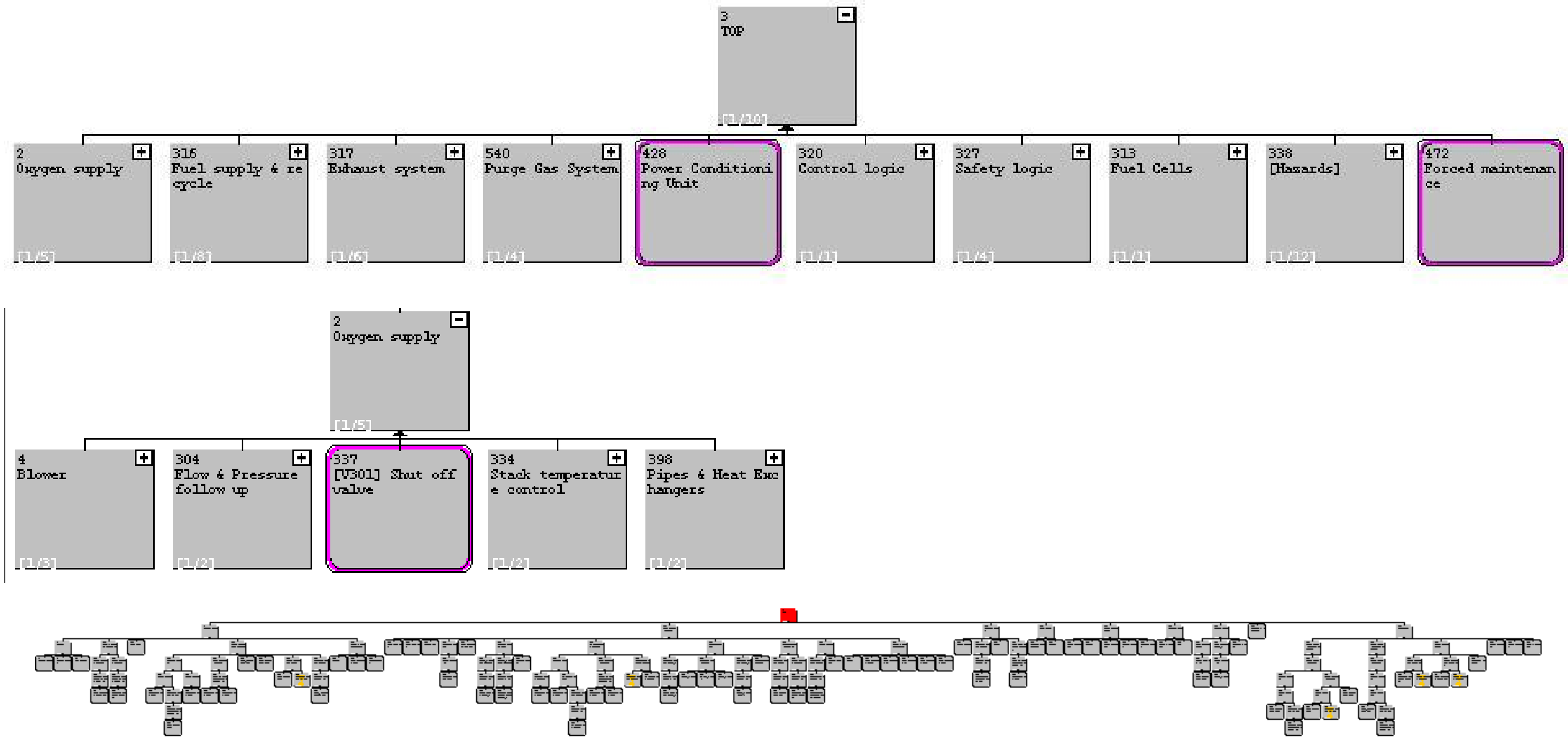
VIKAPUUANALYYSI

- Vikapuun komponentit: juurisyyt ja seuraukset
- Yhdistetään Boolen logiikalla + satunnaisparametreilla



WÄRTSILÄ

DYNAAMINEN MALLINUS

Syötteet:

- Järjestelmän elinikä
- Vikapuu

Kullekin vikapuun juurisyylle (komponentille):

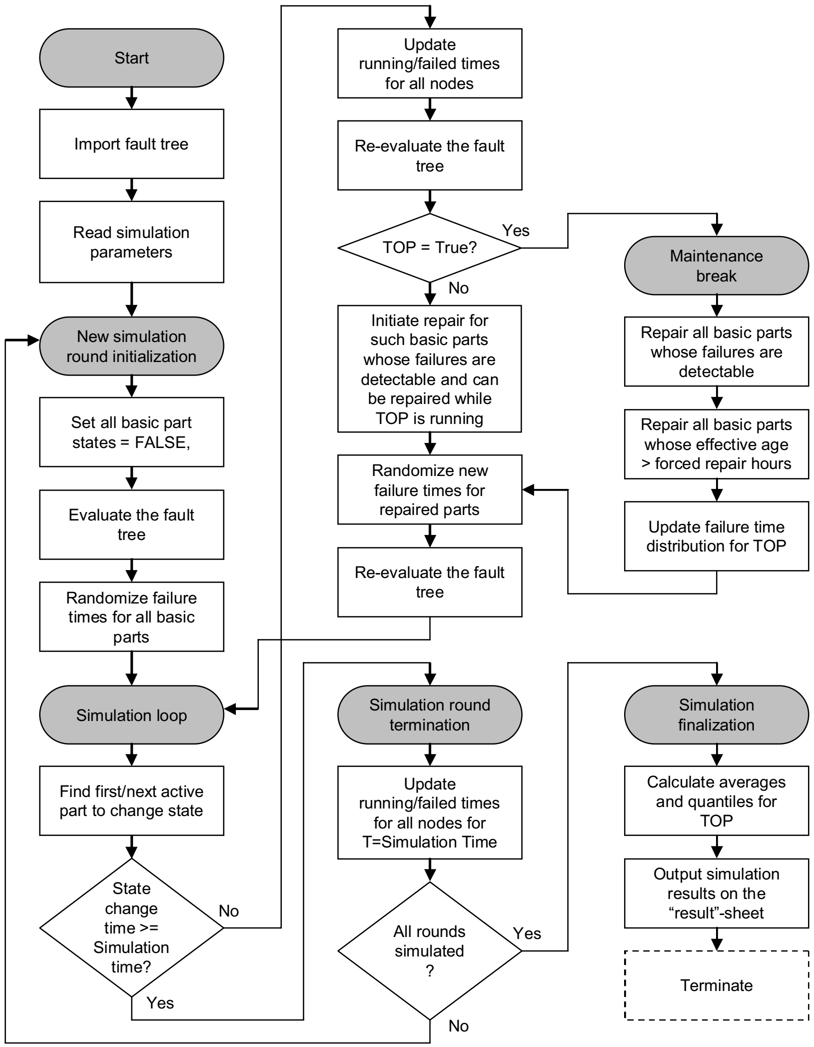
- – Vikaantumis-todennäköisyys käyttöiän funktiona
- – Huoltoon liittyvät parametrit
- – Vian havaittavuus
- – Milloin komponentti on toiminnassa

Tulokset:

- Järjestelmän vikakertymä ajan funktiona
- MTBF
- (Käytettävyys)

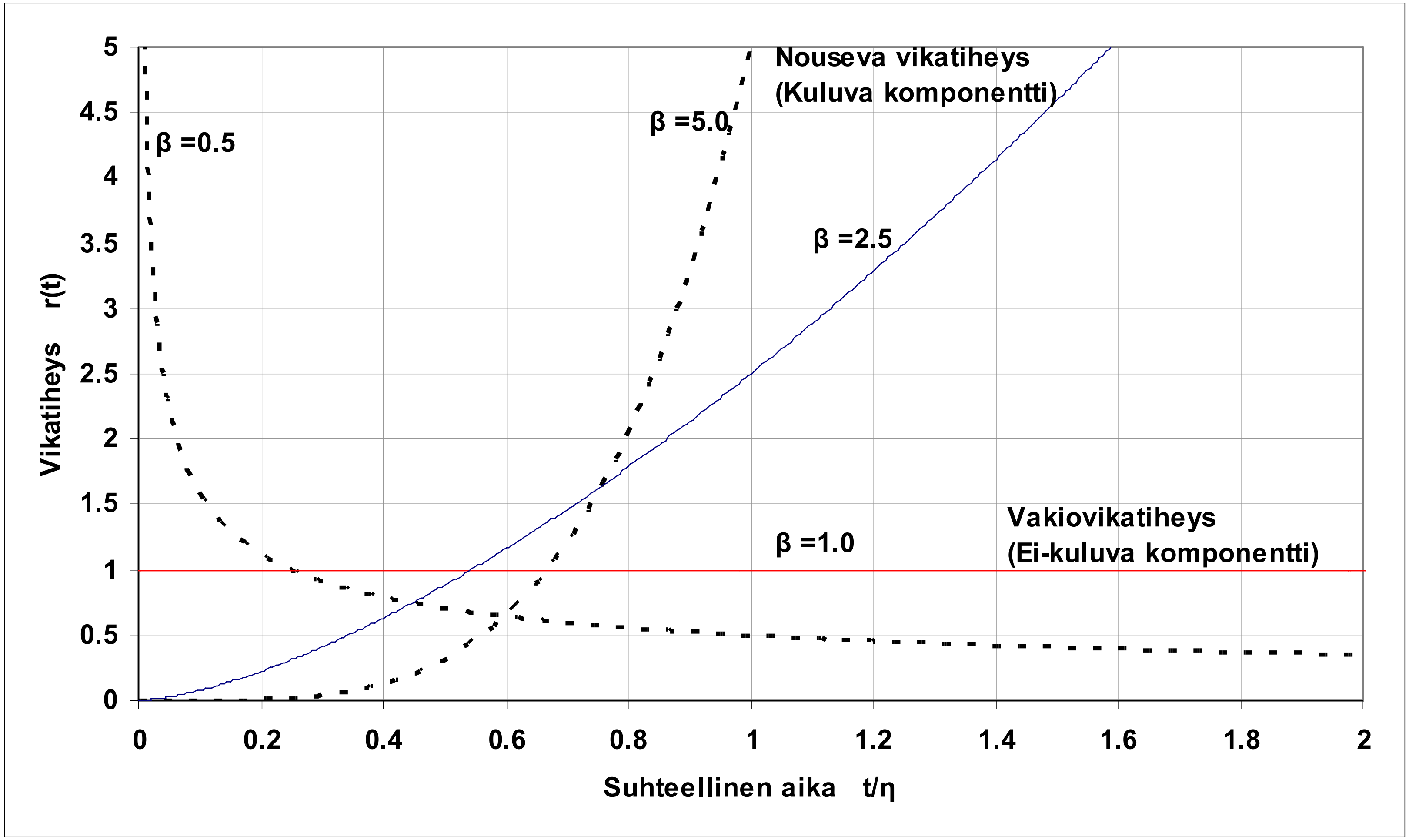
Kullekin vikapuun juurisyylle (komponentille):

- – Vikojen lukumäärä
- – Aika toimivassa ja vikaantuneessa tilassa
- – Huoltotoimen-piteiden lkm



VIKAJAKAUMIA

- Komponenttien vikajakaumina käytettiin yksinkertaista Weibull-jakaumaesitystä
- Komponentit jaoteltiin karkeasti kuluviin ja ei-kuluviin



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TIETOLÄHTEITÄ

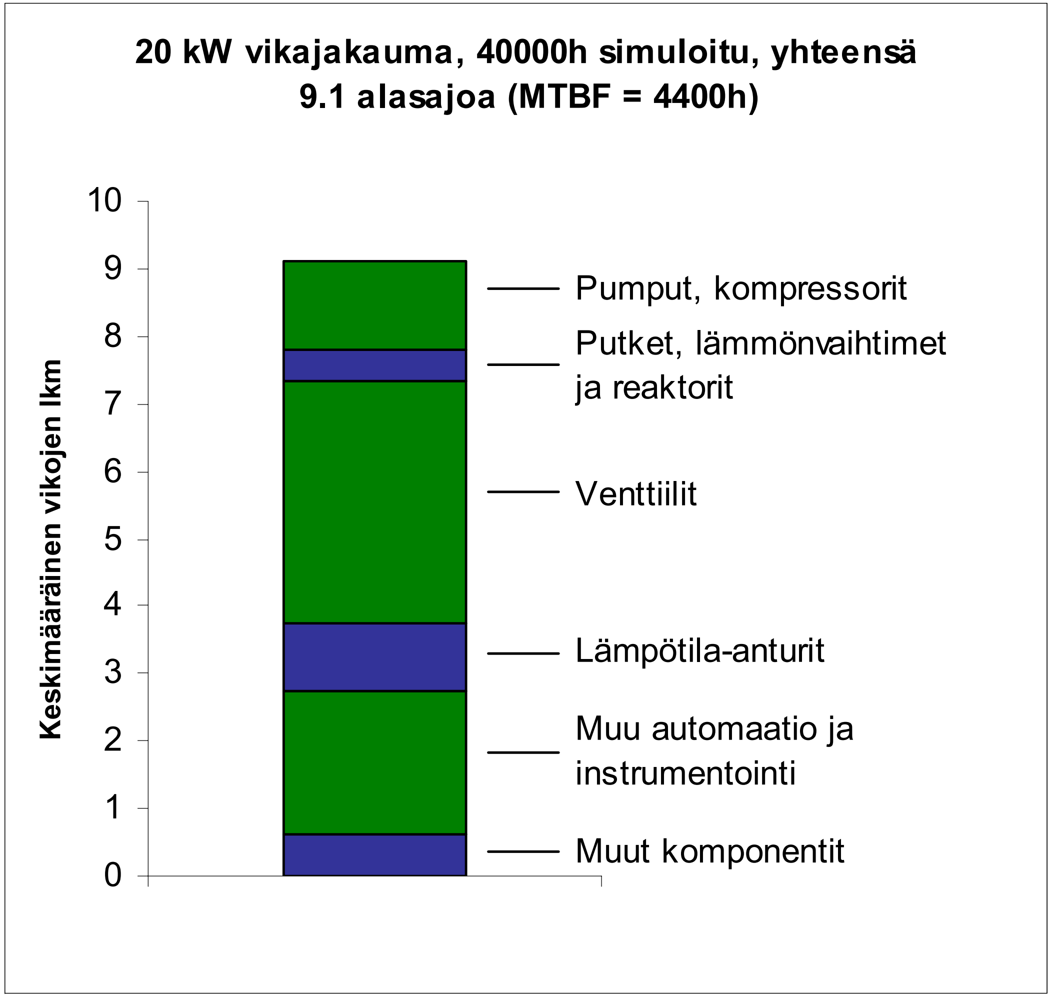
- Lukuisia luotettavuusdataa luettelevia tietolähteitä olemassa esim.
  – OREDA Offshore Reliability Data
  – SINTEF Reliability Data for Safety Instrumented Systems
  – EXIDA Safety Equipment Reliability Handbook
  – T-book Reliability Data of Components in Nordic Nuclear Plants

  Tiedon sovellettavuuteen yleensä syytä suhtautua varauksellisesti

- Komponenttivalmistajat
- **Oletukset ja omat arvioinnit**

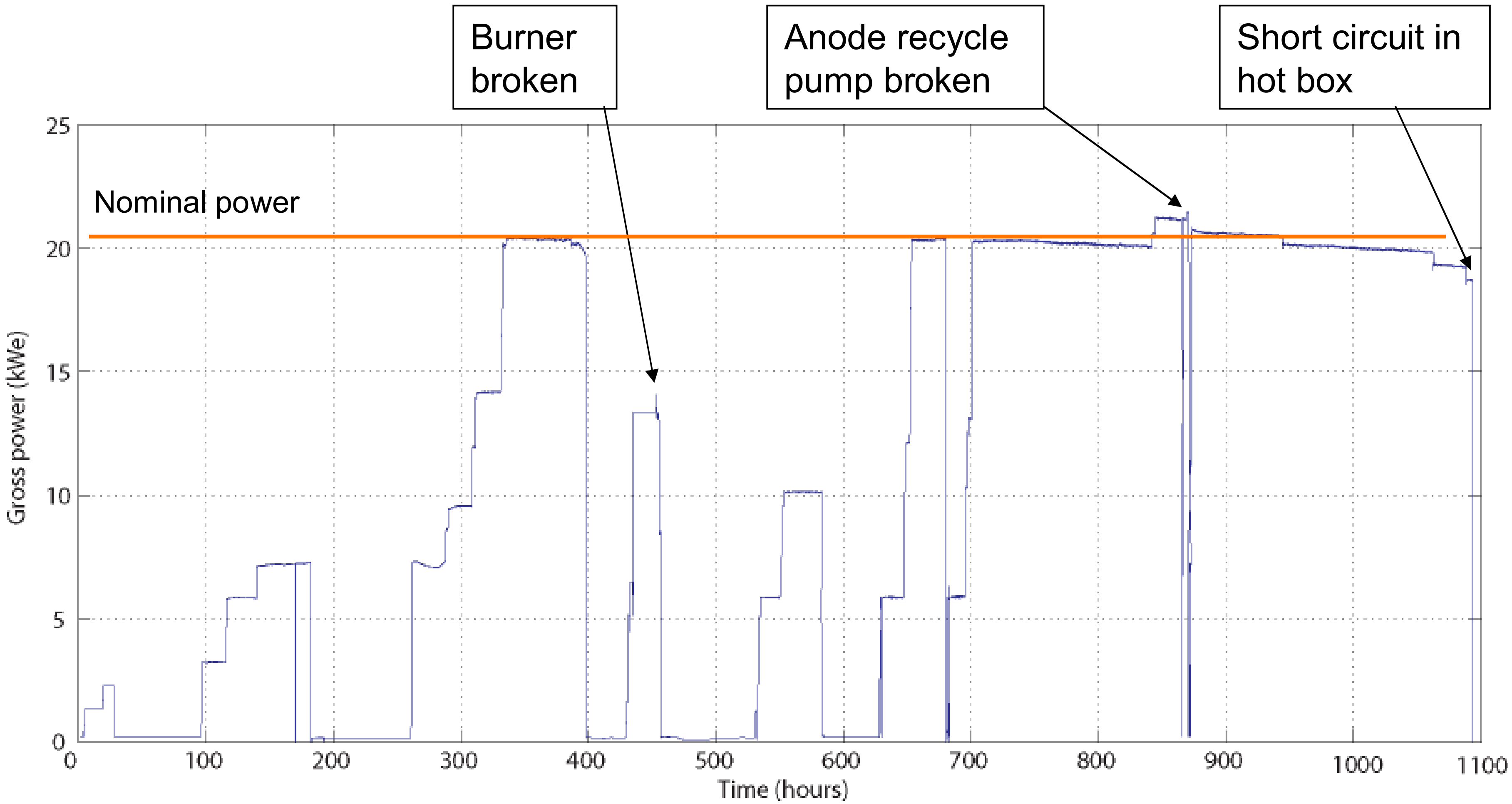
- *Huoltoraportit, kokemukset "kentältä"*

TULOKSIA, ESIMERKKI



WÄRTSILÄ

Alpha gross electric power output during 1096h



POLTTOKENNOJEN LUOTETTAVUUS

- Järjestelmässä 24 polttokenno”stäckiä” keskenäisessä vuorovaikutuksessa
- Polttokennojen degradaatio on tunnustettu ilmiö, luotettavuudesta (äkillinen vikaantuminen) ei ole tietoa
- Ymmärrys luotettavuudesta on keskeinen tieto polttokennojen yhteenliittämisen ja kaasusyöttötopologian suunnittelussa
- Fysikaaliset degradaatioon / vikaantumiseen liittyvät ilmiöt liian monimutkaisia käytettäväksi luotettavuusanalyysissä
- Semi-kvalitatiivisen mallin avulla voidaan tutkia keskeisten luotettavuusparametrien vaikutuksia

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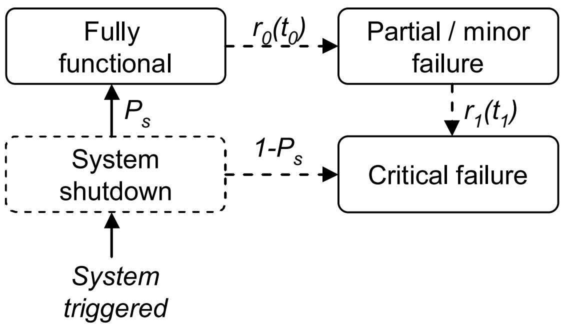
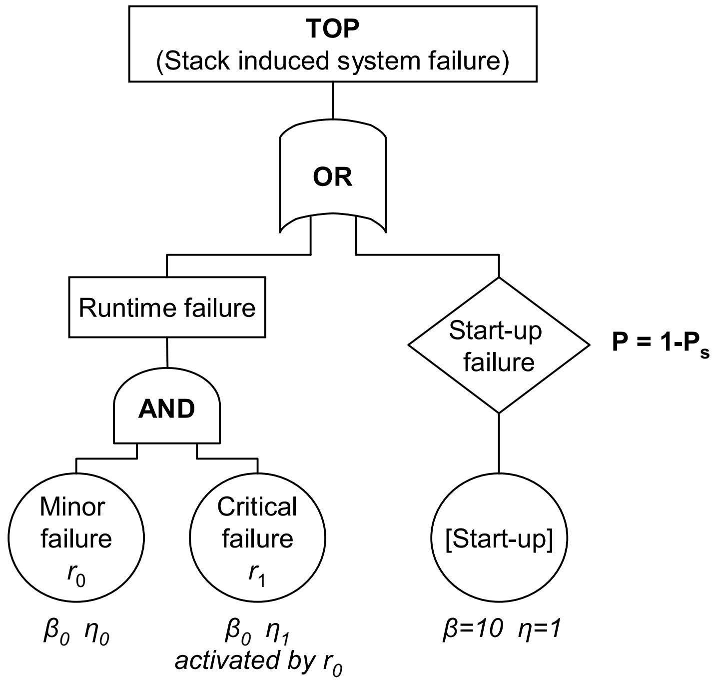
Stack Reliability, Simple Qualitative Model





Model parameters:

$r_0(\eta_0,\beta)$

$r_1(\eta_1,\beta)$

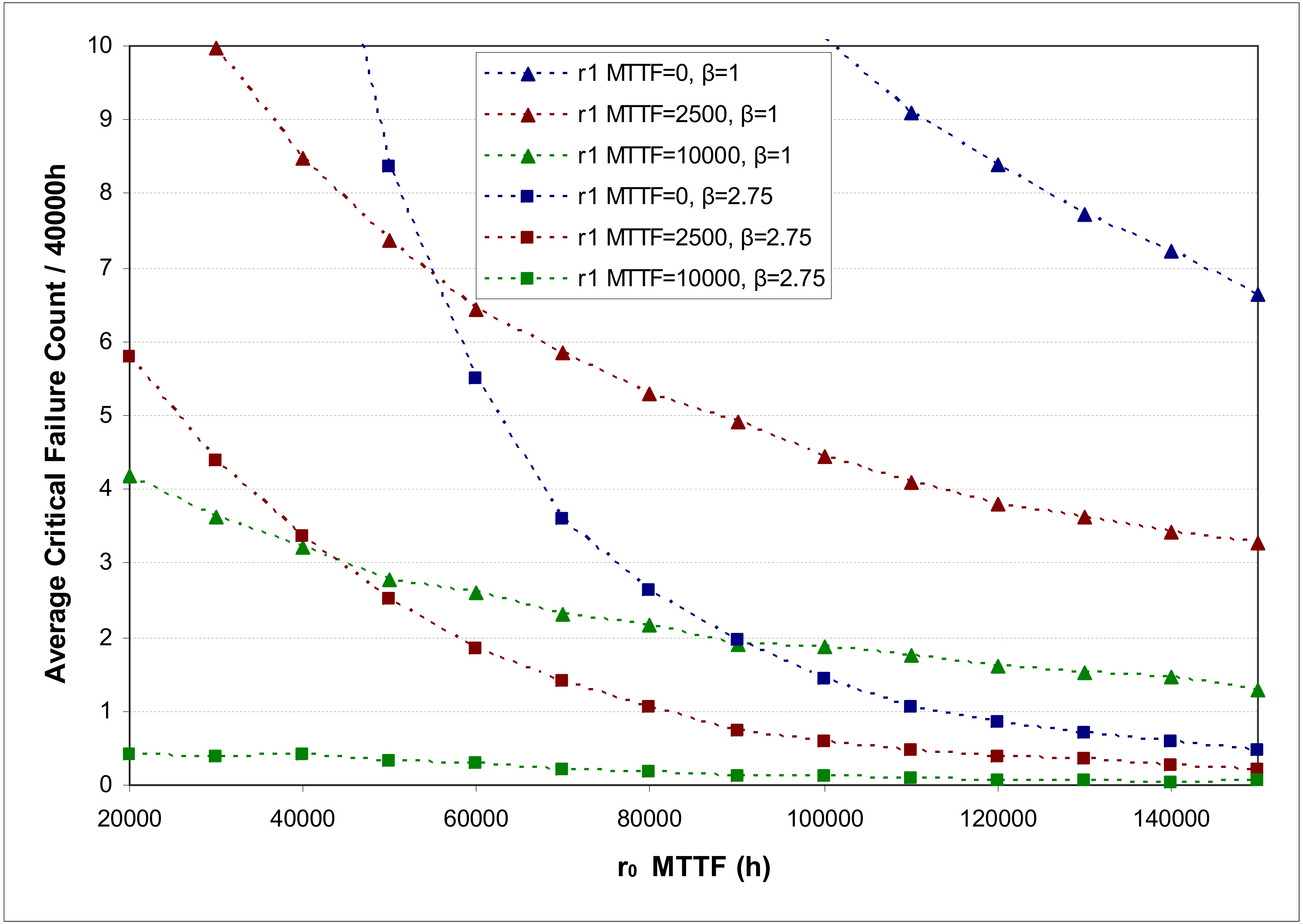
η=Weibull scale factor

β=Weibull shape factor

Ps=Probability of surviving thermocycle

$$MTTF = \eta \underbrace{\Gamma\left(\frac{1}{\beta}+1\right)}_{\substack{=1,\ \beta=1 \\ \approx 0.89,\ \beta=2.75}}$$

Stäckimalli, tuloksia



KÄYTÄNNÖN HAASTEITA

- **Tuottavuuden määrittäminen** luotettavuusanalyysityölle vaikeata
  - Mikä on sopiva panostus luotettavuusanalyysiin?
- **Tekijöiden löytäminen**
  - Suomessa varsin vähän koulutusta alalle
  - Vaatii pioneerihenkeä
  - Luotettavuusanalyysin ja suunnittelun erillä pitäminen haastavaa
- Luotettavuusanalyysin **integrointi osaksi suunnitteluprosessia**
  - Mitä tehdään, milloin tehdään ja miten se vaikuttaa suunnitteluprosessin etenemiseen
  - Sallitaanko hidastava vaikutus aikatauluun
- **Datan hallinta**
  - Datan keruu ja olemassa olevan datan hyödyntäminen ja jäsenteleminen
- **Epävarmuus**

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TURVALLISUUS

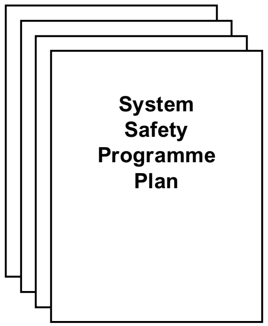
Lähtökohta: Ei kompromisseja turvallisuudessa, oltava hallinnassa alusta asti

- **Laitteistoon liittyvät riskit**
  - Palavat kaasut ja nesteet (räjähdysturvallisuus)
  - Terveydelle haitalliset aineet (kemikaaliturvallisuus)
  - Sähköturvallisuus
  - Prosessiturvallisuus
  - Muut (korkeat paineet, kuumat pinnat …)

- **Erityisiä haasteita**
  - Asennus- ja käyttöönottoaikainen turvallisuus
    - Konfiguraation hallinta
  - Softan luotettavuus
  - Käyttäjien virheet

System Safety management

- System Safety Programme Plan *(not a project specific)*
  - Definitions
  - Objects for safety assessment
  - Working practices
  - Risk assessment criteria
  - All the efforts shall serve the same goal
  - If possible, all the results from different analyses should be commensurable
  - It is beneficial if other disciplines could be integrated with safety tasks



System Safety practices

- System Safety Analyses & reporting
  - Potential hazards analysis
  - PHL, Preliminary Hazard List
  - HAZOP
  - FMECA

Hazard identification		Safety assessment	Corrective actions	Reporting
• HAZOP	▶	- causes	- re-design	- hazard log
		- effects	- safety device	- safety
• FMEA/ FMECA	▶	- probability of	- warnings	reports
		occurrence	(labels etc.)	
• PHL /PHA	▶	- accident severity	- instructions	
			- training	

⇨ Safety Assessment Report & Hazard Log

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Comparison of analyses

Method	Risk identification is based on	Strenghts	Weaknesses
PHL/PHA	SFS-EN 1050 "Safety of machinery. Principles for risk assessment." Appendix A: List of potential hazards, hazardous situations and hazardous events.	Easy and fast method, inherent features	no process-risks, man-machine interfaces, erroneous actions
HAZOP	The hazards and operational concerns of a system	The process deviations are systematically analysed	A human-intensive activity, inherent risks are not necessarily identified
Design FMECA	Each assembly is analysed part by part	Failure modes which will hamper functionality	Time-consuming analysis
Process /sequence FMECA	The process is analysed step by step to find abnormal events	Failure modes related to process	Time-consuming analysis

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Risk Matrix

		Consequence			
		1	2	3	4
Freq	a	A	A	A	B
	b	A	A	B	C
	c	A	B	C	C
	d	B	C	C	D
	e	C	C	D	D
	f	C	D	D	D

Risk Class	Interpretation	Decision by
Class A	Intolerable risk	---
Class B	Undesirable	Project Manager & experts
Class C	Limited tolerable risk	The System Safety Working Group
Class D	Tolerable risk	Manufacturer

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Results

- Personnel hazards. Tot 34 pcs, 25% of 138

		Consequence			
		1	2	3	4
Frequence	a				
	b			1	1
	c		1	2	
	d		5	6	3
	e	5	3	1	2
	f	1	1	1	1

- System hazards. Tot 90 pcs, 65% of 138

		Consequence			
		1	2	3	4
Frequence	a				
	b			1	1
	c		1	6	3
	d		16	16	5
	e	5	15	5	1
	f	1	10	3	1

- Environment hazards. Tot 14 pcs, 10% of 138

		Consequence			
		1	2	3	4
Frequence	a				
	b				1
	c				4
	d			2	3
	e				2
	f			1	1

WÄRTSILÄ

KOKEMUKSET & LOPPUPÄÄTELMÄT

- Prototyyppiasteessa olevan teknologian luotettavuusanalyysi on pitkälti uusi konsepti
  - ⇒ Parhaiten soveltuvat menetelmät ja käytännöt haettava empiirisesti
- Kvalitatiivisista menetelmistä (FMEA, HAZOP) eniten konkreettista hyötyä
  - – Etenkin automaation suunnitteluun runsaasti syötettä
  - – HAZOP turvallisuuden kannalta välttämätön, luotettavuuden kannalta ei FMEAn veroinen
- Kvantitatiivisten analyysien ja niiden edellyttämän datan välillä ”muna-kana” problematiikka
- Prototyypille (käyttö)kokemuksen perusteella keskeiset luotettavuusongelmat ovat ilmeisiä ilman tarvetta analyyseille.
- Turvallisuusanalyyseissä runsaasti työnsarkaa

Seminar 12.12.2008

Kalle Lehtinen

CARGOTEC

BRED project results

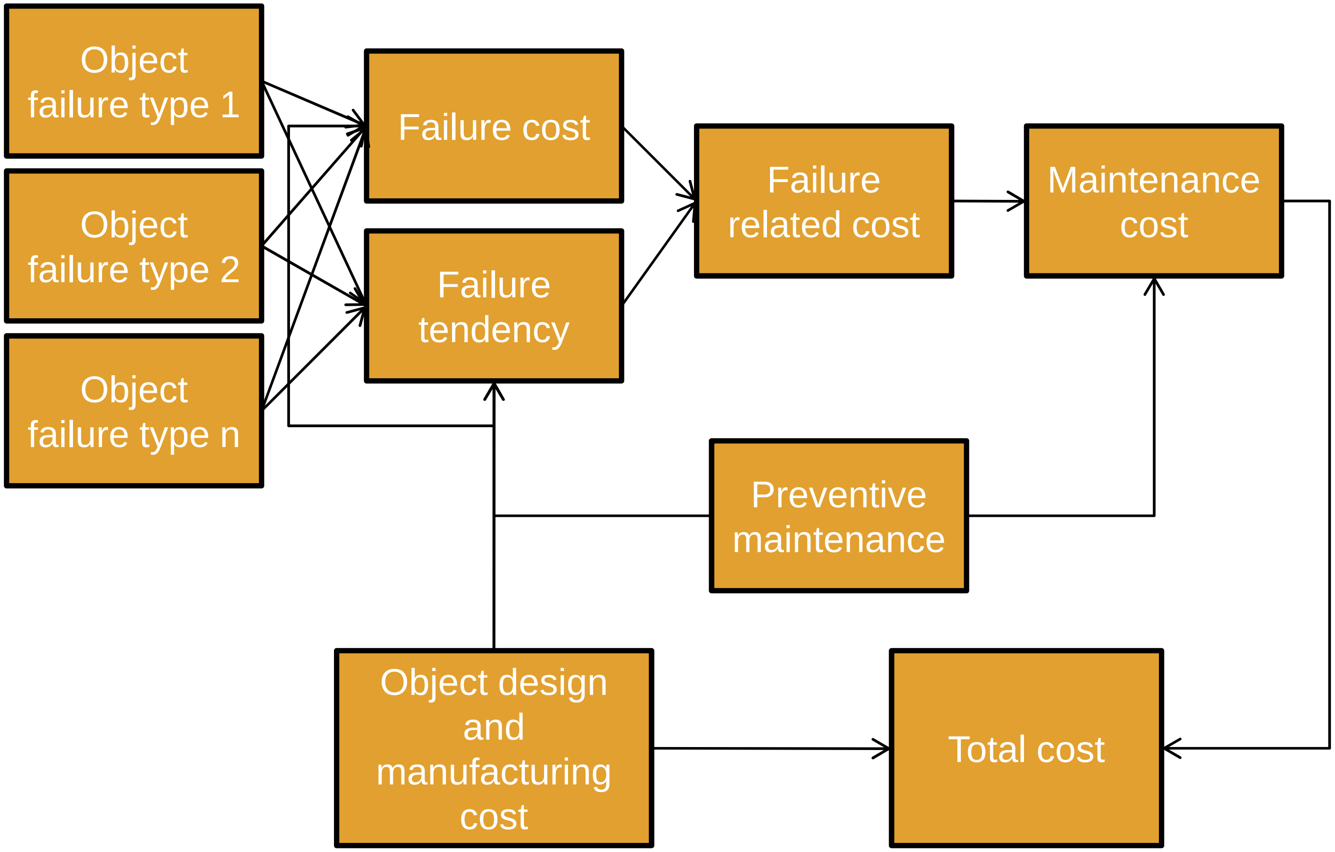
HIAB · KALMAR · MACGREGOR

Evaluating equipment reliability effects on warranty and service contracts

- Purpose is evaluate how a change in design or production will affect warranty and service contract production costs
- Do we get the money invested in reliability back?
- Interaction between service and new sales
- Calculation for reliability investment payback
- Focus on one equipment, part of equipment or single design change
- Critical parts can be analyzed individually by taking account failure tendency of the part but including failure related costs for the complete equipment

CARGOTEC

Calculation framework



CARGOTEC

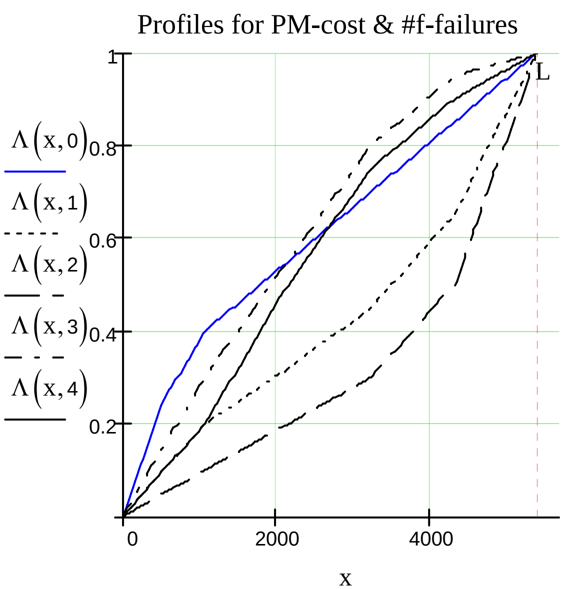
Inputs

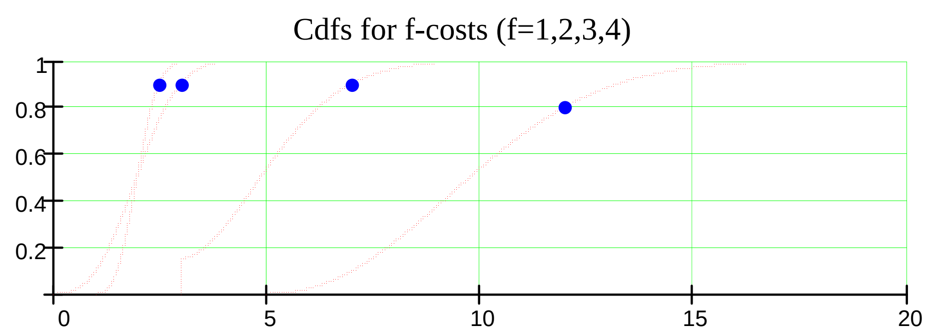
- Total calculation time period
- Preventive maintenance cost for object for calculation time period
- Number of failures for calculation period
- Failure cost per failure

Life of item	$L := 5400$			
PM-cost /item 0..L	$Pm := 20$			
Type of failure [a]	$f = 1$	$f = 2$	$f = 3$	$f = 4$
#f-failures /item 0..L [b]	$F_1 := 0.4$	$F_2 := 1.2$	$F_3 := 2$	$F_4 := 2$
f-cost /f-failure [d]	$\mu_1 := 10$	$\mu_2 := 5$	$\mu_3 := 2$	$\mu_4 := 2$

Inputs

- Preventive maintenance and failures cumulating during the complete calculation period given with point information
- Failure related costs with minimum and quantile information which forms a cdf of the failure cost



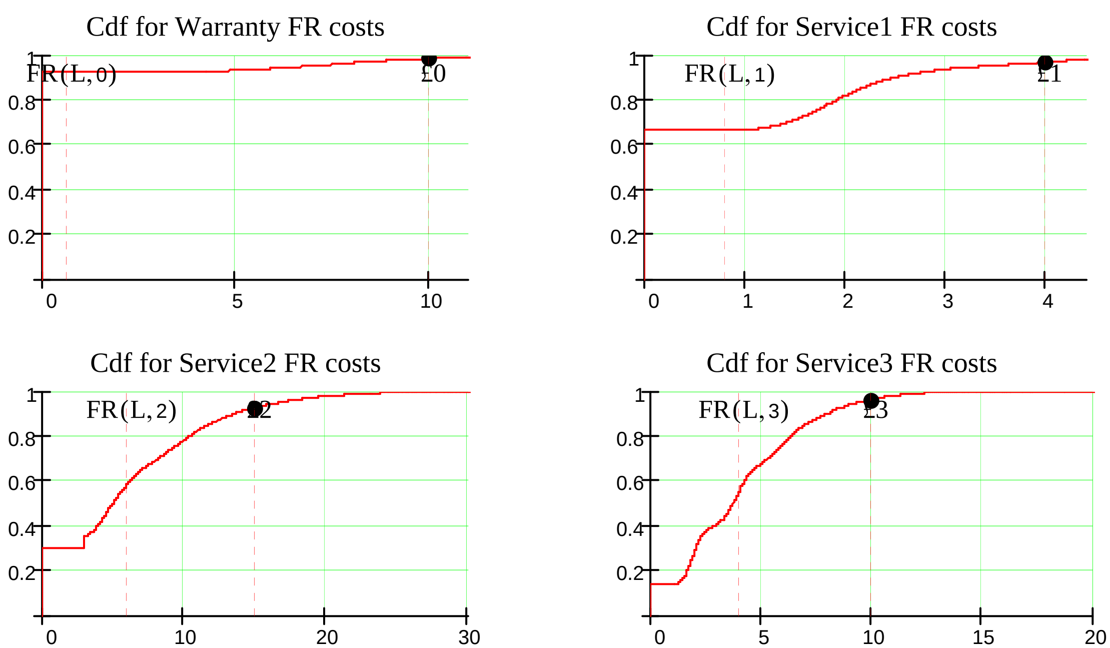


Inputs

- Warranty and service contract periods are given within the total calculation period
- For each period the division of costs between the manufacturer and customer is given
- The division is formed based proposed service contract model
- Service contract can also be taken into account when failure tendency is estimated

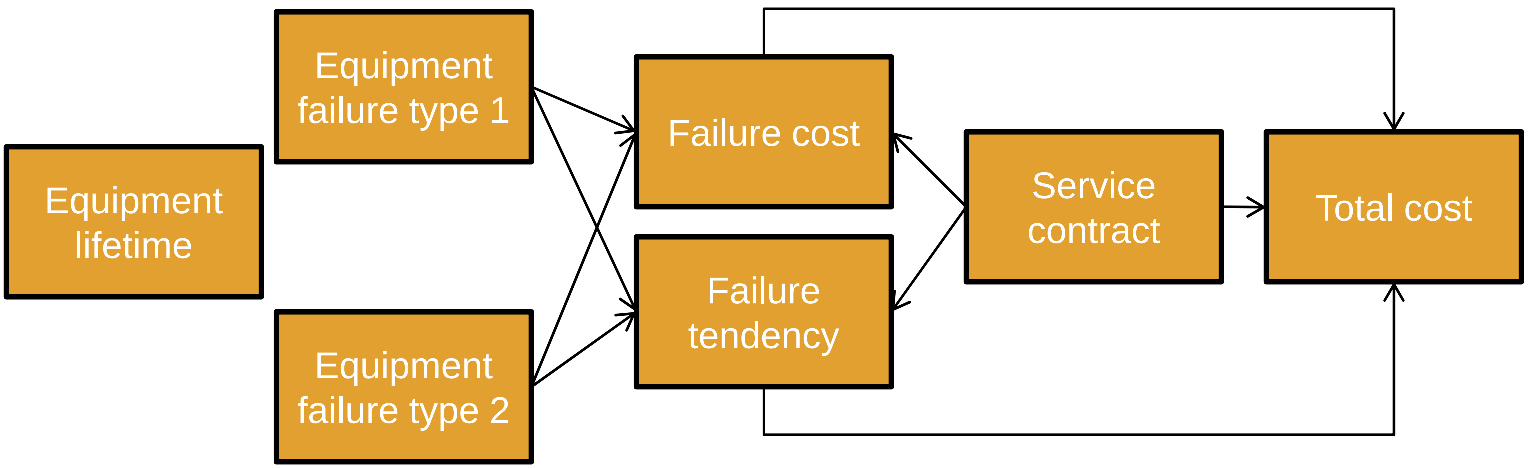
Results

- Preventive maintenance costs
- Failure related costs in each time period
- By comparing different solutions and their design and production costs the most economical solution can be found



Model for evaluating service contracts

- Customer perspective
- Purpose of the model is to estimate potential savings that could be obtained with taking on service contract
- Simplified view on failures
- Effect of different service agreement components on failure costs evaluated



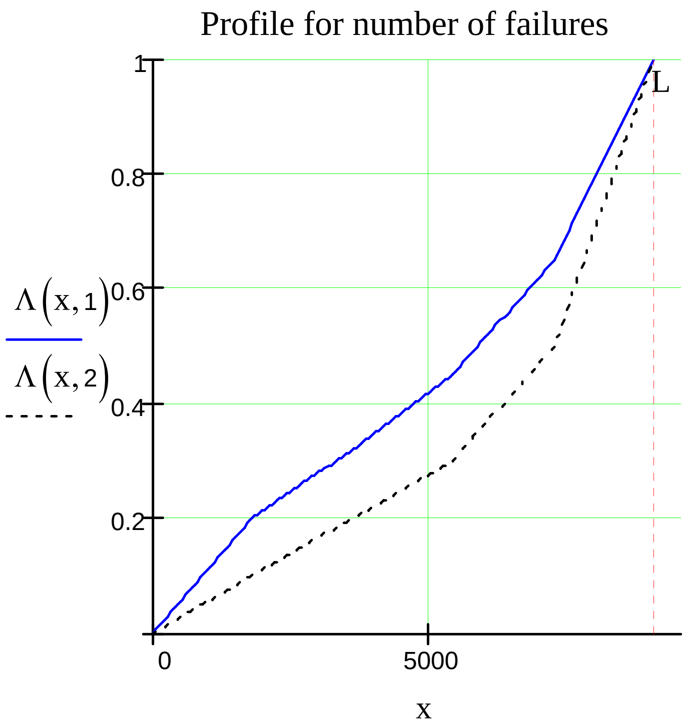
Inputs

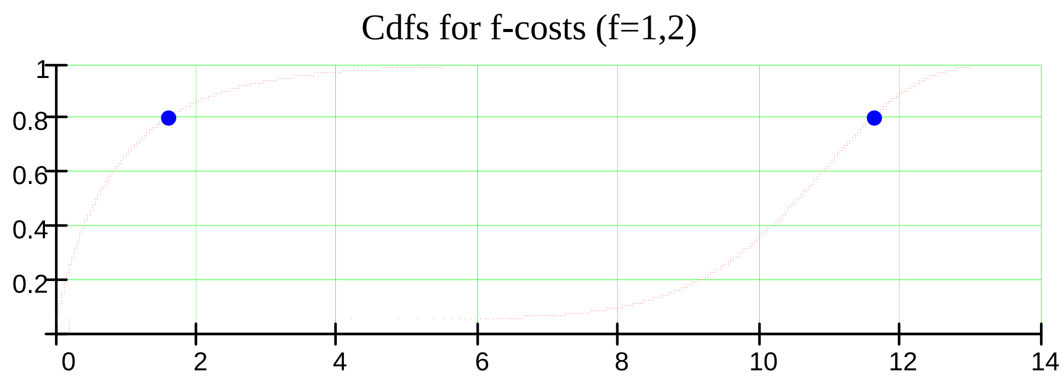
- The complete lifetime of the equipment is considered
- Two types of failures are considered
  - Failures that causes an emergency repair
  - Events that cause a need for maintenance (deterioration)

Life of item	$L := 9125$	
Type of failure [a]	$f = 1$	$f = 2$
#f-failures /item 0..L [b]	$F_1 := 4$	$F_2 := 500$
f-cost /f-failure [d]	$\mu_1 := 10$	$\mu_2 := 1$

Inputs

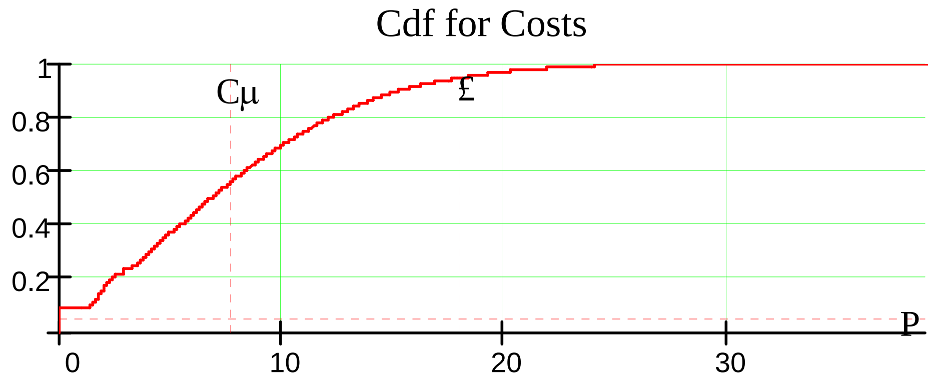
- Failure distribution for complete lifetime
- Costs for single failure





Outcome

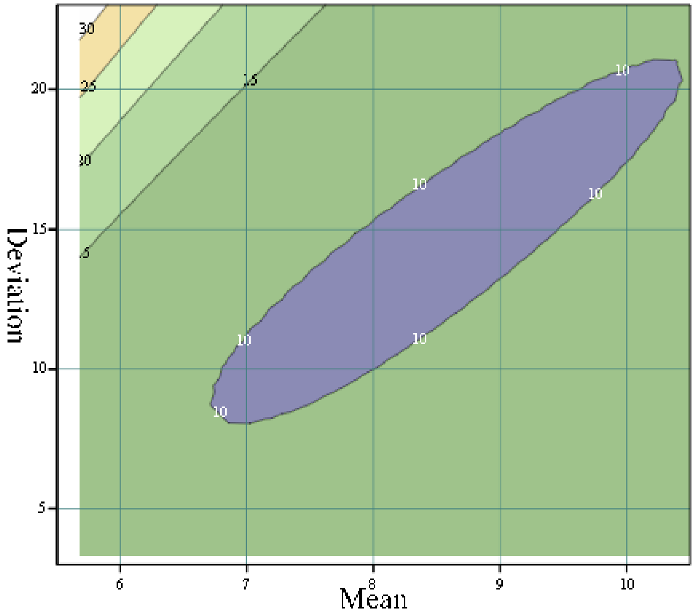
- Potential cost for failure types and combined cost
- When different scenarios are calculated it can be found what kind of service contract could be feasible
- The goal is to use the calculation frame in creating an easy to use tool for marketing purposes that will take vessel or fleet and service contract concept data in and calculate the proposed concept feasibility



Failure tendency modeling using group method

- Method was created to handle data reliability data that does not have information on any specific part but from a group of similar parts
- For example pumps in group which we know that some of the pumps have been replaced
- Method also provides a mean for censoring the data if there is lots of uncertainty about data quality from beginning or from the end of the calculation period

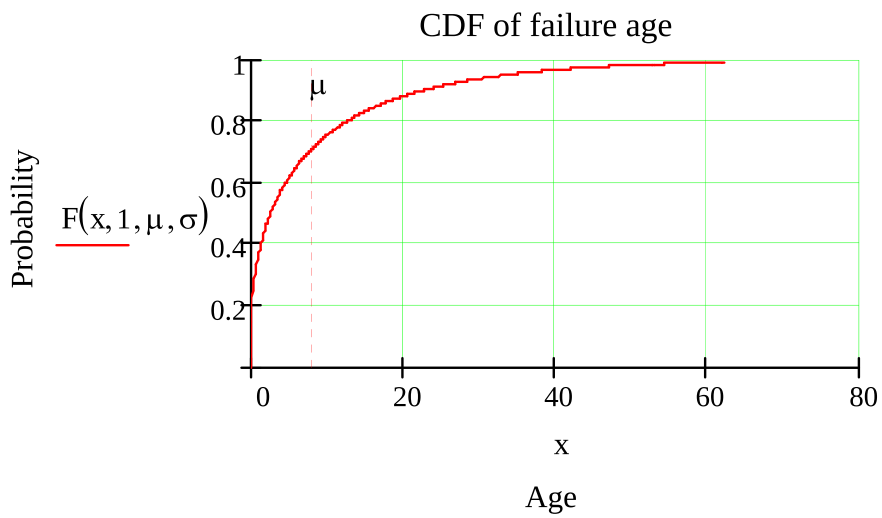
Inputs

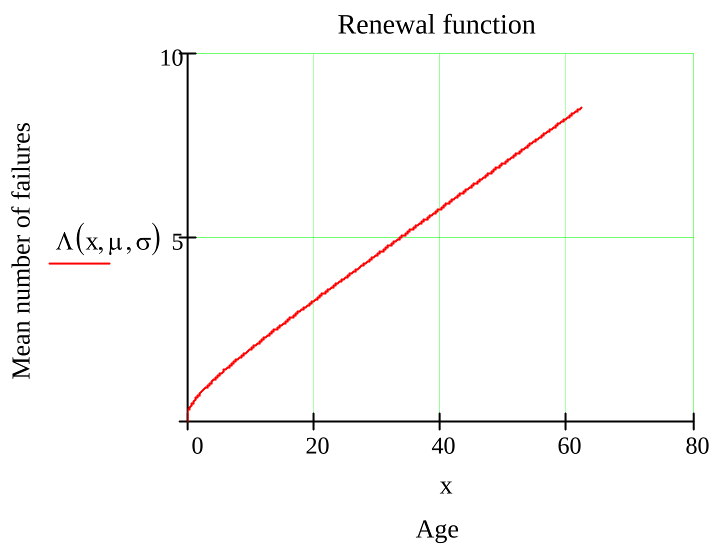


- Number of parts in the group
- Age of the group at the start
- Age of the group in the end
- Number of replacement s done to the group
- Model uses least square method to fit the data into gamma distribution fit is presented as a landscape graph

Results

- As a result model provides the distributions optimum mean and deviation
- From the distribution numerous different results can be calculated which can then be used further





Lessons learned

- Combination of engineering and financing analyses provides good results
- It’s all about processes – if don’t know what you are doing you cannot analyze and improve it
- Circle of insufficient data -> no analyses -> no need for data needs to be broken

KOTEL	Nimike - Title KOTEL 256: Integrated Business and Technical Product Reliability Design

Tiivistelmä – Abstract

The traditional and still dominating method for product design is focused on optimising the technical performance of a product. The reason for this is simple, there is no easily available and comprehensive design method or tool to integrate the reliability and maintainability (R&M) considerations and effects in product design.

As more the companies' management have experienced the meaning of Product's R&M as competitive factors in their business, as more they have started to invest R&M engineering and development. This was also a starting point from where this project was launched.

The purpose of the project was to develop a design methodology that includes the interactions and links between the customer needs, the manufacturer business targets and the product R&M performance. This makes it possible to find and simulate in detail, which are the specific customer product R&M requirements and what influence the R&M performance has on the customer satisfaction. The method enables product R&M facts to be taken into account at business decision level.

Results of the project are presented in the following appendixes:
1) Publications, 2) Master Thesis, 3) Developed Models and 4) Case-Studies; Companies Presentations.

Avainsanat - Key words

reliability design, product development,

Kieli - Language	Sivuja - Pages	Tyyppi - Type
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