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MASTER

Degradation analysis of high power LED lamps

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Degradation Analysis of High Power LED lamps

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LED Supply Nederland

Faculty of Technology Management
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LEDNED
Led there be light

TU/e Technische Universiteit Eindhoven University of Technology

Abstract

This Masters Thesis contains the results of a graduation project conducted for the TU Eindhoven and LED Supply Nederland. The project was formed by a reliability study of a GU10 High Power LED lamp and a degradation analysis of the lamps.

Dit rapport bevat de resultaten van een afstudeeronderzoek uitgevoerd voor de Technische Universiteit Eindhoven en LED Supply Nederland. Het project word gevormd door een betrouwbaarheidsonderzoek naar GU10 High Power LED lampen en een degradatie analyse van de lampen.

Preface

This report is the result of my Master's Thesis of Industrial Engineering and Management Science at the Eindhoven University of Technology. The project described in this report is the result of a cooperation between the TUe and Led Supply Nederland (LEDNed). The goal of the project was to develop a degradation model for High Power GU10 LED lamps.

The road to finishing this report was long and full of bumps on the track, but due to the ups and downs the thrill of the end of the ride is even bigger. Just like a rollercoaster! Of course I could not have completed this report without the help en support of many people.

First I want to thank Prof. Aarnout Brombacher for his support throughout the whole period and especially for his never ending positive attitude. Two other people I want to thank are Josephine Sari, for continuing the measurements during my absence and the help with statistics, and Jan Rouvroye for his criticism that helped me make the report Master's-worthy.

I also want to thank Jurjen Visser and his collegues from LEDNed for making this interesting project possible. Although the actuality of this report has passed I hope the methods in this project have helped your goal of conquering the market with good and reliable LED lamps.

I also want to thank my friends Joost, Nancy, Teun, Reinoud and Martin and my housemates Karlien, Ding and Jeroen for their help, advice and moral support and of course the good times that helps keeping spirit high!

Last but not least I owe my parents, big time! Without their financial support but more importantly their moral support I would not have come this far. I have let you down a few times but with the completion of my Master's Thesis I hope we can let that in the past. Now I can go and try to earn my own livelihood!

Martin Kools

Summary

Introduction

This is the Masters Thesis of Martin Kools for the Eindhoven University of Technology, department of Quality and Reliability Engineering. This graduation project is supported by LEDNed (Led Supply Nederland). Subject is the reliability of LED lamps, more specifically the degradation patterns of LED lamps.

Research Question

There are two research questions that were answered in this theses: “What are the characteristics of the degradation pattern of the high-power LED lamps?” and “What degradation model fits the characteristics of these LED lamps?”

Reliability Test

LEDNed sells different kinds of LED lamps with several kinds of LEDs in them, an example are the high power LEDs. The reliability of the lamps with this kind of LEDs in them is not yet known because this is a new product for LEDNed. A new test can help determining whether these lamps show similar failures or degradation patterns to the Par 30 lamps which were tested earlier. To gain more insight in the sensitivity of these lamps to Class II failures (see figure S.1), degradation patterns, and what potential failure mechanisms play a role, more information about the state of the lamps during the test will be needed; therefore a quantitative analysis of the lamps will be conducted. This quantitative analysis can for example consist of illuminance (or luminous emittance) analysis and power use analysis.

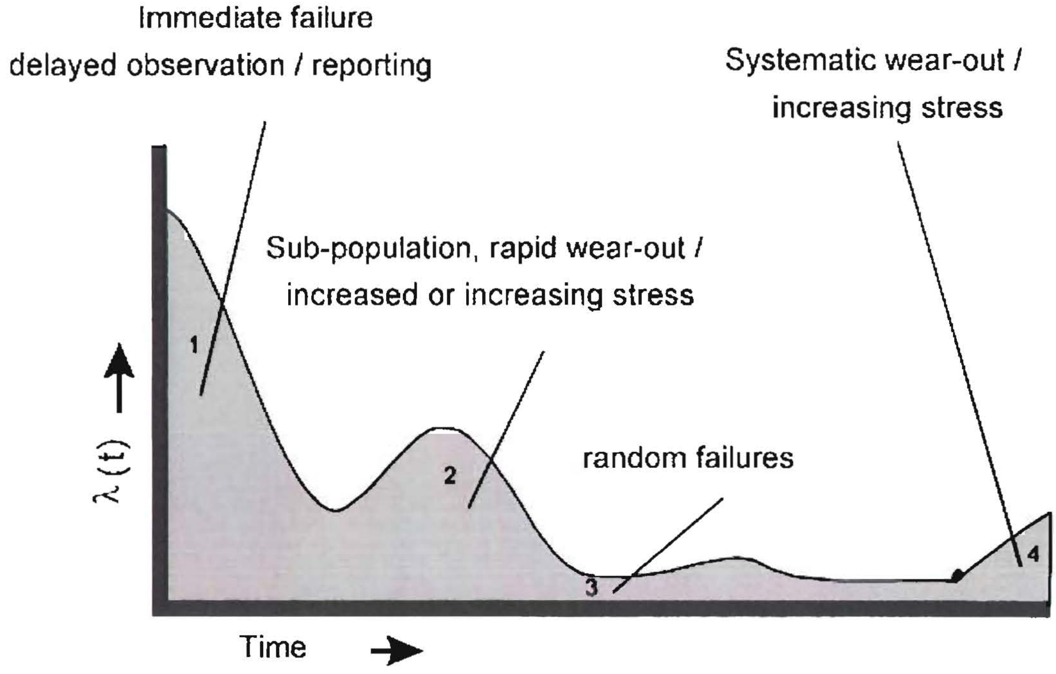

Figure S.1: Roller coaster curve

The type of lamps that will be tested is spot light with one high power LED inside. The bulb base is type GU10, the LED power is 3W and the beam angle is 20°. A new test setup is needed because the new base of the lamps requires different sockets and because more detailed information is needed for the quantitative analysis.

For the new spot lights, a hypothesis similar to the one of the LED Par 30 lamps can be defined. Because the spot lights are supposed to last 50.000 burning hours on average, the expected mean time to failure (MTTF) is 50.000 (μ_0). If the spot light would have a degradation pattern similar to the LED Par 30 lamps, the alternative MTTF would be much smaller ($\mu < \mu_0$). This results in the following hypotheses about the MTTF that need to be tested.

H_0 is $\mu = \mu_0$

H_1 is $\mu < \mu_0$

The hypotheses will be tested in an experiment in which a sample of lamps will be conducted to a 'normal' stress or load (stress within specifications). The time to failure will be monitored to determine whether the hypothesis can be rejected and the alternative hypothesis can be accepted. It is not known what failure rate can be expected with the new spot lights, therefore an estimation of a sufficient sample size cannot be calculated.

Test Results

The manual measurement proved to be much more helpful than the automated measurement methods. However it was not without limitations. There was quite a big variability in the manual illumination measurements. This has several reasons:

- Due to the form of the fittings, they cold not be mounted 100% perpendicular to the base mounting plate which makes it difficult to measure exactly above the middle of the lamp.
- Due to the form of the lamps, mainly the two "paws" for mounting in the fitting, not all lamps could be mounted perpendicular to the board.
- Because of the above 2 points, the tubes around the lamps could not be fitted into place but had to be mounted loose in order to manually adjust them.
- The lux-meter was fitted with a cardboard mounting device to ensure its placing above the tubes to be exactly in the middle, this device is fitted manually an can cause a slight difference in measurement
- The manual measurements were conducted by several people, possibly with each his own interpretation of the best way of measuring.

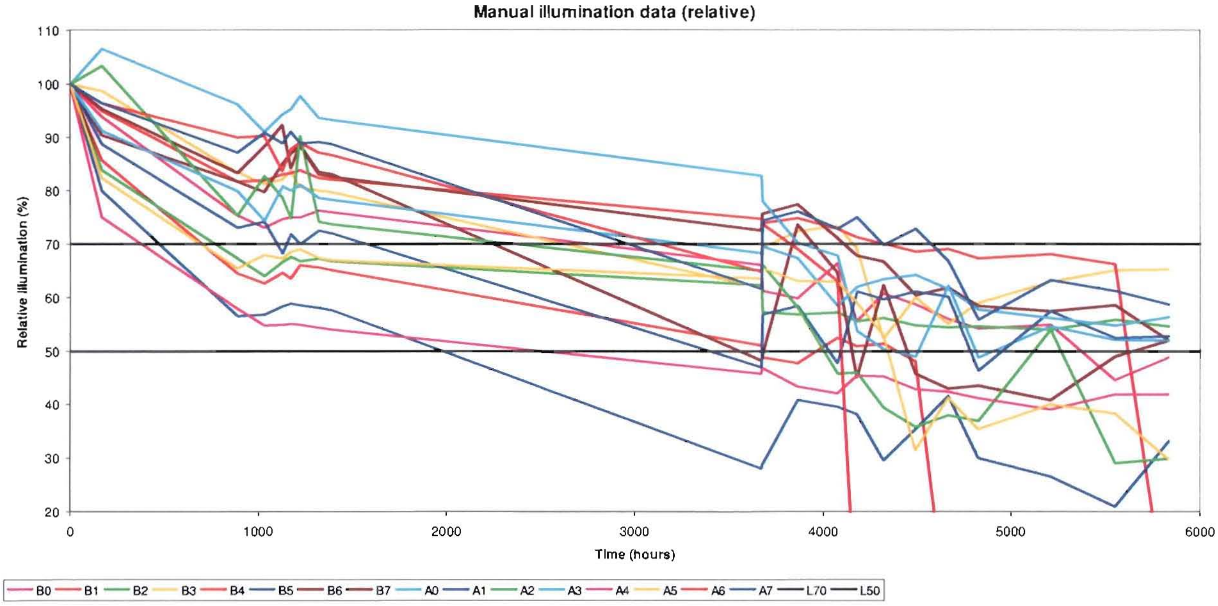

Figure S.2: Relative manual illumination data

Since the lamps have not yet stabilized at the end of the test, this means the lamps are not yet in Phase 3 of the roller coaster curve. The three lamps that suffered catastrophical failures can be regarded as Phase 2 failures. Once the lamps have stabilized, a failure rate can be calculated, how many lamps fail per hour per day or per year. During Phase 3 of the rollercoaster curve this calculated failure rate should be constant. For this experiment, there is no constant failure rate yet. Therefore the MTTF (=1/labda) is not constant either, and thus it is not possible to determine the MTTF.

If a failure of the GU10 High Power LED lamps is defined as the moment that the relative degradation reaches a level of 70% (L_{70}) or 50% (L_{50}) or when a lamp suffers a catastrophical failure and stops working completely, then the failure moments of the lamps during the experiment can be determined and a failure rate can be calculated. However, since the fluctuation in measured illumination values is quite big this cannot be done directly, the data is too unreliable to determine the exact moment that a lamp reaches L_{70} or L_{50}.

The average expected lifetime cannot be calculated either, the degradation pattern is too rough to estimate the AEL based on the graphs. Depending on how the lamps degradation pattern is this can be estimated. An example: if the intersection of the L50 line in figure S.2 is regarded as failure and thus end-of-life for the lamps, the AEL can be estimated. However some lamps have not yet reached that line and the degradation pattern can both be linear or exponential. If degradation is linear, the AEL can be very soon, for example around 6000 or 7000 hours, but if the degradation pattern is exponential, this may well be 20000 or 30000 hours. Therefore it is impossible to estimate the AEL based on the experiment data. A simple best guess method is used to calculate a range in which the AEL can be expected. This best guess method is given in section 4.4.1.

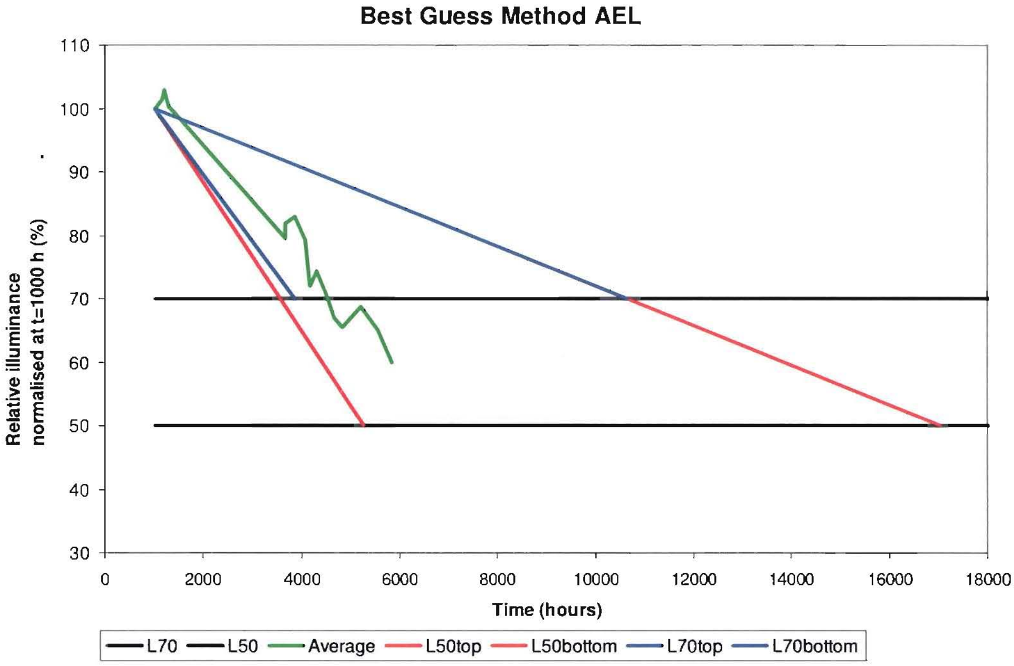

Figure S.3: Estimation 2 of AEL

Calculations for L70 are most reliable because the time period over which an estimation is given is shorter, therefore the deviation from reality is less.

Conclusions

The first research question can easily be answered, and is already partly answered above. The lamps start degrading the moment they are functional. They keep degrading until the experiment is stopped for safety reasons. And based on the observed degradation pattern it is also likely that they keep degrading after the time period during which the experiment was held. On the other hand, a detailed degradation pattern cannot be given. The measurement data from the practical experiment was not as reliable as desired. The measurement flaws from the manual measurements were too big to make a reliable and detailed degradation analysis, therefore only two best guess methods could be used to estimate the average expected lifetime (AEL)

The second question cannot be answered completely. Since there were some issues regarding the reliability of the measured data, no definite conclusions about possible degradation models can be drawn. However, there can be concluded something; the lamps do degrade and keep degrading throughout the experiment time of nearly 6000 hours (more than half a year). At first they degrade faster than in the end, it cannot be concluded however that this is only due to the burn-in time. After a possible burn-in period, the lamps keep degrading in a way that resembles a linear degradation pattern. However, this can also be resemblant to an negative exponential degradation pattern. One fact that can be concluded is that the lamps are not yet stabilized during the experiment time.

As pointed out in the first part of this section, two best guess methods were used to estimate the average expected lifetime (AEL). The first method, a best guess method, resulted in a high and a low border for both L_{70} and L_{50}. The AEL is expected to be somewhere between the upper and lower tome border. For L_{70} the estimated AEL is between 3,870 and 10,640 hours. The estimated AEL for L_{50} is between 5,280 hours and 17,040 hours. The second best guess method was given by J.Sari, her analysis showed an expected AEL between 8,000 and 10,500 hours. It should be noted that she did not use all measurement data that was available.

All these values of the AEL are far less than the advertised 50,000 hours and it is highly probable that the GU10 High Power LED lamps expected lifetime is much lower. Again, due to the unreliable measurement data, accurate estimations cannot be given.

Recommendations

As already explained in Chapters 1 and 2, LED technology is a promising technology. LED lamps have several advantages over conventional light bulbs, they are reliable, small, light weight, impact resistant, they emit less heat, can have direct coloured light, quiet and they have a long life. However, the technology is still immature which is proven by the two tests that were described in this thesis. Reliability and life time are not as good as advertised yet, at least for the kind of LED lamps that were tested. Since the production volume of LED lamps is increasing, manufacturers are able to produce more reliable lamps and production methods are improving with experience, the price of the lamps is getting more competitive compared to the conventional light bulbs, but even more compared to energy efficient lamps.

If reliability is improved, there is much potential in the lighting market for LED lamp manufacturers and companies like LEDNed. Research is needed to help those companies improve their products. Since the market for LED lamps is emerging, new products are pushed onto the market. Therefore there is a big pressure on the speed of design and testing of the lamps. To help shortening the time-to-market, early in the product development process (PDP) information about the previous generation lamps and the currently designed lamps is needed. Thus research to degradation patterns should be done, but in a way that after a short period of testing a good estimation of the reliability and possible failure mechanisms can be given with high confidence levels. Accelerated testing methods may help iproving fast feedback from testing. This is already applied by Yiu Man Kan in his Master's Thesis [Kan07], however more research on how accelerated testing can be applied for LED lamps is needed. Research to underlying causes of failures can also help identify problems faster. Research to differences and similarities between different LEDs and LED lamps can help determine whether models for one kind of LED or lamp can be applied to other kinds too and vice versa.

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1 Introduction

This is the Masters thesis of Martin Kools for the Eindhoven University of Technology, department of Quality and Reliability Engineering. This graduation project is supported by LEDNed (Led Supply Nederland). Subject is the reliability of LED lamps, more specifically the degradation patterns of LED lamps.

1.1 Report description

This chapter starts with the description of the background of the subject, the context of the subject and reason for dealing with the subject in this graduation project and ends with the formulation of the research question.

In the next chapter, the underlying assumptions made and assumptions behind the research are clarified. Existing methods used for assessing lighting are clarified, the focus is on the portion that is relevant to LED lighting. For the clarification of concepts and backgrounds a closer look at literature about quality and reliability (quality and reliability) is taken.

The results of the literature are prerequisites for the practical implementation of the graduation itself, where a certain type of LED lamps is subject to a practical degradation experiment. This is described in chapter 3.

After describing the intent of the experiment, the results of that experiment discussed in chapter 4.

In conclusion follows a discussion of the graduation project results and recommendations for future research follow.

1.2 Context

1.2.1 Business trends

Individuals, companies, as well as society in general, are becoming more dependent on increasingly complex technical systems and products. Because of this, the Netherlands Study Centre for Technology Trends (an organization related to the Royal Dutch Society of Engineers) performed a study on how this affected the reliability of several larger industrial systems and products in and around the Netherlands [Bro01]. The study identifies four related trends that influence product reliability:

- *Increasing product complexity:* Extra functionality is added to products because customers want it, because competitors' products already have it or because customers are anticipated to want extra functionalities in the product in the future.
- *Increasing complexity of the underlying business processes*: Globalisation of companies and the outsourcing of business processes increases the complexity of some processes, and besides that, it is possible that complex products also require more complex business processes to support the production of these products.
- *A strong pressure on 'time to market'*: Products are pushed onto the market because companies need to keep up with competitors and beat them to gain competitive advantage.
- *Increasing customer demands on product quality and reliability*: Consumers want better products that do not break down and they are getting more demanding, for example about reliability, costs, availability and introduction time of products.

These trends also apply to Electronics business and therefore the Consumer Electronics business (which includes LED lamps) too. The Consumer Electronics business with its LED lamps is the focus area of this Masters thesis. In this business there is a strong competition among the high volume electronics manufacturers. Especially innovation speed has become a key success factor; companies are pushing increasingly innovative products in shortening times to the market. Together with the trends this has a big impact on organizations and on the internal processes within these organizations. One of these processes is the product creation process where the quality and reliability of the products are determined; therefore the trends can also influence the quality and reliability of products.

The way how the business trends influence product reliability could for example be the following [Bro05]:

- The increasing complexity of products makes the validation of product quality and reliability more complex and therefore also costly and time-consuming.
- The increasing complexity of business processes may slow down knowledge accumulation with respect to quality and reliability.
- The strong pressure on 'time to market' on the other hand requires fast and efficient methods to ensure product reliability in the very early phases of the product development process.
- Because with strongly innovative products there is a possibility that problems will still appear in the field, either due to flaws in the process and/or due to unexpected or even unintended use of the product. A strong feedback system is needed to learn fast and efficient especially from these unexpected failures.

1.2.2 Research areas

Brombacher et al. [Bro05] state that an important question, and therefore subject for research, is whether the current industrial quality and reliability management methods are able to handle the above reliability problems. To answer this question two parameters are used: the speed of the quality control loop or feedback loop in the product development process (PDP) and the information density of the quality control loop. This will be explained in sections 1.2.3 and 1.2.4. To be able to understand the answer to this question some basic knowledge about quality and reliability and the PDP is needed; this is stated below in section 1.2.1.

1.2.3 Quality and Reliability

Before a product can be introduced to a market, it has to be developed; this happens in the product development process (PDP). During the PDP customer requirements are listed, translated to product specifications and the product is developed and created. The PDP does not end when a product is introduced to the market, even then problems in the product need to be solved and future versions of the product can be improved. Several feedback loops are included in the PDP to ensure the quality and reliability of the product. The quality control loop mentioned in section 1.2.2 is defined as the overall feedback loop where data from the actual use of the product in practice is fed back in to the ongoing PDP of the same product or a related product (for example from the same product family or a different version of the product with more functionalities).

Because a product is developed and created during the PDP, the quality and reliability of this product are also formed during the PDP. One of many definitions of quality is given by Berden et al [Ber00]; product quality is the conformance to product-related customer requirements (or in a broader sense, customer expectations). Product reliability can be defined as product quality over time, the longer the product quality is good, the more reliable the product is.

When the product is introduced into the market, then the product life cycle starts. During the product life cycle of a product different kind of problems that negatively influence quality and reliability can be experienced. These problems or failures can be classified with the help of the roller coaster curve; this curve and its background will be explained in the next section.

1.2.4 Roller Coaster Curve

“The behaviour of failure rates with time is quite revealing. Unless a system has redundant components, the failure rate curve usually has the general characteristics of a “bathtub” such as shown in figure 1.1. The bathtub curve, in fact, is a characteristic of living creatures as well a s of inanimate engineering devices, and much of the failure rate terminology comes from demographers’ studies of human mortality distributions. Comparisons of human mortality and engineering failures add insight into the tree broad classes of failures that five rise to the bathtub curve” [Lew96].

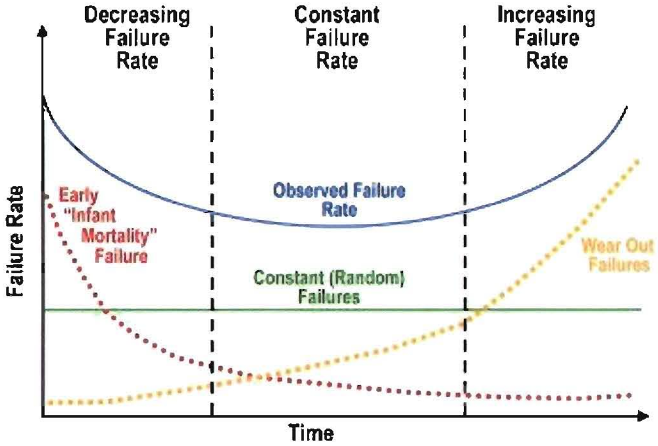


Figure 1.1: The bathtub curve

Wong and Lindstrom [Won88] state that the idea of the bathtub shape and the constant hazard rate has caused many erroneous decisions and give some examples. Too much work was done to refine ways to obtain more precise mathematical expressions for use with the flat bottom of the bathtub curve. They only deal with actual physical failures in electronic systems.

In 1968 Peck [Pec68] already describes 'humps' on the hazard rate curve. He indicated that the humps on semiconducting device hazard rate curves were caused by what he called freak failures. Such freaks should be eliminated via stress screening. In 1979 Peck [Pec79] discerned a new trend in the hazard rate of integrated circuits. This trend was the lengthening of the infant mortality region. Jensen and Petersen [Jen82] concluded in their book, Burn In, that the failure distribution of electronic parts with respect to operating time would be a tri-modal distribution consisting of an infant mortality subpopulation, a flat region, a weak (freak) subpopulation, another flat region and then a strong (main or wear-out) subpopulation. Wong and Lindstrom [Won88] combined the lengthened infant mortality and the tri-modal distribution to form a hazard rate curve for semiconducting devices. This shape of the curve resembles the track of a roller-coaster and is therefore called the 'roller-coaster curve'.

Wong and Lindstrom conclude that data presented in their paper indicates that the hazard rate curve for electronic systems takes the shape of the track of a roller-coaster. "An explanation drawing upon engineering fundamentals and quality control practices was provided to describe the forming of such curves. Understanding of the roller-coaster behaviour will: 1. prevent one from mistakenly identifying freak failures as an indication of the system approaching wear-out and making the incorrect decision of reducing screening, 2. provide an impetus to improve inspection and test methods to eliminate the flaws that caused the freak failures in the useful life time of a system, and 3. most importantly of all, help to reshape the course of reliability development away from the bathtub misconception. Reliability engineering is for control of failures. When we understand how failures com about we will have a chance in controlling them."

As Wong and Lindstrom already identified, a theoretical failure rate curve for electronic products can be described as the four-phase roller coaster curve. This theory is later explained in several other articles, such as: [Luy00] [nog meer refs]. The roller coaster curve is shown in figure 1.2; the vertical axis represents the failure probability and the horizontal axis represents time. Starting moment is the moment of purchase of the product by a customer, this moment can also be defined as phase 0. The other four phases are explained below.

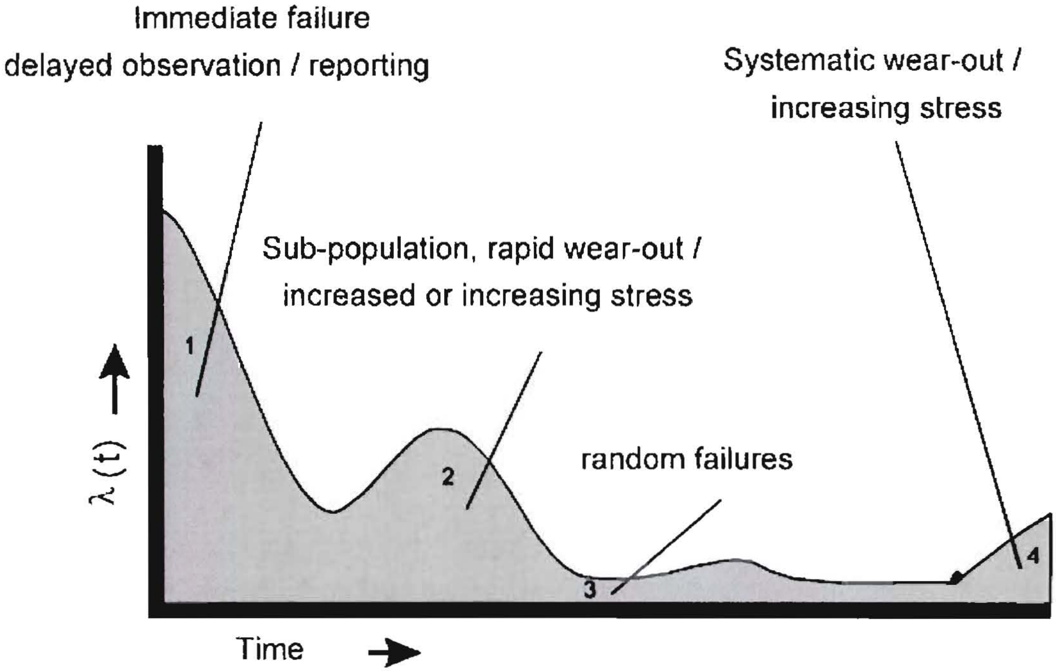


Figure 1.2: Roller coaster curve

Phase I - Hidden 0-hour failures

Hidden 0-hour failures are product failures that occur immediately after arriving at the customer. These failures can be experienced by the users of the product while unpacking the product, while installing it, or during first usage. Although, theoretically, these (often performance or quality related) failures should all be observed at the moment of commissioning of the product, complex functionality (software) or delay in customer reporting can cause delay in observing and reporting a failure. One of the major sources is a mismatch between the technical product specification and the customer specification (which is derived from customer requirements), thus the product is not technically defective. Possible explanations are that these products have either slipped through final tests or have failed after tests were performed, have been damaged during transport, or are used by (certain groups of-) customers in an unanticipated manner.

Phase II - Early or rapid wear-out failures

In some cases situations are observed where a distinct sub-population of products, due to some discrete event during manufacturing or due to a discrete difference between users in product use, shows different quality and reliability behaviour compared to the main population with respect to wear-out. Examples are products that are produced with internal flaws. In contrast with products of class 1 these products are able to function for a while but due to the extremes in the product (flaws) or the customers they show a different, faster, wear-out than the main population. These subpopulations are quite difficult to test during production because on the product level they initially perform according to specifications.

Phase III - Random failures

Products can fail due to random events. These failures are either internal in the product or are caused by consumer use or other external influences. A homogeneous population results in a failure probability which is to a certain extend constant in time. Products are designed to be used against anticipated ('normal') user conditions. It is, however, difficult to anticipate and to design against all events to which a product can be subjected. External events with a strong 'random' character, such as lightning and mechanical shocks, can cause product failure at any moment in time.

Phase IV - Systematic wear-out

Products can fail due to aging or systematic degradation. Or users consider the product as obsolete but then the product is technically not defect. Failures from this phase can be similar to the early wear-out but now for a homogeneous population (all products). Many products, particularly mechanical products but also certain categories of electronic products, show some form of degradation over time. Well-known time effects are corrosion of metals and increased brittleness of plastics.

The failures in phases 3 and 4 can occur for all products and all users; the failures from phases 1 and 2 however do not. The products with failures in phase 1 and 2 can be slightly different than other products, for example a batch of products with an internal flaw. The users that experience failures from phases 1 and 2 can also differ from other 'regular' users. Users that use the product in an unanticipated matter may experience failures in phase 1 or 2 and users that expect a slightly different product than they use while the product itself has no technical faults and specifications are according to plan may also experience this as a failure of the product ('No fault found'-failures, phase 1).

1.2.5 Theory on solving different reliability problems

Early failures in engineering devices are nearly synonymous with the 'product noise' quality loss stressed in the Taguchi methodology. As discussed in Chapter 4, the preferred method for eliminating such failures is through design and production quality control measures that will reduce variability and hence susceptibility to infant mortality failures. If such measures are inadequate, a period of time may be specified during which the device undergoes wear-in. During this time loading and use are controlled in such a way that weaknesses are likely to be detected and repaired without failure, or so that failures attributable to defective manufacture or construction will not cause inordinate harm or financial loss. Alternately, in environmental stress screening and in proof-testing product are stressed beyond what is expected in normal use so that weak units will fail before they are sold or put in service [Lew96].

Random failure can be reduced by improving designs: making them more robust with respect to the environment to which they are subjected. As discussed in detail in Chapter 7 this may be accomplished by increasing the ratio of components capacities relative to the loads placed upon them. The net outcome may be visualized as in fig 6.2, where for an assumed operating environment, the failure rate decreases as the component load is reduced. This procedure of deliberately reducing the loading is referred to as derating. The terminology stems from the deliberate reduction of voltages of electrical systems, but it is also applicable to mechanical, thermal, or other classes of loads as well. Conversely, the chance of component failure is decreased if the capacity or strength of the component is increased [Lew96].

1.2.6 Dimensions of reliability problems

Based upon the aspects addressed above, it is possible to define different 'dimensions' or aspects of reliability problems in modern products. This paper will use three different 'dimensions' to explain a wide range of reliability problems (see figure 1.3 for a graphical representation):

- different failure classes (physical or functional failures)
- the relevance of statistics (failures happening only in certain (sub-)groups of products or in all products)
- the influence of time (random failures or failures due to cumulating of time or customer use of a product)[Bro05]

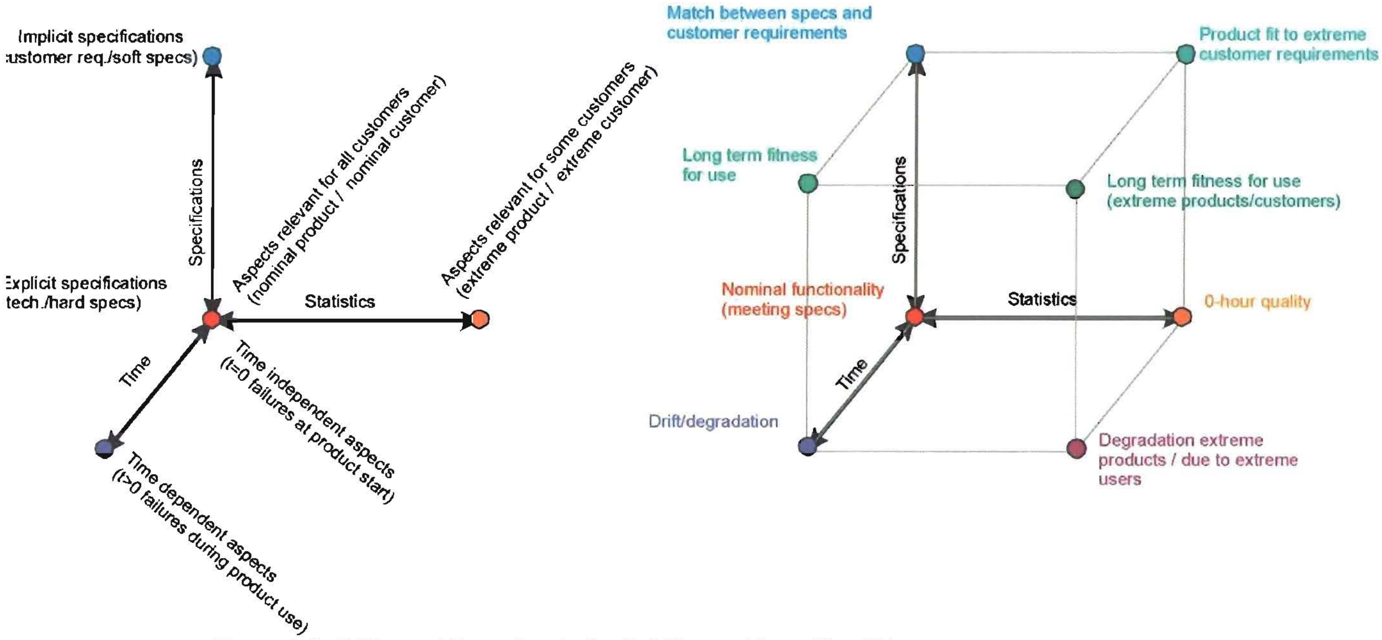


Figure 1.3: Different 'dimensions' of reliability problems [Bro??]

1.3 Climate changes, energy savings and LED lamps

The climate change is a hot topic. People around the world are getting more aware of the dangers of environmental pollution. This is one of the biggest threats to the survival of life on earth as we know it now. Several recent successive natural disasters such as hurricanes, slight changes in local climate and the melting of the ice on the north and south pole has increased the awareness of the environmental problem even more.

Since man is assumed to be the greatest influence on the climate, people want to help the environment. In politics environment is a hot topic too and therefore measures to improve the environment, such as the reduction of carbon dioxide, are introduced. One way to do this is by technological innovations.

The industry is examining various strategies to respond to the demand for more environmental friendly production and products. One possible strategy is environmental friendly design: design products in a manner that both the production and use have no bad influence on the environment. Another strategy is designing with (partial) reuse. No matter what strategy is chosen, it will have an effect on product quality and reliability. New, partly unknown production, products and materials are creating new problems and challenges [Bro07]. In this graduation project two strategies to reduce influence on the environment are shown, namely the increase of lifetime of products and the reduction of energy consumption of products.

Lighting is responsible for the consumption of about 20% of all generated electricity [Mis06]. Big energy savings and carbon dioxide emission reduction can be accomplished by improving lighting solutions. Even more because the conventional light bulb is not very energy efficient: only 10% of the used energy is converted to light, the rest is lost as heat.

In Australia the goal is to phase out the sale of conventional light bulbs by 2010 [Syd07], other governments are also engaged in similar proposals, including the Netherlands [Fin07]. The largest lamp producer in the world, Philips, is also pushing energy efficient lamps to the market and wants to stop the production of the standard light bulb within 10 years. Each year in Europe 2 billion bulbs sold. After successes in the European Union, the United States are also lobbying to get the light bulb out of the stores before 2016. There exist no less than 4 billion fittings for light bulbs [Ein07]. The market for energy-efficient light bulbs is enormous; especially when you consider that there is not even talked about other lighting sources where there are all sorts of economical alternatives are emerging. The low-energy light bulb is currently the best-known alternative to the inefficient, traditional light bulb. However, there is a technology which is heavily in advance, even more promising is terms of energy savings and also has a number of important advantages compared with the fluorescent lamps (including bulbs and fluorescent tubes), lamps based on LED technology.

Common named advantages of LEDs in the literature include: long life, reliable, small, light weight, impact resistance, low heat, direct coloured light and quiet [Wil78].

As noted in the previous paragraph LED lamps usually have a longer life time than conventional light bulbs. This is a second advantage which helps reducing the impact of lighting products on the environment. A longer life means that less lamps have to be produced, less pollution from production.

1.4 LED Supply Nederland

Led Supply Nederland (LEDNed) is a company situated in Helmond. They are developing and delivering LED lighting solutions since 2004. Besides that, they give advice to companies about the advantages of LED lighting, practically and financially, to offer a complete soltion. LEDNed is one of the early companies in the Netherlands that saw the advantages of LED lighting over regular lighting. Production of the lamps usually takes place externally, mainly in China. LEDNed delivers their lighting solutions in the Netherlands, Belgium and France. Due to continuous improvements in LED lighting technology, the LED lamps are becoming more and more a threat to conventional light bulbs and thus the interest in the solutions of LEDNed is growing.

1.5 Reason for reliability research

Led Supply Nederland recently received a number of complaints from their customers that the long life and high reliability of the LED lamps is not as high as they supposed to be. A certain type of lamps, LED Par 30 lamps, is supposed to have an average technical life time of 50.000 burning hours at 230V AC. The complaints from customers are that about 30 to 40% of the lamps fail after just 200 burning hours. The reliability of the lamps seems to be (much) lower than expected. To check this, LED Supply Nederland wants an independent reliability test in order to find out what the actual reliability and expected life time is. Other objectives of the test are to find out why the products fail and in which part of the rollercoaster-curve the product failures can be classified.

1.5.1 The Test

This is a summary of the test, the complete description and results can be found in Appendix A. Because the LED par 30 lamps are supposed to last 50.000 burning hours on average, the expected mean time to failure (MTTF) is 50.000 (μ_0). The complaints from customers lead to an alternative MTTF that is much smaller ($\mu < \mu_0$). This results in the following hypotheses about the MTTF that need to be tested.

H_0 is $\mu = \mu_0$

H_1 is $\mu < \mu_0$

A test was set-up in the facilities of the Quality and Reliability Engineering group at the Paviljoen building at the TU/e. The test is designed to measure and monitor the lifetime (in hours) of the LED Par 30 lamps. The expected failure behaviour is high, 20-30% of the lamps are expected to fail within the first days/weeks (based on complaints by customers of LEDNed). Given the expected failure behaviour a test with only 10 lamps was considered adequate for a first scan to obtain results with sufficiently high confidence (calculations are shown in Appendix B).

Initially, all test lamps work correctly, so they show no 0-hour or phase I failures (assuming LEDNed did not omit these lamps from the test). However, not all lamps emit the same colour of light while all packing boxes of the lamps are marked with the same colour code. Lamps 4 and 7 show a yellow light while the other 8 lamps show a more whitish light (with some small discolouration). Besides that, the glass hood of the lamps show some differences, this however should not influence the test results. For lifetime testing purposes, these discolorations were not regarded as a failure, only lighting degradation and catastrophical lighting failures (when a lamp stops emitting light) were regarded as failure for this test.

Within 24 hours lamp number 7 encounters a failure, a number of LEDs in the lamp stops working; a few hours later some more LEDs fail. The lamp still works but the outer ring of LEDs and a part of the second ring stopped emitting light. After 1 week (168 hours) 5 out of 10 lamps emit significantly less light compared to the starting situation. Lamps 1, 2, 5, 8 and 9 are the ones that fail to work correctly. After about 2,5 weeks of testing, the remaining four lamps also emit less light than a new one, the difference between these lamps and new ones becomes clear around 400 hours.
This results in an estimated MTTF of 246 hours [Lew96].

The conclusion of this test is that the expected average lifetime (H_0 is $\mu = \mu_0$) is not correct. If the MTTF is approximately normally distributed with an expected value of 5.7 years, then:

$$E(X) = \mu = 5.7$$

$$\operatorname{var}(X) = \sigma^2 = \text{unknown.}$$

If the results from the experiment would be that 1 lamp fails after 21 hours and 5 lamps fail after 168 hours of burning time, this would mean that 4 lamps are still in function after 168 hours. Those 4 are then assumed to be reliable as specified and burn for 50.000 hours before a failure occurs. This would result in an average MTTF in the sample of 2.3 years (about 20.000 hours).

If the variation of the total population is unknown and thus approximated by the sample variation (normal distribution) than, the test statistic $t_0 = -2.44$. Because $t_0 < -t_{0.02,9}$ ($-2.44 < -2.398$), thus H_0 can be rejected with 98% confidence.

1.5.2 Possible explanations of results

In order to allow a better translation of product reliability to the underlying business processes, the rollercoaster curve is used (see section 1.2.4). A standard figure of the rollercoaster-curve which could be expected if the lamps were as reliable as advertised is shown in figure 1.4.

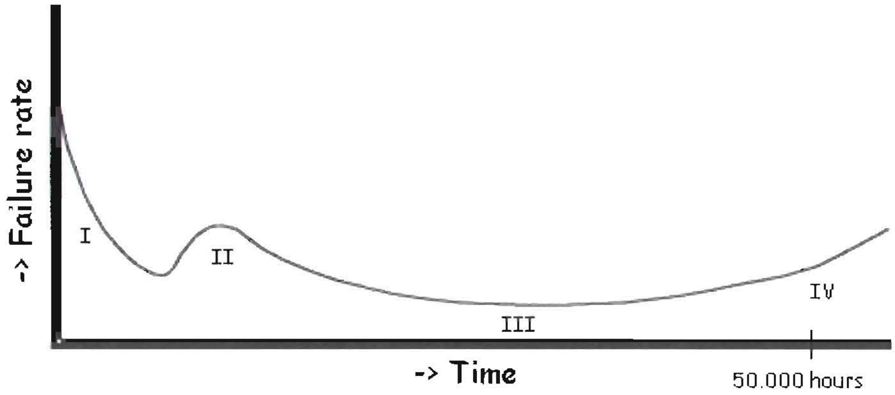


Figure 1.4: The roller-coaster curve

There are three kinds of failures that are observed during the test:

- Discolouration of the LEDs
- Failure of LEDs in the lamp
- Degradation of the LEDs

These failures can be classified in several ways, to know which explanation is best, more information about the lamps is needed like the selection procedure of the lamps, the existence of subpopulations of lamps, etcetera. The most likely explanations are given below.

The discolouration of the LEDs can best be classified as a Class II failure. Although the lamps arrive out-of-spec (they emit yellow light instead of white light), it is expected that due to a problem during manufacturing a distinct sub-population of the Par 30 lamps shows this discolouration and is therefore a Class II failure.

The degradation of the LEDs is already visible after just one week of burning time. It seems that every lamp suffers from early degradation, this can clearly be seen by the bare eye if a new lamp is compared to the lamps that have burnt for some time. Besides that is can also be partially seen in the webcam images as can be seen in figures C.3, C.4 and C.5 in Appendix A. Because all lamps show the degradation, there are two possible explanations. One is that the design of the lamps is so bad that their life time is extremely low, in this event the failures belong to the Class IV failures. However if the failures are the result of low quality components or if only a (big) subpopulation of the lamps suffers from the failures, then the failures belong to the Class II failures.

The failure of a number of LEDs within a lamp are actually a 'post-mortem failure'. Because upon arrival, lamp 7 showed a yellow light instead of white. Therefore the lamp has already 'failed' but after a few hours of burning some LEDs also stopped working at all. More information about this failure and the rate of occurrence is needed to be able to classify it correctly.

1.5.3 Conclusion of the first test

It is clear that the LED Par 30 lamps do not have an average lifetime of 50.000 hours. The test shows that this hypothesis can be rejected with at least 99,9% confidence.

Because it is not known exactly when the light intensity of the Par 30 LED lamps is too low an approximation has to be made. It is clear that after just one week the intensity of the light is significantly lower, therefore the Class II/Class IV failures already occur after 168 hours. This results in a different roller-coaster curve for the test lamps, an estimate is shown in figure 1.5.

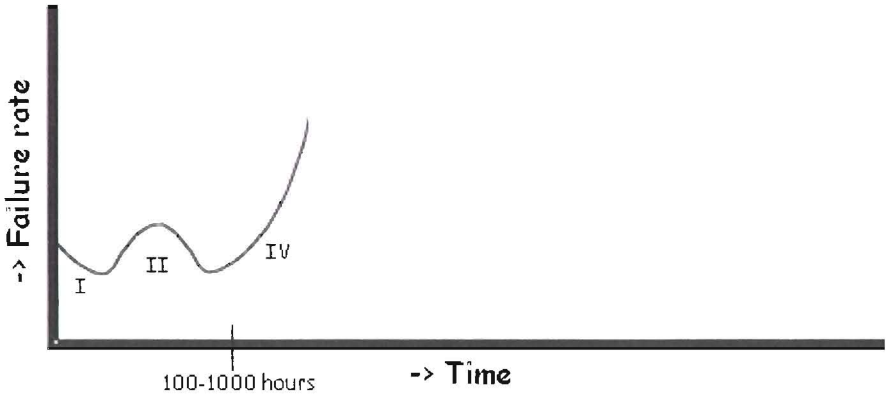


Figure 1.5: The approximated roller-coaster curve for the LED lamps

The observations from the test can form the basis of further research to the causes of the different kinds of failures. However, more information about the underlying business processes is needed to perform this further research.

1.6 Initial Research Question

The exploratory test showed the expected results: Class I & Class II failures, but in extreme form. It was even observed that every lamp showed Class II failures. The theoretical explanation for these failures is that there is a fault in the lamps. Further research by prof. Brombacher showed this, he discovered that low quality electronics were used in the lamps. This was the main reason for the failures.

The latest generation LEDs, white LEDs and so-called High Power LEDs and High Brightness LEDs, differ from early generation coloured LEDs. As explained earlier, the long life of LEDs of 50,000 to 100,000 hours, is one of the important properties. The latest generation LEDs haven't proven their long life yet. According to Burmen et al. [Bur07], the lifetime of state-of-the-art LEDs is expected around 50.000 hours for coloured LEDs, but only 10.000 hours for white LEDs. For high demanding applications, the expected lifetime is even lower, upto ten times lower. Bulloughs [Bul06] is more positive and estimates that latest generation LED-configurations will have about 80% of their illumination after 20.000 hours.

Buyers of LED lamps sometimes are confronted with new technologies that are rushed to the market due to the earlier mentioned business processes (section 1.2.1). This may confront them with lamps that are insufficiently tested. The technology therefore may not lead up to expectations of buyers [Luy00]. With LEDs, the expected lifetime may not be realistic as I have shown with the first test of the Par 30 lamps.

LEDNed came to the department of Quality and Reliability Engineering because they had doubts about the lifetime of their LED lamps. This resulted in a cooperation with this Masters thesis as a result. The eventual goal of the cooperation is to construct a model in which the reliability and lifetime of LED lamps can be predicted. This thesis is one of the steps in making and improving such a model.

A problem with a lifetime model is that there is no set standard for LED lamps. The traditional definition of lifetime for lamps is based on the average lifetime that is expected under specified circumstances [IES00]. With fluorescence lamps this specified circumstance is the cycle 3 hours on, 20 minutes off at 25 degrees Celsius. When this definition is applied to LED lamps, lifetime will often be more than 100.000 hours.

LEDs rarely show catastrophic behaviour. Illumination, however, does deteriorate over time. Different types of white LEDs have different degradation mechanisms and therefore different degradation speeds [Nar04a]. Lifetime of LEDs often used to be defined as the time until illumination is half of the initial illumination, at 25oC and 20 mA [Bur07]. This L50 is not always useful as research shows that users find a loss of illumination up to 30% (L70) acceptable. Besides degradation of illumination, LEDs show a change in colour over time. This should also be taken into account.

During the first test, LEDNed had just received a new kind of lamps, namely High Power GU10 LED lamps. These lamps are advertised by the Chinese manufacturers to have a long lifetime of 50.000 hours. As stated in the paragraphs above, this may not be a realistic figure. The first test also caused some doubts of the credibility of advertised lifetimes by the Chinese manufacturers. Therefore the initial assignment for this thesis was:

> *"Develop a degradation model for High Power GU10 LED lamps."*

This degradation model can show the development of the lighting characteristics of the lamps during their lifetime and estimate the actual lifetime. In order to construct and develop this degradation model, an actual degradation pattern is needed. Therefore this assignment was further specified into two research questions:

> *"What are the characteristics of the degradation pattern of the high-power LED lamps?"*

And:

> *"What degradation model fits the characteristics of these LED lamps?"*

The next chapter deals with the theoretical background for these questions and with methods to help answering these research questions.

2 Research Methods

2.1 Introduction

In this chapter, the research hypotheses and the specification of the research are explained by showing underlying theorems, which mainly follow from literature. An important part of the theoretical background is already explained in the first chapter, namely the roller coaster curve and the 4 classes of failures.

2.2 Research methodology

For a Masters Thesis of Industrial Engineering and Management Science are two basic methods of research. An empirical cycle is used when a project aims to develop a theory or improve or if it is a certain empirical phenomenon should be explained. A regulatory cycle is used when a project aims to solve a specific problem.

The goal of this thesis is describing a phenomenon, namely the degradation of a certain type of LED lamp. Therefore, the empirical cycle is used as the base for this report. This is done as follows: Using empirical data assumptions are made. These assumptions are then defined in measurable variables and thus a theory with expected results is developed. This theory is supported by new empirical data and the results are interpreted from the perspective from the new theory. This in turn can provide ideas for other studies and the development of new hypotheses. I as writer of this report and investigator am not part of the situation and I have no influence on the phenomenon, compared to an improvement process where an intervention can be done with a certain kind of situation.

The investigation of the degradation behaviour of LED lamps that leads to hard errors is a relatively pure empirical cycle. Previously it has been established that hard errors only partly the rejection of consumers. If the lamps do not meet the expectations of consumers comply determines to a great extent the kind of rollercoaster curve. That is why in this thesis, a research into actors that in various ways influence the quality and reliability of LED lamps is done.

2.3 Quality and Reliability

2.3.1 Definitions

There are several definitions of failures, quality and reliability. A number of definitions is taken from the course Reliability by Prof. Newby, Lewis [Lew96] is part of the literature that is used for that course.

Quality: The ability of a product to fulfil its intended purpose (fitness for use).

Reliability: The ability of a product or system to fulfil its intended purpose for a certain period of time. Expressed in terms of the random variable T (time-to-system-failure): R(t)=P{T>t}, the probability that a system operates without failure for a length of time t.

Failures: A failure is an unplanned transition to a state in which the system cannot properly perform its intended function.

Hazard rate: (Only for non-repairable items) The conditional probability of an instantaneous failure given that the component is still intact.

Failure Rate: The frequency with which an engineered system or component fails, expressed for example in failures per hour. It is often denoted by the Greek letter λ (lambda)

In words appearing in an experiment, the failure rate can be defined as the total number of failures within an item population, divided by the total time expended by that population, during a particular measurement interval under stated conditions. (MacDiarmid, *et al.*)

Here failure rate $\lambda(t)$ can be thought of as the probability that a failure occurs in a specified interval, given no failure before time t. It can be defined with the aid of the reliability function or survival function $R(t)$, the probability of no failure before time t, as:

$$\lambda = \frac{R(t_1) - R(t_2)}{(t_2 - t_1) \cdot R(t_1)} = \frac{R(t) - R(t + \Delta t)}{\Delta t \cdot R(t)}$$

where t_1 (or t) and t_2 are respectively the beginning and ending of a specified interval of time spanning Δt. Note that this is a conditional probability, hence the $R(t)$ in the denominator.

Mean Time to Failure:

Probably the single most-used parameter to characterize reliability is the mean time to failure (or MTTF). It is just the expected or mean value E(t) of the failure time t [Lew96]. Hence $MTTF = \int_0^\infty t \cdot f(t) \cdot dt$, written in terms of reliability:

$MTTF = \int_0^\infty R(t) \cdot dt$. The MTTF is often denoted by the symbol Θ .

If the failure rate is constant, in other words if the time-to-failure is exponentially distributed, then $MTTF = 1/\lambda$. This fact is often used in literature regarding failures and failure rates.

2.3.2 Time dependent failures/time independent failures

Brombacher [Bro05] gives a model based on a set of common used reliability definitions and, from that different types of reliability problems (or failures) are described.

"From a customers' point of view there can be a problem if there is a mismatch between the customers' requirements and the product performance. From the manufacturers' point of view, these reliability problems can be caused by fundamentally different processes. The first process related to the product reliability is the role that specifications play in the lifecycle of products. Specifications are defined as the set of documents that companies use to describe the intended functionality of a product. Specifications are supposed to reflect (intended) product functionality in interaction with the user of the product, therefore the development of a product is based on those specifications. A common approach is to assume a product fails at the moment is does not meet its specifications. Physical failures can be ...

Companies rely on specifications when they develop a product and these specifications are supposed to reflect (intended) product functionality in interaction with the user of the product. A common approach is to assume a product fails at the moment it does not meet its specifications. For such a failure there can be many reasons. One of the most common class of failures are the so-called physical failures. Many traditional reliability models assume that a product consists of components and that a failure happens when a (physical) gradual or instantaneous change occurs in a component. Such an event is called a (component) failure. If such a component fails and this failure is not covered by some form of redundancy, the entire product will fail [1,2]. Depending on the nature of the failure mechanism these failures can have a time-independent random character, or they can be, if mechanisms involve some form of wear, time or use dependent [2].

A cause for products unable to meet with customer requirements only after a certain amount of time, could be

the due to gradual change of behaviour in time due to a gradual change in physical properties (drift or degradation). All these events can occur either systematically at all products due to inherent (structural or physical) product properties, can happen only at some products depending on individual products or users, and can be structurally present in a product or can manifest itself in a product only after a certain amount of time or product use. In other words: the fact that, at a given moment in time, a product is not able to meet with its users requirements can be due to a large number of different causes."

2.3.3 Hard/soft reliability problems

"Next to these physical failures, a second group of failures consists of the so-called functional failures; there can be situations where there are no physical failures in a product but in spite of the absence of physical failures the product does not meet customer requirements. For problems in this class there can be, conceptually, two reasons. Either the product is, for other reasons other than physical failures, not able to meet specifications or there is a mismatch between specifications and customer requirements. This paper will distinguish between:

- Specification violations/hard reliability problems: Situations where the product is not able to meet both the explicit (technical) product specifications and customer requirements.
- Customer expectation deficiencies/soft reliability problems: Situations where in spite of meeting with the explicit product specifications, a customer explicitly complains on the (lack of) functionality of the product.

A special category in this context, is the situation where the product is only partially specified. With simple mono-functional products it can be assumed that a product can be (almost) fully specified. Both the functionality (does the product do what it should do) and the freedom from adverse effects (does the product not do what it should not do) can be written down in a set of explicit specifications.

Especially in the case where software is involved, due to the large state-space of software products, it can be very difficult to write a specification with a high coverage. Failures can be structurally present in the product but occurring only intermittently (due to the occurrence of so-called 'triggering events'). In other situations the product just may not be able to meet with the requirements of (some) customers. In order to keep a clear distinction between the different failures this paper will assume all failures (also software failures) that clearly violate specifications as hard reliability problems and all causes (hardware, software, user interface, etc.) for customer complaints that cannot be traced back to a violation of product specification as soft reliability problems."

2.3.4 The influence of product/customer statistics

One of the advantages of the old, component based, reliability approach was that product failure was due only to the (catastrophic) failure of components. Issues like hard/soft reliability and/or the influence of gradual failure mechanisms were not taken into account. The effect of taking a broader view, such as presented in the previous paragraphs, is that differences in products and differences in users must be taken into account. If, with respect to time related effects, user profiles influence the degradation rate some products will have different failure characteristics than others. Also product internal aspects, such as product tolerances, can play a role.

Especially with respect to soft reliability problems: since there are no clear-cut specifications that are violated the situation that causes a customer complaint may be different from product to product and from customer to customer.

2.3.5 A taxonomy for performance, quality and reliability problems

Although it is always a sound balance between the three business drivers, i.e. quality, time and costs, that is sought in a business process, differences in focus can be identified in the three classes of business processes. The class A business process, generating short lifecycle products, distinguishes itself by its focus on 'time'. Since new technology keeps becoming available at a continuing high speed companies will want to take maximum benefit from this technology. Therefore in order to maximally benefit from new technology companies will drive for the shortest possible 'time to market'. Business processes of type C, concerned with systems where high capital investments are required, will have a focus on maximizing the utilization of the investments made. The product has therefore to fulfill its function with a high efficiency during a long period of time. Safety, availability and reliability are important issues, requiring business processes that are quality-driven. Although a business process of class B can be seen as an 'in-between' type of process there are some remarkable differences. Often the main driver in B-type business processes will be on costs. People buying typical products generated by these business processes will not buy them for their innovative character or because of very high availability. Since business processes in this group do not share the innovative advantage of class A and do not have the requirements on capital investments of class C the competitive advantage will often be the price of the end-product.

2.3.6 The relevance of different failures for different business processes

All business processes try to meet their typical requirements as good as possible. An A-type business process tries to deliver their consecutive generations of products at the predefined moments of time, while a C-type of business process tries to meet its quality requirements agreed upon. Performance regarding the differently focused requirements, i.e. 'time' versus 'quality', requires different approaches and different operational structures.

The different operational structures of business processes will perform differently in terms of 'quality' and 'time', due to their performance capabilities. Combining the failure taxonomy presented earlier with the different types of business processes leads to a number of combinations that are interesting for further research.

- A. Business processes depending on products where the economical lifetime is considerably smaller than the technical lifetime. Due to the short economical lifetime detailed considerations on phase 4 class of failures are not very relevant; at the moment it can be safely assumed that the onset of phase 4 is beyond the economical lifetime of the product. In some cases the economical benefit of applying new functionality can be such that a certain amount of phase 1 and/or phase 2 class reliability problems are accepted. The number of these failures should, however, not be such that the economical benefit of applying this new technology is endangered. Due to the constant evolution of new technology the related business processes show a very strong pressure on time to market and limited provisions to ensure flawless designs and will only to a certain extend use proven, mature, technology. Therefore the most relevant class of reliability problems for this type of business processes is phase 1 and 2. That failures in these categories exist is, generally speaking, not a problem but the number of failures should be limited in order to keep economic benefits.

- B. Business processes depending on products where the economical lifetime is comparable to the technical lifetime. Because of the limited degree of innovation and modest time-pressure and the often large impact of especially class 1 failures, not too many risks are taken with the application of new technology6. Maintenance strategies to handle class 3 and 4 problems are, to a limited extent, accepted but, if possible, avoided by taking adequate measures in the design. Replacement strategies in this category resemble class A business processes but, due to the lower degree of innovation and the larger economical consequences of replacement, with a lower frequency.

- C. Business processes depending on products where the economical lifetime is much larger than the technical lifetime. Many systems in this class of products (process industry, large infrastructure such as railroads) require very high investments. Therefore replacement of a total system due to some innovation is done only when this is economically justified.

Class 1 an 2 failures are not common in these systems since due to the, on one side, limited time pressure and, on the other side, large consequences of failures, detailed test and verification programs are usually put in place. Class 3 and especially class 4 type of reliability problems can be expected here, due to the long lifecycle. Some parts of a system are susceptible to degradation and/or random failures and these failures are often accepted. Management of reliability for these products is therefore often concentrating on the selection of adequate redundancy or the application of adequate maintenance strategies to minimize the risk of an accident, within economic boundary conditions.

The fact that different business processes have different problems may not be entirely new. Product development processes, however, are by no means static; due to the influx of new technology it is possible that business models that where considered unacceptable for certain products in the past become, for competitive reasons, a necessity in the future.

2.4 Lighting and LED Technology

2.4.1 Light Quantities

Light is part of the electromagnetic radiation spectrum which forms in an impression of brightness in the human eye. The visual light lies within a radius of wavelengths between 380 and 780 nm (in vacuum) and can be divided in to wavelength which represent different colours. Wavelengths around

650 nm are red and wavelengths around 450 nm are blue [Rut96]. The human eye is not evenly sensitive to different wavelengths (colours). The largest sensitivity within daylight is around 550 nm (yellow-green) and around 500nm (blue-green) in the dark.

The optical quantity used in lighting theory can be regarded as energetic quantities corrected for the human eye. Table 2.1 shows the lightning quantities used in this thesis [Kan07],[Wik08]. An explanation is given below [Kan07], [Wik08]. The index v indicates visual quantities and the index e indicates energetic quantities.

	Quantity	**Quantity (Dutch)**	**Unit (SI)***
Φ_v	luminous flux	lichtstroom	lumen (lm)
E_v	illuminance	verlichtingssterkte	lux (lx = lm/m_2)
I_v	luminous intensity	lichtsterkte	candela (cd = lm/sr)
L_v	luminance	lichtintensiteit	cd/m_2 (=$lm/(sr*m_2)$)
R	luminous efficacy	lichtrendement	lumen per watt (lm/W)

Table 2.1: Lighting quantities

Luminous flux is the total quantity of light produced by a light source in all directions.

Illuminance is the luminous flux that covers a surface area. For lighting inside houses and workspaces there are rules regarding illuminance; for example to uphold a certain level of ergonomics in an office. These rules are composed with quantities of lux, usually there is a range in which minimal illuminance is about half to two third of the maximum illuminance of a certain source. This is reasonably equal to the definition of lifetime of a lamp in terms of lumen upkeep L_{50} and L_{70}.

Luminous intensity is the luminous flux per angle. This sometimes can be found on the packaging of lamps, however, for lamps that do not emit light evenly in every direction, this is quite useless information. Because the luminous intensity differs per angle at which one looks at the light source. Without additional information this quantity is not usable to compare lamps.

Luminance is the luminous flux radiated in a certain direction per surface area.

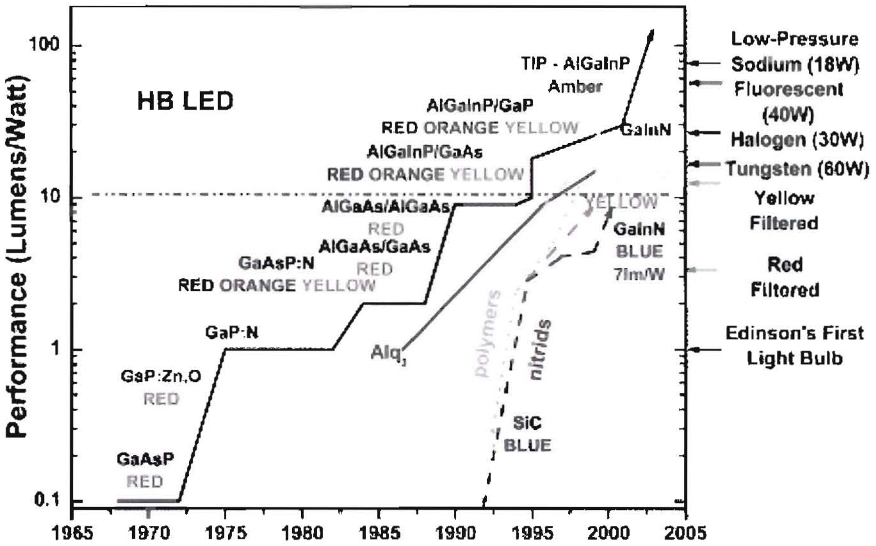
Luminous efficacy is the emitted luminous flux form an artificial light source per used electrical power P (W). This quantity can be used for comparing the efficacy of different kinds of light sources. Usually the electrical power of additional equipment such as casings or sockets is omitted.

The comparison between different kind of lamps is not always possible with all quantities. The GU 10 High Power Lamps are spot that emit light to a small surface, the Par 30 lamps have a much wider surface to enlighten. Some lamps use reflecting layers within the casing to deflect the luminous flux to a certain direction, other lamps may partially absorb the luminous flux in the casing.

2.4.2 LED Technology

Henry Joseph Round published the first article about electroluminescence (the basis of the Light Emitting Diode) around 100 years ago [Sch03]. According to Zheludev [Zhe07], Round can be regarded as the discoverer of the electroluminescence phenomenon. Oleg Losev from Russia is believed to be the one of the inventors of the LED. It was however Nick Holonyak from General Electric who developed the first actual LED in 1962. By the end of 1960's, a high volume of LEDs became available on the market [Sch03]. After that the sales kept growing fast [Rot97]. At that time, only red LEDs were available. They were used in several kinds of displays for calculators, watches and electronic instruments [Wil78][Str88]. But the best known application of (mainly red), now and then, is the status indicator of electronic devices, the on/off status for example. Since the 1970's there were continuous improvements to LED technology [Gil87]. More colours became available but one of the biggest challenges was to develop material that could emit blue photons efficiently [Str88]. When blue LEDs were available, almost every colour could be made by combining red, green and blue LEDs.

The development of LEDs can be visualised with the help of Crawford's Law. Crawford's Law states that every 10 years the performance of LEDs improves 10 times the original value. This can be seen in figure 2.1.[Kov03]



Figuur 2.1: Craford's Law: evolution of the LED performance [Kov03]

In 1993, the first blue LEDs came onto the market [Zei06]. This was a major step towards white coloured LEDs too. There are several ways of creating white LEDs [Cre07][IES00]. One is to combine red, green and blue LEDs. Another is to add a so called phosphorescent layer to blue or ultraviolet (UV) LEDs [IES00] [Nar00]. The technique in these LEDs is similar to fluorescence lamps such as tube lights and energy saving lamps. This process in LED technology is improving just as in regular lighting to a warmer white colour [All07].

Now that it is possible to make white light it is likely that LEDs become the new standard lighting method over time. When that is depends on how fast the quality of LED lamps improves and how fast the costs keep dropping. They cannot yet compete with the common light bulbs, but that moment comes closer and closer [Nar07].

2.4.3 High Power LEDs

The latest generations LEDs are so-called High Power LEDs and High Brightness LEDs. There is no specific definition for these LEDs, depending on the manufacturer or reseller different names are used for this kind of LEDs. These LEDs operate at a significantly higher amperage than the standard 20mAand a bigger power consumption than 0.5 W. The advantage of these High Power LEDs is that the luminous flux and illuminance is much higher than with a conventional LED. The drawback of using a higher current is that more heat is generated. The casing of the lamps should be able to cope with this heat, otherwise the performance and reliability of the lamps will be negatively influenced [DeJ99].

2.4.4 Degradation mechanisms of LEDs

There are two kinds of degradation mechanisms that occur in LEDs. The mechanism that correspond to the material that emits the light and the mechanisms that correspond to the interface between the material and the electrode. Different types of LEDs have different degradation mechanisms. The most important influences on the emitting material are oxidation, photo-oxidation, diffusion of the electrode and heat effects. The most important influence on the LED itself is junction temperature [Nal01].

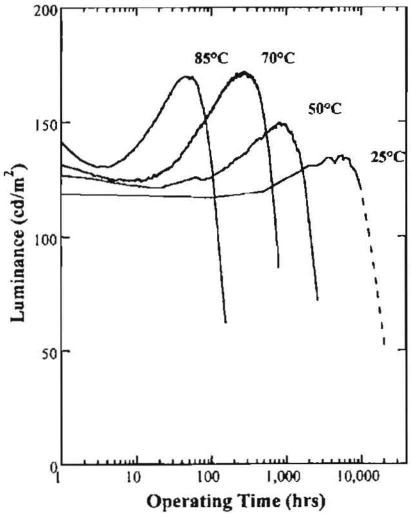


Figure 2.2: Degradaion of illumination of polyLEDs [Par99].

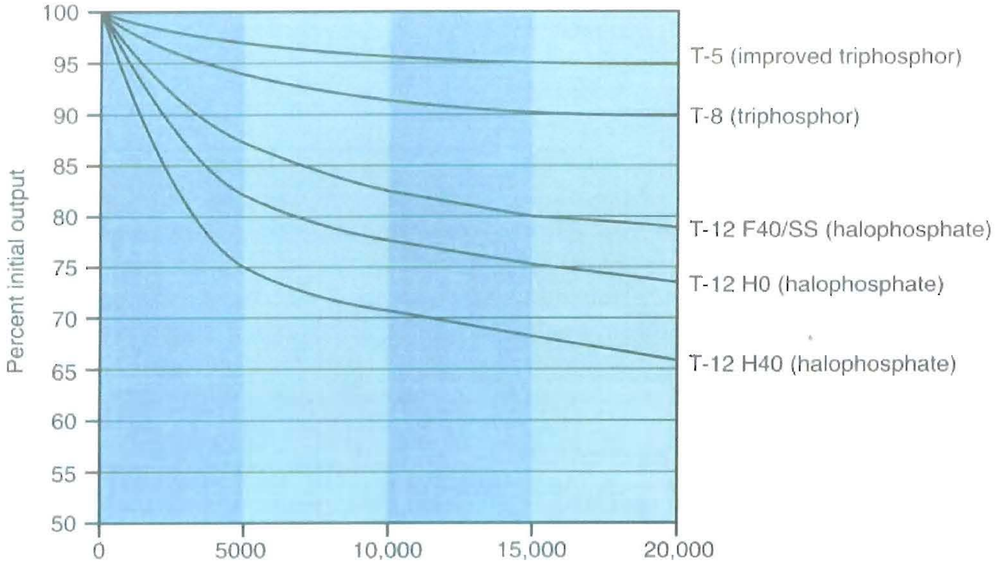
In general LEDs show a degradation pattern that is shown in figure 2.2 [Par99]. After a slight decay and a slight rise in luminance, a gradual degradation starts for a long period of time. White LEDs however show a big degradation in the beginning of the lifetime, this is stated by [Nar04] and [Chi01]. The test in chapter 1 also suggests a relatively high degradation during the first weeks of the lifetime.

Narendran et al. [Nar01] and [Nar04] concluded after several tests that white LEDs show and exponential degradation during the first 2000 hours of use. This is therefore also expected in the experiment with the GU10 lamps. They use the formula $y = e^{-a \cdot t}$, with y being the relative illuminance, a being a degradation constant and t is time. They also show that there is a connection between the degradation constant and electric current. This means that an accelerated degradation can be accomplished by increasing the current through the led. [Yan05] and [Lev05] applied this in their research. Thus if a higher current than standard runs through the LEDs, they will probably degrade faster, so if a LED lamp degrades fast it is possible that a too high current is generated by the electric circuit within the lamp. Therefore the current to the lamp will also be measured during the experiment with the GU10 lamps. There is however no direct connection between the current in the fitting and the current in the lamp (AC versus DC).

2.4.5 Discoloration

Besides degradation of the illumination of LEDs, there is another form of degradation. The colour of the light emitted from a LED can change over time [Nar01]. This happens with all fluorescent lamps because after a certain amount of time the phosphorescent layer loses its ability to fulfil its purpose, changing the colour of the light beam that goes through it. Phosphors degrade over time too. Degraded phosphor means a lower luminous flux too [IES00]. With white pcLEDs this occurs too and since the phosphor loses its working ability, the colour emitted from the LED then changes towards blue [Cre07].

Narendran et al [Nar04a] show that LEDs with a phosphor layer further from the LED chip degrade less. The shape and size of the encapsulation with the phosphor layer which the LED chip is therefore important for the degradation speed. The encapsulation works as a lens and protection of the diode, but it contributes to the degradation of the LED.



Figuur 2.5: Fluorescente lamps with different phosphors [IES00]

Junction temperature and short wavelength emissions affect the degradation speed of white LEDs too. The resul and results in yellowing of the epoxy encapsulation. Narendran et al. [Nar04a] state that there is not much difference in degradation between different types of white LEDs (UV versus blue, both with phosphor). The difference in wavelength of the two LED types does not have as much influence as the junction temperature. However, they also state that more research on this topic is needed.

In this thesis, the reliability of the colours are not included. The main reasons are that there is no agreement to which colour shift is still acceptable and which is not and that no objective measuring method is available at the start of the experiments described in this thesis.

3 Experiment Set-up

In this chapter the characteristics of the measurement experiment with the High Power LED lamps are described. With the help of an experiment is the expected lifetime of the lamps is analyzed. The hypotheses of the experiment and the parameter of the experiment are clarified in this chapter.

3.1 Introduction

The previous test, described in chapter 1, showed that there is a reliability problem with LED Par 30 lamps. Together with observations at the manufacturing site of the lamps about the production facilities and the knowledge of the normal 0.5 mm LEDs, LED Supply Nederland (LEDNed) decided not to continue with this kind of lamps for now.

LEDNed also sells different kinds of LED lamps with other kinds of LEDs in them, such as high power LEDs. The reliability of the lamps with this kind of LEDs in them are not yet known because this is a new product for LEDNed. A new test can help determining whether these lamps show similar failures or degradation patterns to the Par 30 lamps. To gain more insight in the sensitivity of these lamps to Class II failures, degradation patterns, and what potential failure mechanisms play a role, more information about the state of the lamps during the test will be needed; therefore a quantitative analysis of the lamps will be conducted. This quantitative analysis can for example consist of illuminance (or luminous emittance) analysis and power use analysis.

Besides the research questions, some side-goals for this test are determined:

- To test how sensitive a new type of LED lamps are to Class II failures
- To check whether early occurrence of possible Class IV failures is present
- To test what degradation patterns and potential failure mechanisms are present

The type of lamps that will be tested is spot light with one high power LED inside. The bulb base is type GU10, the LED power is 3W and the beam angle is 20°. A new test setup is needed because the new base of the lamps requires different sockets and because more detailed information is needed for the quantitative analysis.

3.2 Hypothesis

For the new spot lights, a hypothesis similar to the one of the LED Par 30 lamps can be defined. Because the spot lights are supposed to last 50.000 burning hours on average, the expected mean time to failure (MTTF) is 50.000 (μ_0). If the spot light would have a degradation pattern similar to the

LED Par 30 lamps, the alternative MTTF would be much smaller ($\mu < \mu_0$). This results in the following hypotheses about the MTTF that need to be tested.

H_0 is $\mu = \mu_0$

H_1 is $\mu < \mu_0$

The hypotheses will be tested in an experiment in which a sample of lamps will be conducted to a 'normal' stress or load (stress within specifications). The time to failure will be monitored to determine whether the hypothesis can be rejected and the alternative hypothesis can be accepted. It is not known what failure rate can be expected with the new spot lights, therefore an estimation of a sufficient sample size cannot be calculated.

3.3 Experiment

The new spot lights require a new test board. Besides that, more information about the possible failures is needed. This information is created by performing measurements; these measurements are described in section 3.4. Section 3.5 shows the practical aspects of these measurements along with the setup of the new test board. In Section 3.6 it is stated what the expected results of the experiment are.

3.4 Measurements

The LED light output is the total amount of light that is emitted from the lamp, called luminous flux or luminous power. According to the specifications on the packaging of the 3W (750mA) Warm White lamp this is 56 lumen. This luminous flux cannot be measured directly, but for a certain surface which is lit by the lamp the illuminance in lux (=lumen per m^2) can be measured. Thus the illuminance of the spot lights is one aspect that can be measured to determine in great detail if and when a lamp shows degradation. If a minimum level of illuminance is known, a detailed time of failure can be determined whether this minimum level is reached. Light-dependant resistors or photo resistors can be used to measure this.

To be able to determine what lamps show failures and what parts of the lamp have failed if a failure occurs during the test, a comparison of the lamp with a failure and a lamp without a failure should also be made. This can be done for example by measuring electrical resistance of certain parts of the lamp, if the resistance of a part is much higher or much lower than the same part in a new lamp, there must be something wrong with that part in the failed lamp. An other possible measurement is the measurement of electric currents through various parts, if the current through one part rises, another part may be broken down. Power usage of the lamps is another measurement that can help determining whether failures have occurred; failing lamps may for example show a higher power output. The above measurements are all related because of the relation between voltage, resistance, current and power. Besides this quantitative analyses, plain and simple observations by the human eye can sometimes also be helpful to determine what parts have failed, in the previous test for example, an array of LEDs in one lamp failed which caused a visible change in the other LEDs that were still operating.

3.5 Test board, practical aspects and requirements

As stated before, photo resistors are needed to determine the illuminance of the spot lights. One resistor per lamp is needed to be able to determine the individual levels of illuminance for each lamp. With a constant power supply, resistors and photo resistors and voltage measurements, the illuminance of the lights can be determined (for electrical schedule see figure 3.1). The voltage measurement should be recorded, for example every hour. To be able to measure 24 hours per day to minimize the total testing time, the measurements should be recorded automatically (on a computer), therefore a 'USB mini-measurement lab' is used to transfer the data of the voltage measurement to the computer for analysis. A lux-meter can be used to check whether the voltage measurements (resulting from the lux-measurement by the photo resistors) is consistent with manual measurements.

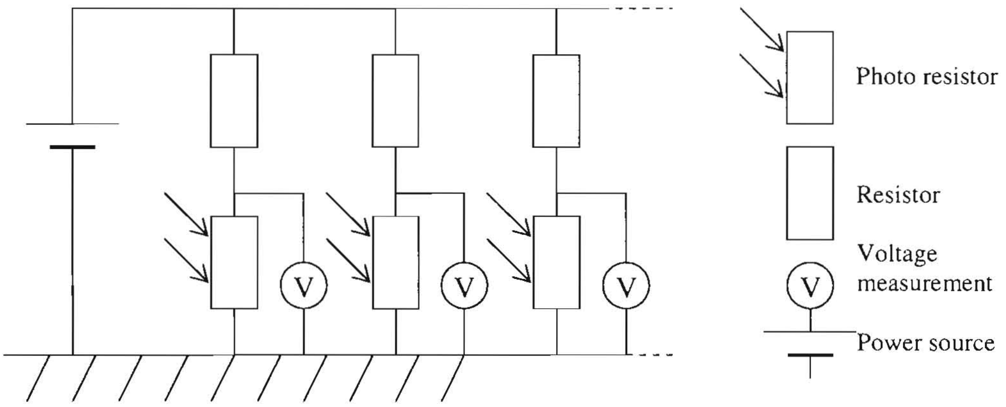


Figure 3.1: Electrical scheme of test two

An oscilloscope is needed to analyze the electric current through the lamps or parts of the lamps, especially when a failure occurs or over a period of time to analyse the possible degradation of the LEDs.

The interface between the photo resistors and the measuring computer, the USB mini-measurement lab, has a maximum of 8 inputs. This means that only 8 lamps could be tested with one interface. Since it is not known what failure rates are expected from the spot lights, a minimum sample size cannot be determined; but assuming the failure rate of the spot lights is equal or lower than the failure rate of the LED par 30 lamps, 10 or more lamps are needed and therefore at least two interfaces are needed. Because lamp sockets and measuring devices like the photo resistors are quite inexpensive, it is best to use the full capacity of the interfaces. Results from testing 16 lamps have higher confidence levels than the results from testing 10 lamps.

To be able to check whether lamps have actually failed a control group of lamps and fittings need to be present. Because of the 2x8 measuring possibilities in the USB interface are available, 16 GU10 sockets and at least one control GU10 socket are needed. This also results in the requirement of 16 resistors and 16 photo resistors.

The amount of ambient lighting should be controlled to minimize the influence on the measurements, this can be done by separating the light from each individual lamp and by ensuring that there is minimal reflection of the light from the lamps, this can be done for example with mat black paper or cardboard but the construction of this is not very firm. A pvc tube with mat black paint is more suitable, and because the rigidity of this material, it can also be used to mount the photo resistors. Using a pvc tube around the spot lights may however cause a heating problem so sufficient ventilation should be present.

Assumptions that are made in order to describe the experiment:

- The lamps used for the experiment come from a homogeneous group and is therefore representable for the complete population (all lamps are the same apart from possible variability in the production process and variability in the components of the lamps)
- The lamps are used continuously, so switching the lamps on and off should not influence the reliability of the lamps, if this does affect reliability a second test should be done where the lamps do not burn continuously but where the lamps are also switched on and off.
- The environment in which the lamps are tested is similar to the environment in which the customers of LEDNed use the lamps.

3.6 Expectations

The lamps will undergo a degradation test at constant stress. The degradation pattern and the expected failure rate of the LED lamps are unknown at the start of the experiment. Besides that, LED lamps can have a stabilization time, before this point, the illumination fluctuates. It is also unknowns how long the stabilization period is. Thus the illumination measurement will begin immediately when the experiment starts. ASSIST proposes to normalize at 1000 hours. The assumption is that after 1000 hours in almost all cases the LED lamp components and systems are stabilized. The first experiment however showed that during that period a lot of failures can occur for certain lamps. Therefore it is chosen that no normalisation will be applied during this experiment.

For determining the time of failure during a degradation process, a certain level of illumination needs to be crossed. Common values are 70% and 50% of the original or normalised lumen level. Since in this experiment no normalisation takes place, the values refer to the original lumen level. These levels are from now on refered to as L_{70} and L_{50}.

Previous experiments described by Narain [Nar05] show that the light output of LEDs can be modelled in the form of exponential degradation. Now a general model of the expected degradation pattern can be constructed. This is shown in figure 3.2

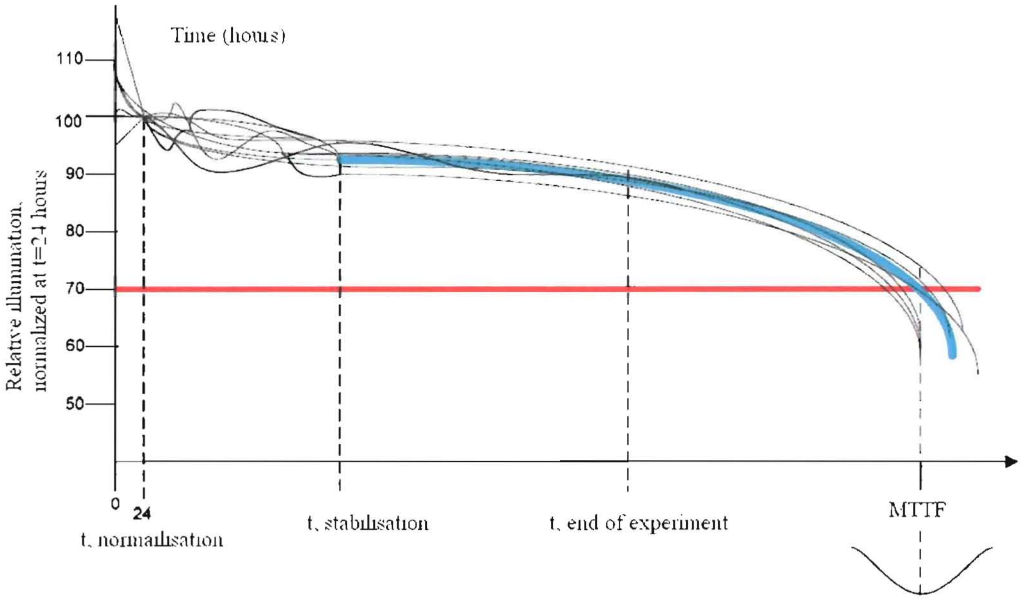


Figure 3.2: Schematic visualization of expected results of this Thesis [figure from Kan07].

At t = 0 hours the experiment starts. If the lamps behave as advertised and/or if H_0 can be accepted, then the degradation pattern is likely to resemble the pattern in figure 3.2.

4 Results and analysis

In this chapter the results of the experiment and the analysis of those results are shown.

4.1 Summary experiment data

A test with GU10 High Power LED lamps was conducted with the following goals:

- To test how sensitive a new type of LED lamps are to Class II failures
- To check whether early occurrence of possible Class IV failures is present
- To test what degradation patterns and potential failure mechanisms are present

Because the LED lamps are supposed to last 50.000 burning hours on average, the expected mean time to failure (MTTF) is 50.000 (H_0). If the spot light would have a degradation pattern similar to the LED Par 30 lamps, the alternative MTTF would be much smaller (H_1). This results in the following hypotheses about the MTTF that need to be tested.

H_0 is $\mu = \mu_0$

H_1 is $\mu < \mu_0$

The hypotheses will be tested in an experiment in which a sample of lamps will be conducted to a 'normal' stress or load (stress within specifications). The time to failure will be monitored to determine whether the hypothesis can be rejected and the alternative hypothesis can be accepted. It is not known what failure rate can be expected with the new spot lights, therefore an estimation of a sufficient sample size cannot be calculated.

Assumptions that are made in order to describe the experiment:

- The lamps used for the experiment come from a homogeneous group and is therefore representable for the complete population (all lamps are the same apart from possible variability in the production process and variability in the components of the lamps)
- The lamps are used continuously, so switching the lamps on and off should not* influence the reliability of the lamps, if this does affect reliability a second test should be done where the lamps do not burn continuously but where the lamps are also switched on and off. The environment in which the lamps are tested is similar to the environment in which the customers of LEDNed use the lamps.

4.2 Experiment results

The measurements started at 13 December 2006 and lasted until 13 August 2007. This results in a total measuring time of 8 months, 243 days or 5.832 hours. At first sight all sixteen lamps showed similar light output (illumination) and colour; this means that there were no Class I failures. This ideal for the degradation test. The more lamps that can be used for degradation analysis, the more reliable the results will be.

As described in section 3.4 all lamps were subject to several measurements. First an automated illumination measurement was conducted to determine the degradation, second a manual amperage and voltage measurement was conducted to be able to determine possible failure reasons, and third a manual illumination measurement with a lux-meter was conducted as a control measurement to the automated illumination measurement.,

During the measurement time it became clear that the first and second measurements were not suitable for the degradation analysis for different reasons. Therefore the manual illumination measurement is the main analysis tool for the degradation analysis.

4.2.1 Automated illumination measurements

The test design was based on the expectation that the measurements of the electrical resistance of 'light resistors' could be used to automatically measure the illuminance and therefore also the degradation of the illuminance. Due to measurement flaws this could not be achieved. The internal variability of the measurement system generated too much noise. The noise generated by the system made it impossible to interpret and analyse the actual measurements.

The automatic measurements were discontinued because the manual lux measurements proved to deliver information on illuminance and degradation much better. The measurement intolerance of the electrical components of the automated measuring circuit/system appeared to be bigger than the actual electrical difference caused by the degradation of the lamps which was measured by the light cells.

4.2.2 Amperage and voltage measurements

These measurements were discontinued because there was no correlation with the illuminance. This is because of the internals of the lamps. The LEDs need DC while the power net delivers AC. The measurements at the AC side of the electrical system of the test board including the lamps cannot show fluctuations or failures within the internal electrical system of the LED lamps.

Looking back at the experiment, it may have been interesting to see what happened to the amperage just before a failure in one of the lamps. However, during a following experiment by Yiu Man Kan the amperage measurements were continued and showed changed values just before a failure.

Due to the fact that the goal was to set up an experiment quite quickly because of the fast changing market of LED lighting, not all aspects of the measurement could be prepared perfectly into detail. The help of an electronics expert would possibly result in better measurement methods. On the other hand, this was the first in a series of experiments with LED lighting. The following measurements will benefit from the above setbacks in measurement I encountered because in the future researches they can now be avoided.

4.2.3 Manual illumination measurements

The manual measurement proved to be much more helpful than the first and second measurement methods. However it was not without limitations. There was quite a big variability in the manual illumination measurements. This has several reasons:

- Due to the form of the fittings, they cold not be mounted 100% perpendicular to the base mounting plate which makes it difficult to measure exactly above the middle of the lamp.
- Due to the form of the lamps, mainly the two "paws" for mounting in the fitting, not all lamps could be mounted perpendicular to the board.
- Because of the above 2 points, the tubes around the lamps could not be fitted into place but had to be mounted loose in order to manually adjust them.
- The lux-meter was fitted with a cardboard mounting device to ensure its placing above the tubes to be exactly in the middle, this device is fitted manually an can cause a slight difference in measurement
- The manual measurements were conducted by several people, possibly with each his own interpretation of the best way of measuring.

The above points can cause measurement flaws. These flaws can be minimized by trying to position the lux meter exactly above the middle of the LED lamps, however this position is based on the eye of the person that makes the measurements. If the measurement position is not exactly perpendicular to the lamps, a measurement flaw up to 1000 lux (over 25 %) can exist. To minimize these measurement flaws, each measurement three samples were taken and the average was reported as the expected actual value of illumination. It is also possible to assume that the measurement flaws can only result in a lower illumination. Since the highest illumination is measured exactly in the middle of the lamp at the right angle (90°). The best or most reliable way to implement this would be to manually delete data that does not seem to fit the other measurements or let a graph that uses only the top points of the graphs in figure 4.1. This is also not very accurate, because there still could be a lot of discussion because the lamps may not be stable yet, and can therefore show unstable measurements.

The results of the manual illumination measurements are shown in figures 4.1 and 4.2. The big humps in figure 4.1 can be interpreted as measurement flaws. Three lamps suffered catastrophical failures (the red graphs)

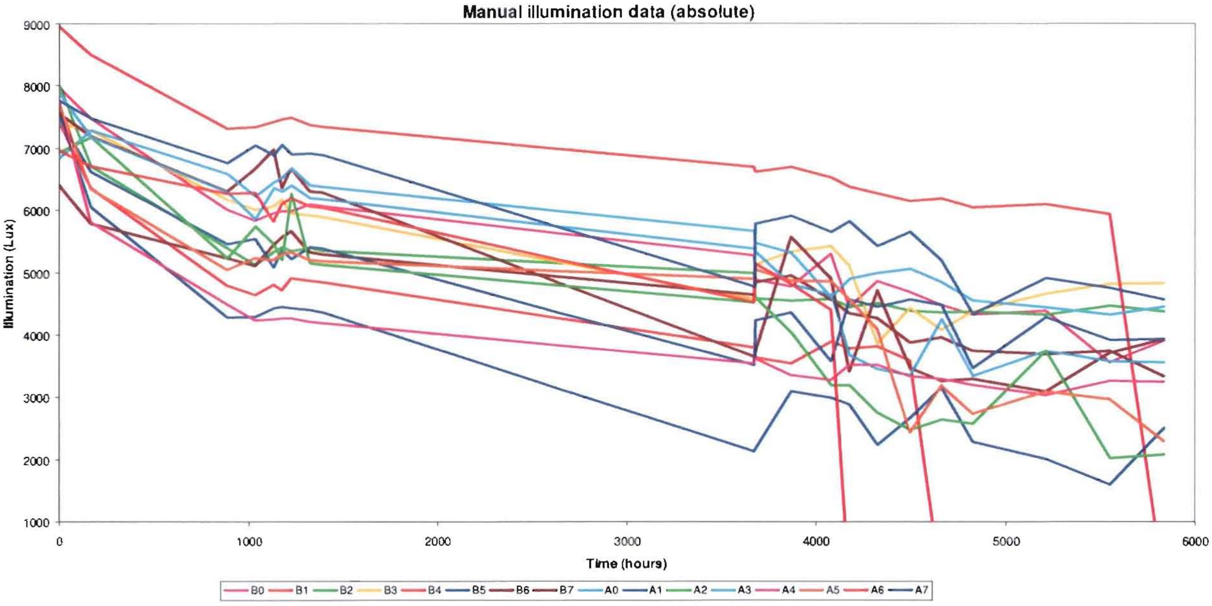


Figure 4.1: Absolute manual illumination data

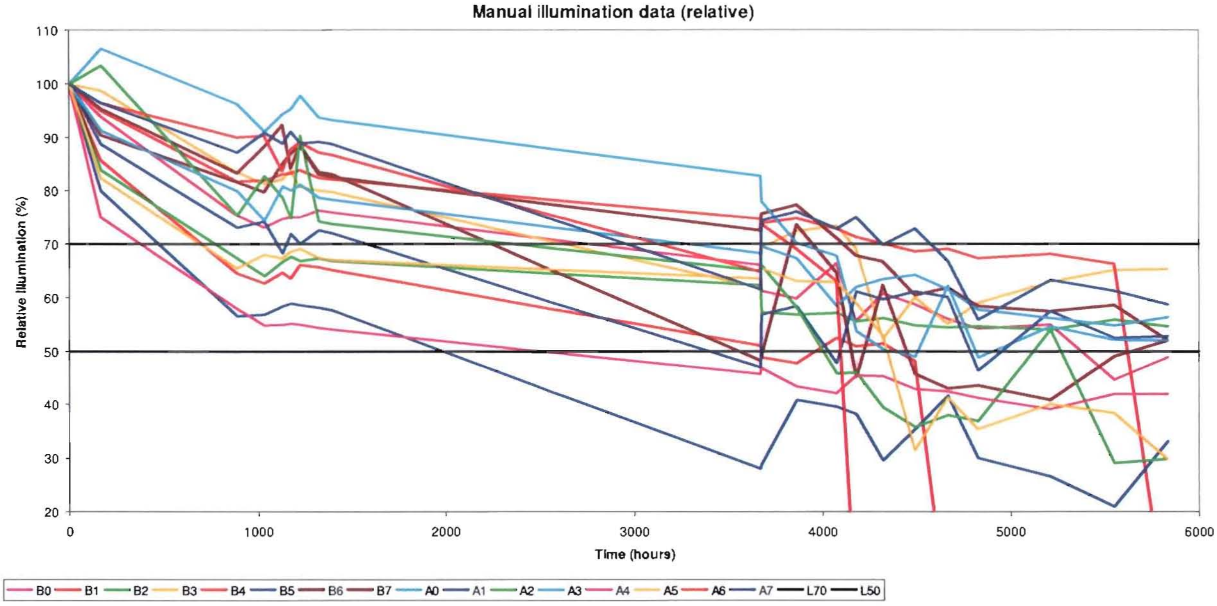


Figure 4.2: Relative manual illumination data

The above figures show that degradation is present and it appears to slow down a little (similar to an exponential degradation function), but another interpretation of the figures can be that after the start the lamps first have to settle (burn-in time) and degradation is linear after that. In order to say something about this, statistical analyses have to be performed on the data.

4.2.4 Variability within the sample size

Figure 4.1 shows that there is some variability between the individual lamps. It is also shown that the degradation pattern is roughly the same for each lamp, regardless of the starting value of illumination. Figures 4.1 and 4.2 show that there are significant differences between the lamps. Instead of normalising to a relative illumination level, it may be better to compose boundaries with a nominal illumination level for the lamps. This however can only be done if the manufacturer provides these boundaries; it is not useful to determine nominal borders according to samples which are drawn on the basis of the average value for a given time.

4.3 Failures

Besides the obvious degradation, three lamps showed catastrophical failures during the testing period. One lamp (A6) just stopped working, but lamp B1 even exploded (obviously also resulting in a failure), lamp B4 exploded too and even caused a short fuse in a whole wing of the Paviljoen building. After this failure the experiment was ceased for safety reasons. The risk of more short fuses and possibly even fires as a result of the short fuses also caused following experiments with LED lamps to be conducted in a more controlled and safe environment at the university campus.

Lamp B4 had the highest illumination level; one may be tempted to see this as the cause of the failure. Since both other lamps are around the average illumination level or even lower this is not expected to be true. The failures seem to be caused by the internal electrics of the system, maybe combined with the 'stuffing' in the lamps to minimize noise and vibration from the electric components. The failues appear to be random, thus Class III failures, but since the lamps are not stabilized yet during the experiment, they can also be regarded as Class II failures.

4.4 Mean Time-to-Failure

To determine whether the expected MTTF of the High Power LED Lamps is confirmed by the experiment or is actually lower than expected, a detailed analysis of the data is needed.

Since the lamps have not yet stabilized, this means the lamps are not yet in Phase 3 of the roller coaster curve. The three lamps that suffered catastrophical failures can be regarded as Phase 2 failures as explained before. Once the lamps have stabilized, a failure rate can be calculated, how many lamps fail per hour per day or per year. During Phase 3 of the rollercoaster curve this calculated failure rate should be constant. For this experiment, there is no constant failure rate yet. Therefore the MTTF (=1/labda) is not constant either, and thus it is not possible to determine the MTTF.

If a failure of the GU10 High Power LED lamps is defined as the moment that the relative degradation reaches a level of 70% (L_{70}) or 50% (L_{50}) or when a lamp suffers a catastrophical failure and stops working completely, then the failure moments of the lamps during the experiment can be determined and a failure rate can be calculated. However, since the fluctuation in measured illumination values is quite big this cannot be done directly, the data is too unreliable to determine the exact moment that a lamp reaches L_{70} or L_{50}.

The average expected lifetime cannot be calculated either, the degradation pattern is too rough to estimate the AEL based on the graphs. Depending on how the lamps degradation pattern is this can be estimated. An example: if the intersection of the L50 line in figure 4.2 is regarded as failure and thus end-of-life for the lamps, the AEL can be estimated. However some lamps have not yet reached that line and the degradation pattern can both be linear or exponential. If degradation is linear, the AEL can be very soon, for example around 6000 or 7000 hours, but if the degradation pattern is exponential, this may well be 20000 or 30000 hours. Therefore it is impossible to estimate the AEL based on the experiment data. A simple best guess method is used to calculate a range in which the AEL can be expected. This best guess method is given in section 4.4.1.

In order to improve the reliability of the data itself (not the reliability of the lamps of course) to be able to analyse the results better two things can be done.

- Exclude measurement flaws from the data
- Exclude lamp fluctuations from the data

To exclude the measurement flaws per lamp, there are already three actual measurement points of which the average is shown in the graphs (the actual data points can be found in appendix D, the averaged data points can be found in appendix E). If it is assumed that the measurement flaws per lamp are variable and not for all the lamps the same on the same measurement time; the measurement flaws can be diminished by calculating the average data over all lamps. This average is shown as the blue line in figure 4.3. The three lamps with catastrophical failures are excluded since it is unknown whether their behaviour before the failures can be regarded as 'normal' or the same as the other lamps.

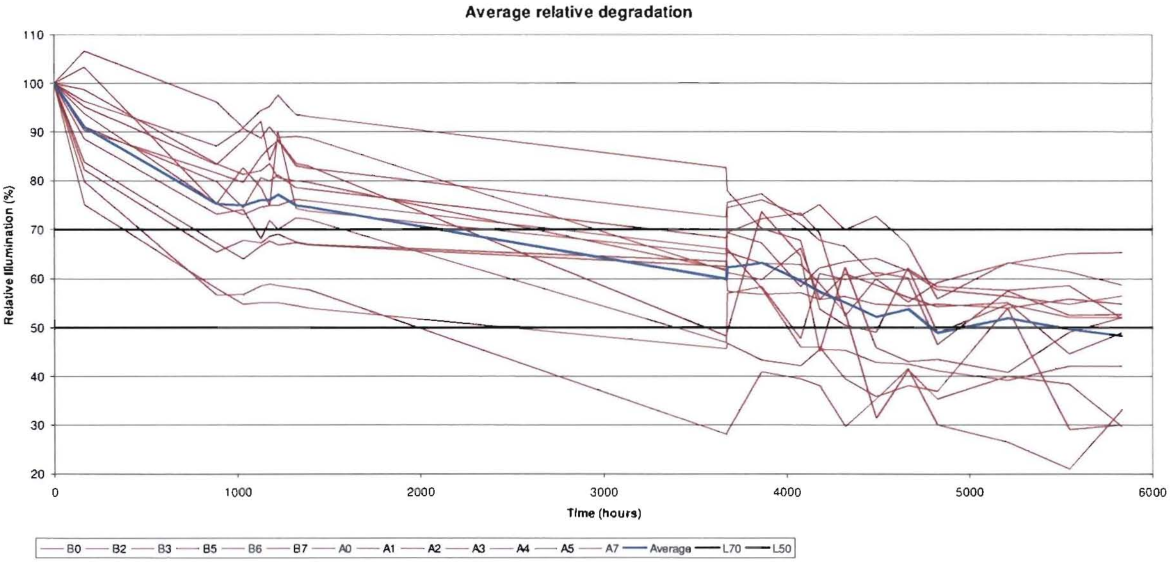


Figure 4.3: Relative degradation and average relative degradation for all lamps

Figure 4.3 shows that the average relative degradation of the lamps has both less and lower 'bumps' than the graphs of the individual lamps, the measurement flaws have been diminished. The graph of the average indicates a degradation pattern which can both be linear or exponential.

Internal lamp fluctuations can exist because the internal electrics of the lamp, more precisely the LED itself. To exclude internal lamp fluctuations the average over a period of time is a more reliable way of measuring the true illumination level of the lamps. A moving average over a time period can be calculated. Two moving averages are calculated, one over 500 hours which is shown in figure 4.4 and one over 1000 hours which is shown in figure 4.5. It seems that the graphs resemble a straight line of a linear function after the lamps have setteled.

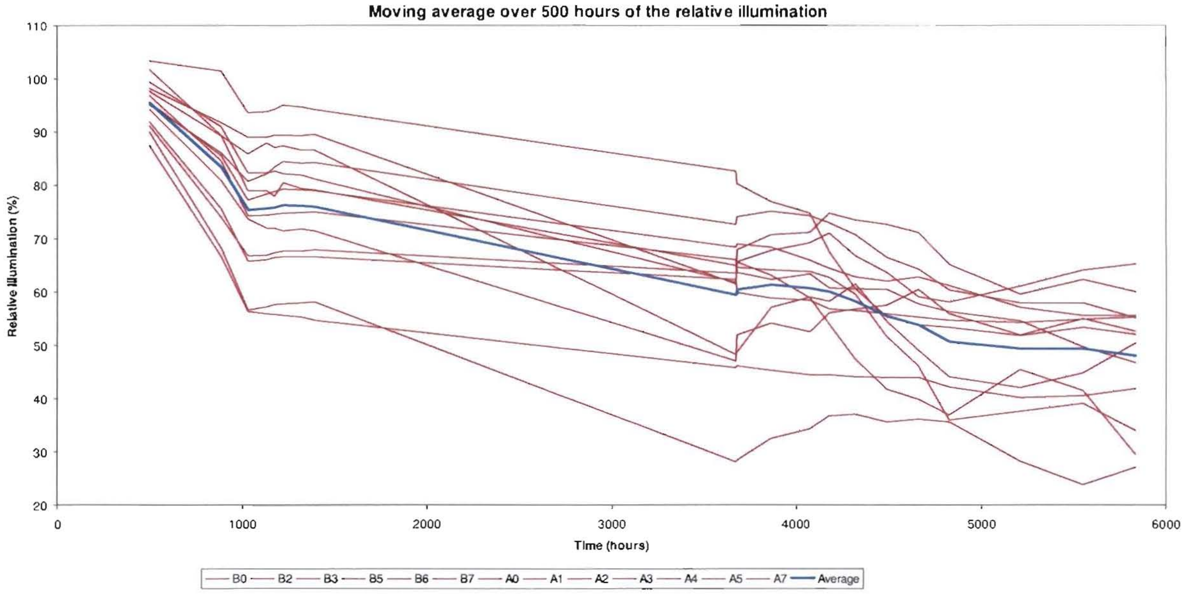


Figure 4.4: Moving average of the relative degradation over 500 hours

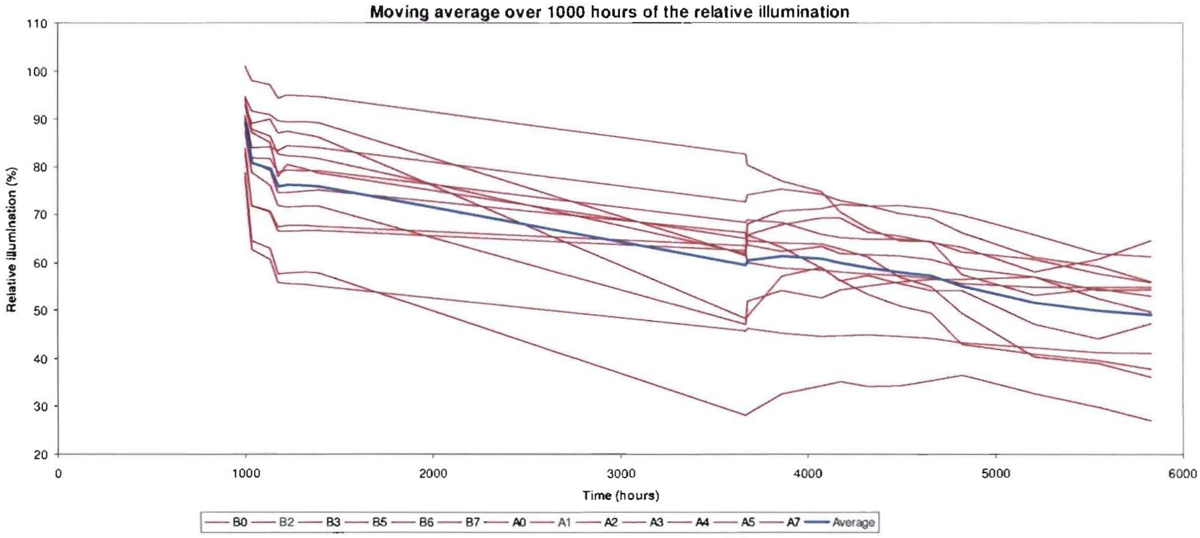


Figure 4.5: Moving average of the relative degradation over 1000 hours

Not only the internal lamp fluctuation are filtered, but also the measurement flaws are filtered by calculating a moving average because a flaw in one measurement may be diminished by another measurement flaw in a later measurement point. However to decrease both fluctuations the best, both the moving average and the average over lamps can be calculated. This is shown in figures 4.4 and 4.5 by the blue lines. The line in figure 4.5 seems almost linear. However one data point in this graph is constructed by calculating the average of more than 50 original data points. Therefore the influence of a slow stabilization of the degradation is almost impossible to see. It can however be seen that the stabilization of the degradation (if present) is not yet completed.

4.4.1 Method 1

As explained before, there is a method that helps calculate a very rough estimation of the AEL. It is a best guess method to estimate the average expected lifetime (AEL) and it is explained below.

For L70 it is simply finding the first intersection of the L70 line in figure 4.2 and the last intersection. These appear to be 380 hours and 4579 hours. Thus het AEL is expected to be between 380 and 4580 hours if a lamp is regarded as failure when a relative illumination level of 70% of the starting illumination is reached.

For L50 some more calculations have to be done because not all lines have yet crossed the L50 line. The first line crosses the L50 line around 2000 hours. The second intersection is expected around 8336 hours. This last intersection is obtained by drawing a line through the (0,100) point and the last measured point of the least degraded lamp (B3), namely (5835,65). Thus the AEL is expected to be between 2000 and 8336 hours if a lamps is regarded as failure when a relative illumination level of 50% of the starting illumination is reached. Both the L50 and L70 results are visualized in figure 4.6. The calculations can be found in Appendix F.

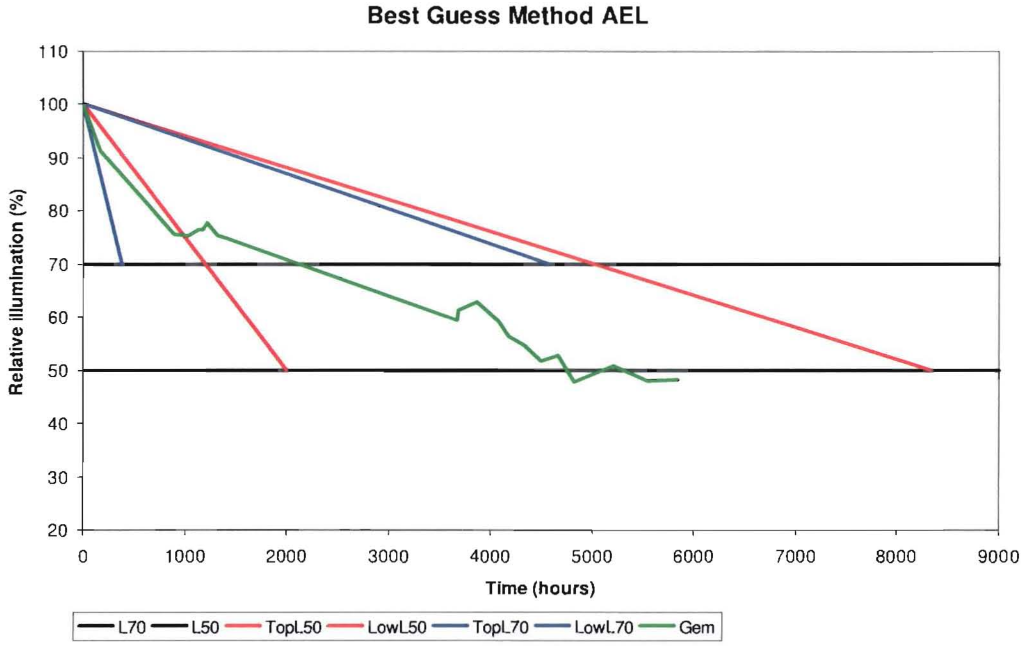


Figure 4.6: Estimation of AEL

A better or more reliable result may be acquired if the burn-in time of the lamps is excluded. This may be better because during the burn-in time the lamps degrade faster than in a later time period. This analysis is given below.

The intersection of the L70 line appear to be around 10,640 hours and 3,870 hours. A much wider range than in the previous analysis, but still much lower than the advertised 50,000 hours. For the L50 range the same can be said. The estimated AEL for L50 is expected to be between 5,280 hours and 17,040 hours. Again, calculations can be found in Appendix F

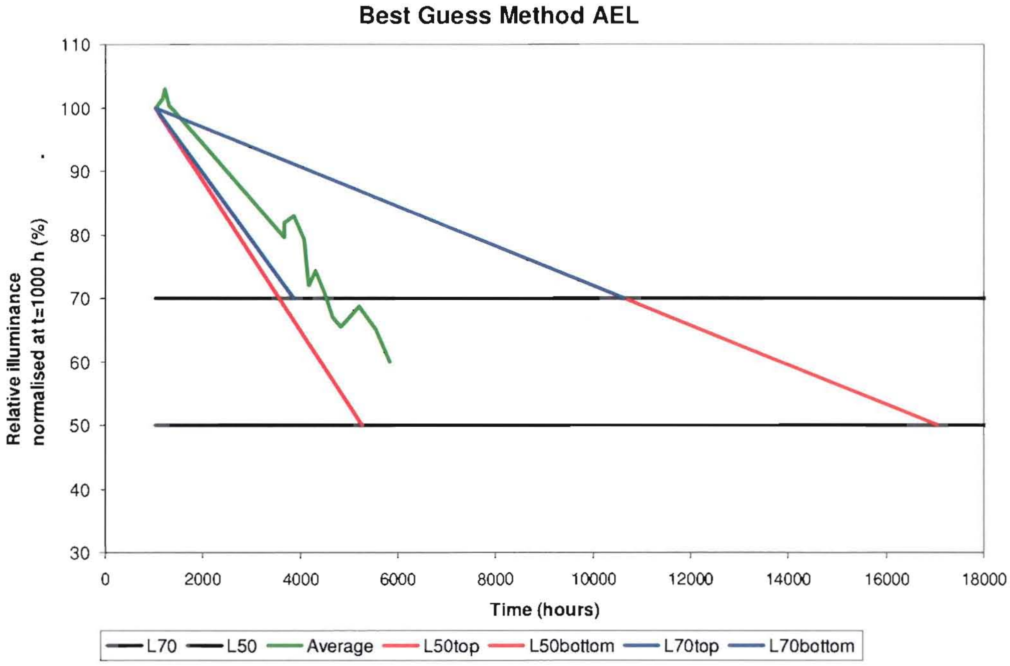


Figure 4.7: Estimation 2 of AEL

Calculations for L70 are most reliable because the time period over which an estimation is given is shorter, therefore the deviation from reality is less.
It can also be seen in both graphs (4.6 and 4.7) that in 4.7 there is more room for the lamps to start stabilizing and still stay within the L70 and L50 estimation boundaries.

4.4.2 Method 2

A second best guess method is based on the analysis of the data by Josephine Sari. She performed an analysis of the GU10 High Power LED Lamps together with LED Tube lights (subject of the Master's thesis of Yiu Man Kan) to test a proposed theorem on bivariate and multivariate failure mechanisms. She developed an alternative reliability quantification model for bi-/multivariate constant stress degradation test data which suits this degradation tests of LED lamps.

The High Power LED Lamp test data was used for the analysis of the multivariate constant stress degradation test (CSDT). In the analysis it was assumed that there was a lighting system that consisted of 4 lighting locations. Two of the locations consist of 8 samples of GU10 High Power LED lamps, both halves of the test board (the A and the B lamps respectively) and the following assumptions were used:

- Each set of samples is assumed to have its own degradation failure mechanism, which is the degradation of the light output. This mechanism is considered as one performance characteristic of the system.
- The system is considered fail if the light output of at least one of the LED light sets degrades to its critical light output value (L50)
- The system is assumed to be arranged as a lighting system which is operated at ambient temperature of 25° C, and the degradation failure mechanism may not be independent of each other. Therefore, dependence analysis is needed.
- The CSDT test that has been performed can provide sufficient data needed for the reliability assessment of the system.

There are 16 high power LED lamp samples that have been tested at 25° C ambient temperature and the samples are labelled as A0..A7, B0..B7. Half of the samples represents performance characteristic 3, PC3 (B0..B7) and the other half represents the fourth performance characteristic, PC4 (A0..A7). In the original measurement times, these samples are tested for 0-, 168-hour and several other measurement times until the 4080-hour of operating time. This is the final measuring time if the measurement is stopped before the catastrophical failures occurred. As explained above in section 4.2, the readings show probable human error during the experiment, which makes the degradation path does not reflect their supposedly physical degradation process. Therefore for some measurement times, that are close to each other with higher possibility of measurement errors, the average of the readings are used. Based on these modified observations, the cumulative degradation data of PC3 and PC4 is calculated and plotted. These are shown below. The same plots without using an average over several measurement periods are shown in appendix H.

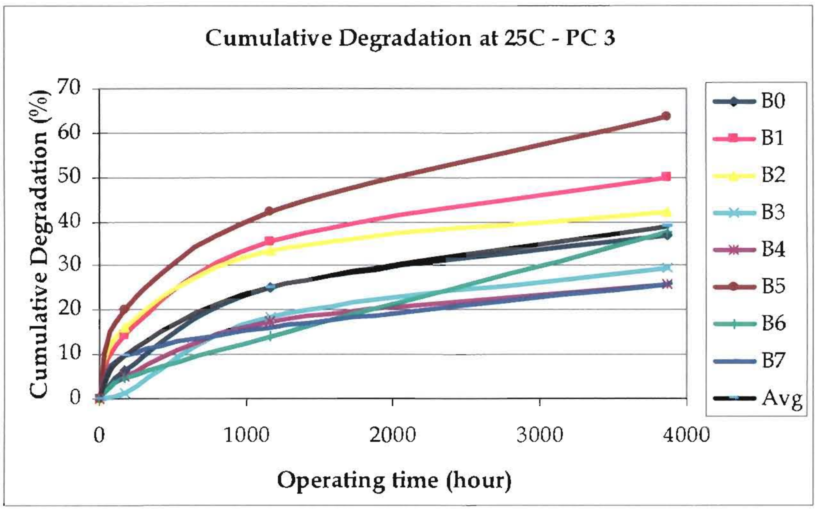


Figure 4.8: PC3 (B lamps) cumulative degradation curve

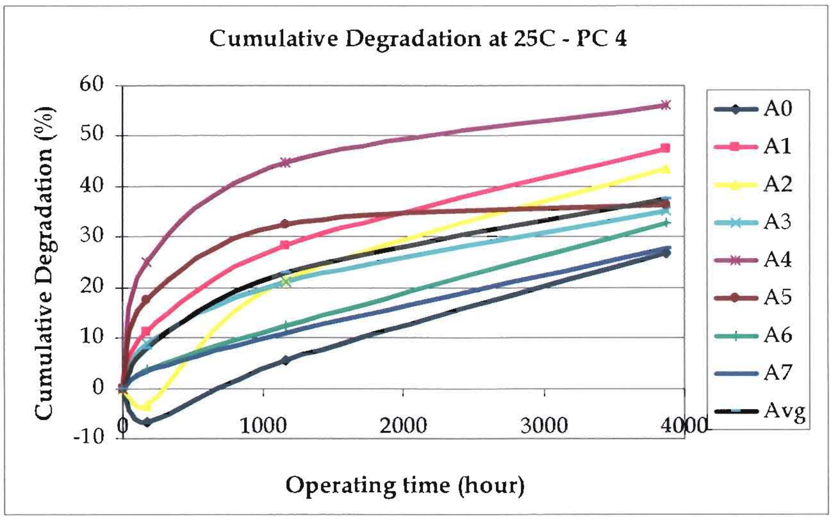


Figure 4.9: PC4 (A lamps) cumulative degradation curve

Only the proposed multivariate CSDT Model 1 can be used to model and analyse the data. To demonstrate the ability of the proposed multivariate CSDT Model 1 to model multivariate degradation data which follows different marginal degradation distribution functions; PCs 3 & 4 with normal marginal degradation distribution assumption will be analyzed together with PCs 1 & 2 with inverse Gaussian marginal degradation distribution assumption. These are the LED tube lights from a second Master's Thesis only additional modelling and analysis of the stage 1 of multivariate CSDT model 1 is needed to assess the marginal degradation data of PCs 3 and 4.

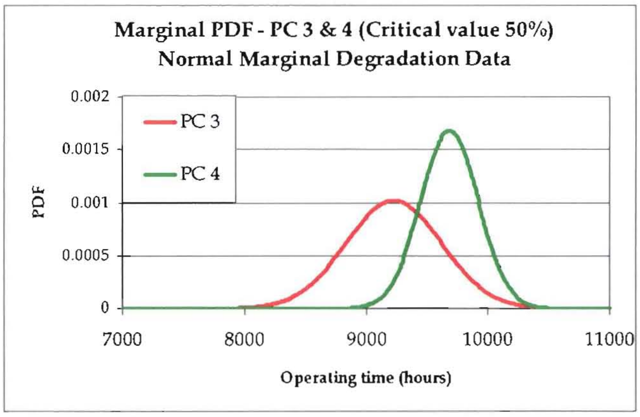


Figure 4.10: Marginal PDF of PCs 3 & 4

These analyses are helpful to understand the behaviour of the lamps and compare it to the LED tube lights. However the goal of these analyses is to show how a certain kind of degradation analysis can be done and to show how a system works. In order to do this a lot of the original data is filtered away and is therefore not very accurate in in this analysis and therefore additional analyses are needed to determine the degradation pattern of the GU10 High Power LED lamps in detail. What can be concluded from figure 4.10 is that the expected AEL with a critical value of 50% (L_{50}), is between 8000 and 10500 hours. This results fits within the L_{50} graphs of figure 4.7 of the second best guess calculations.

5 Conclusions and Recommendations

In this chapter conclusions regarding the research questions are drawn. These conclusions are based on the analysis of the experiment results and theories from literature. The first section deals with the answers to the research questions. The second section deals with discussion of these answers and conclusions. In the final section of this chapter recommendations regarding future research are given.

5.1 Research question answer

Section 1.6 dealt with the research questions for this thesis. The research questions were:

What are the characteristics of the degradation pattern of high-power LED lamps?

And:

What degradation model fits the characteristics of these LED lamps?

The first question can easily be answered, and is already partly answered in chapter 4 Analysis and Results. The lamps start degrading the moment they are functional. They keep degrading until the experiment is stopped for safety reasons. And based on the observed degradation pattern it is also likely that they keep degrading after the time period during which the experiment was held.

On the other hand, a detailed degradation pattern cannot be given. The measurement data from the practical experiment was not as reliable as desired. The measurement flaws from the manual measurements were too big to make a reliable and detailed degradation analysis, therefore only two best guess methods could be used to estimate the average expected lifetime (AEL)

The second question cannot be answered completely. Since there were some issues regarding the reliability of the measured data, no definite conclusions about possible degradation models can be drawn. However, there can be concluded something; the lamps do degrade and keep degrading throughout the experiment time of nearly 6000 hours (more than half a year). At first they degrade faster than in the end, it cannot be concluded however that this is only due to the burn-in time. After a possible burn-in period, the lamps keep degrading in a way that resembles a linear degradation pattern. However, this can also be resemblant to an negative exponential degradation pattern. One fact that can be concluded is that the lamps are not yet stabilized during the experiment time.

As pointed out in the first part of this section, two best guess methods were used to estimate the average expected lifetime (AEL). The first method, a best guess method, resulted in a high and a low border for both L_{70} and L_{50}. The AEL is expected to be somewhere between the upper and lower tome border. For L_{70} the estimated AEL is between 3,870 and 10,640 hours. The estimated AEL for L_{50} is between 5,280 hours and 17,040 hours. The second best guess method was given by J.Sari, her analysis showed an expected AEL between 8,000 and 10,500 hours. It should be noted that she did not use all measurement data that was available.

All these values of the AEL are far less than the advertised 50,000 hours and it is highly probable that the GU10 High Power LED lamps expected lifetime is much lower. Again, due to the unreliable measurement data, accurate estimations cannot be given.

5.2 Other remarks and conclusions

Besides conclusions regarding the research questions, some other conclusions can be drawn. One of them is that not all aspects of degradation are analyzed. Besides illumination degradation LED lamps can suffer from colour degradation. With long lifetimes of LED lamps, Phosphor degradation and other degradation mechanisms can cause a change of colour of the light emitted from the LEDs over time. The reason for not including this in the analysis is that it is hard to analyse and there is no standard accepted measuring method or critical value.

In this thesis, all lamps are assumed to fit the same degradation model. A better or more accurate way to perform the degradation analysis could have been to determine a model of the degradation and MTTF of each sample separately. This is however impossible with current data. More detailed or more reliable illumination measurement data is needed to do this. Another possibility for the data analysis is to split the samples in half. One part of the data could then have been used for modelling and the other part of the data would have been used for validation. This is however not chosen because of the relatively small sample size.

The number of data points available for analysis, being the number of measurement times, is limited. More reliable illumination data would be available if the number of measuring points was increased. Besides that, not all manual measurements were performed by the same person, results may have been more consistent or reliable if all measurements were done by one person. This however does not necessarily increase reliability of the measurement.

The test design was based on the expectation that the measurements of the electrical resistance of 'light resistors' could be used to automatically measure the illuminance and therefore also the degradation of the illuminance. Due to measurement flaws this could not be achieved. The internal variability of the measurement system generated too much noise. The noise generated by the system made it impossible to interpret and analyse the actual measurements.

All equipment has a certain degree of accuracy. Because of this, uncertainties will exist. Under the influence of a number of environmental factors the properties of certain materials can change. Some examples: temperature, pressure or strain, humidity and light. These influences can interfere with certain parts (also the electronic parts) of the measurement [Ebn01].

The so called burn-in time is not included in the analysis. This is because the goal was to make a model of the complete degradation pattern. If a burn in time would have been used, it may have been easier to analyze the degradation pattern after the burn-in time. However it may also be the other way round. This can be dealt with in future research.

The lamps that suffered catastrophical failures are not included in the analysis because it is possible that these lamps already behave different some time before the actual failure occurs. However the moments before the actual failures and after the actual failures, the average illumination level over all burning lamps is very similar. This means that there is no indication that the lamps with catastrophical failures behave different from other lamps.

5.3 Recommendations

5.3.1 Practical recommendations for new experiments

In this section some recommendations for future research regarding LED lamps are given. These recommendations are based on the drawbacks or problems that were encountered during this project, mainly during the practical experiment.

An important recommendation is to take enough time to organize the experiment, don't rush the design of the experiment. In that way, problems such as unusable automatic measurements may be avoided. Since manual measurements may not be as reliable as needed which was proven in the main experiment during this research project automated measuring can have its advantages besides the ease of measuring as often as you want without spending too much time doing performing the measurements. If manual measurement will be used, then it is preferred to have a pre defined and documented way of measuring; it is even better to do this predefined method by only one person to exclude differences in measuring methods between persons. A good quality of materials for the test setup can help improving reliability of measurements too, for example fittings for lamps that are equal and straight.

5.3.2 Recommendations for future research

As already explained in Chapters 1 and 2, LED technology is a promising technology. LED lamps have several advantages over conventional light bulbs, they are reliable, small, light weight, impact resistant, they emit less heat, can have direct coloured light, quiet and they have a long life. However, the technology is still immature which is proven by the two tests that were described in this thesis. Reliability and life time are not as good as advertised yet, at least for the kind of LED lamps that were tested. Since the production volume of LED lamps is increasing, manufacturers are able to produce more reliable lamps and production methods are improving with experience, the price of the lamps is getting more competitive compared to the conventional light bulbs, but even more compared to energy efficient lamps.

If reliability is improved, there is much potential in the lighting market for LED lamp manufacturers and companies like LEDNed. Research is needed to help those companies improve their products. Since the market for LED lamps is emerging, new products are pushed onto the market. Therefore there is a big pressure on the speed of design and testing of the lamps. To help shortening the time-to-market, early in the product development process (PDP) information about the previous generation lamps and the currently designed lamps is needed. Thus research to degradation patterns should be done, but in a way that after a short period of testing a good estimation of the reliability and possible failure mechanisms can be given with high confidence levels. Accelerated testing methods may help iproving fast feedback from testing. This is already applied by Yiu Man Kan in his Master's Thesis [Kan07], however more research on how accelerated testing can be applied for LED lamps is needed. Research to underlying causes of failures can also help identify problems faster. Research to differences and similarities between different LEDs and LED lamps can help determine whether models for one kind of LED or lamp can be applied to other kinds too and vice versa.

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Appendix A: First test

This appendix contains the test proposal which was accepted by both prof. Brombacher and LEDNed, and the description of the results communicated to LEDNed. Some parts are clarified and improved to meet the quality standards of the graduation project.

Led Supply Nederland recently received a number of complaints from their customers that the long life and high reliability of the LED lamps is not as high as they expected. A certain type of lamps, LED Par 30 lamps, is supposed to have an average technical life time of 50.000 burning hours at 230V AC. The complaints from customers are that about 30 to 40% of the lamps fail after just 200 burning hours. The reliability of the lamps seems to be (much) lower than expected. To check this, LED Supply Nederland wants an independent reliability analysis in order to find out what the actual reliability and expected life time is. Other objectives of the test are to find out why the products fail and in which part of the rollercoaster-curve the product failures can be classified. This report describes the results of the first phase of this analysis as it is being executed by the Technische Universiteit Eindhoven, section Quality and Reliability Engineering.

Hypothesis

Because the LED par 30 lamps are supposed to last 50.000 burning hours on average, the expected mean time to failure (MTTF) is 50.000 (μ_0). The complaints from customers lead to an alternative MTTF that is much smaller ($\mu < \mu_0$). This results in the following hypotheses about the MTTF that need to be tested.

H_0 is $\mu = \mu_0$

H_1 is $\mu < \mu_0$

The hypotheses will be tested in an experiment in which a sample of lamps will be conducted to a 'normal' stress or load (stress within specifications). The time to failure will be monitored to determine whether the hypothesis can be rejected and the alternative hypothesis can be accepted. Before a more detailed description of the test can be given, it needs to be calculated what a good sample size would be to be able to form a reliable conclusion. In Appendix B it is shown that a sample size of 10 should be sufficient if the experiment shows expected results of failure rates of 30% within 200 hours of burning time. However, increasing the sample size to 20 or 30 lamps will result in a slightly higher confidence level, especially if only 10 or 20% of the lamps would fail in the test.

Experiment

If an experiment is set up for 10 lamps, each lamp should be independently tested, in other words they should be connected parallel. To be able to check the time of failure the lamps should also be monitored constantly. This can for example be done by capturing an image of the lamps each hour by using a webcam and a computer. Capturing an image each day is also sufficient for this test because a few hours do not make much of a difference if the expected value is about 50.000 hours. In Appendix B it can be seen that there is not much difference between the situation where failures occur at 200 hours or situations where failures occur at 1000 hours. The environment of the experiment should be consistent with the specifications of the lamps, no extremes like very high or very low temperature or pressure should be experienced during the experiment.

The expected duration of the experiment is at least 1 week, because it is expected that about 30% of the lamps will fail within the first week. However if there are less failures than expected, the experiment will have to be extended to gain reliable results.

To be able to check whether lamps have actually failed a control group of lamps and fittings need to be present.

Assumptions that are made in order to describe the experiment:

- The lamps used for the experiment come from a homogeneous group and is therefore representable for the complete population (all lamps are the same apart from possible variability in the production process and variability in the components of the lamps)
- The lamps are used continuously, so switching the lamps on and off should not influence the reliability of the lamps, if this does affect reliability a second test should be done where the lamps do not burn continuously but where the lamps are also switched on and off.
- The environment in which the lamps are tested is similar to the environment in which the customers of LEDNed use the lamps.

The test setup

A test was set-up in the facilities of the Quality and Reliability Engineering group at the Paviljoen building at the TU/e. The test is designed to measure and monitor the lifetime (in hours) of the LED Par 30 lamps. Given the expected failure behaviour a test with only 10 lamps was considered adequate for a first scan to obtain results with sufficiently high confidence.

The hardware which is used is a number of identical fittings which are mounted on a test board, a computer with webcam and a matrix of the LED Par 30 lamps. There are 10 fittings for testing purposes and 1 fitting acts as a control fitting. This control fitting can be used to compare the lamps subjected to the test to other lamps, or it can be used to check whether a test fitting is working correctly if a lamp fails to emit light. The fittings are connected parallel in order to prevent failing lamps to influence the still working lamps. Because the test is situated in a room of the Paviljoen building at the TU/e, the ambient variables such as temperature and humidity are expected to be constant within the range of specifications of the lamps.

In the mentioned scan, performed during this project, the lamps were tested under static conditions in continuous mode under nominal stress (Conditions rated "typical" within specifications). Since transient/dynamic conditions were excluded from this test any failure found during test can therefore not be attributed to extreme and/or dynamic conditions outside specifications. The lamps were used for 24 hours per day in order to maximally reduce the required testing. A computer with webcam with corresponding software was installed to take scheduled pictures of the lamps every hour. This means that high-resolution information of the time of failures (compared to the expected life time of the lamps) and the relating condition of the lamps will be available. For identifying the different lamps, they are marked with a number (see figure C.1). Figure C.2 shows the first image made by the webcam at the start of the test at t = 0.

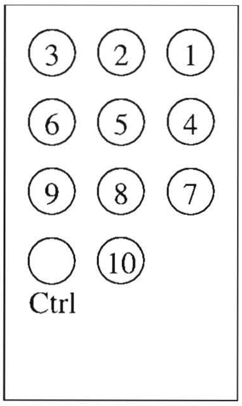

Figure C.1: Lamp numbers.

Figure C.2: Initial situation

Led Supply Nederland has provided TU/e with 20 lamps for the test, 10 of them are tested, the other 10 can be used as reference. It is not known what the criteria were for LEDNed to select the lamps, the lamps are assumed to be selected randomly.

Results

Initially, all test lamps work correctly, so they show no 0-hour or phase I failures (assuming LEDNed did not omit these lamps from the test). However, not all lamps emit the same colour of light while all packing boxes of the lamps are marked with the same colour code. Lamps 4 and 7 show a yellow light while the other 8 lamps show a more whitish light (with some small discolourations). Besides that, the glass hood of the lamps show some differences, this however should not influence the test results.

Within 24 hours lamp number 7 shows a second failure, a number of LEDs stops working; a few hours later some more LEDs fail. The lamp still works but the outer ring of LEDs and a part of the second ring stopped emitting light.

After 1 week (168 hours) 5 out of 10 lamps emit significantly less light compared to the starting situation. Lamps 1, 2, 5, 8 and 9 are the ones that fail to work correctly; this can be seen in figure C.3.

Figure C.3: Comparison between t = 0 hours and t = 168 hours.

Because of some imperfections in the test setup (ambient lighting), the quality of the pictures is not perfect. The images after two and three weeks (336 and 504 hours) are more clear (see figures C.4 and C.5).

Figure C.4: Comparison between t = 168 hours and t = 336 hours.

Figure C.5: Comparison between t = 336 hours and t = 504 hours.

Assuming the sample is from a homogeneous population, the expected lifetime of the lamps can be calculated. The second failure of lamp 7 occurred already after 21 hours, the other lamps have slowly degraded over time. The difference becomes obvious after 168 hours of burning time.

If the remaining four lamps have a lifetime of 50.000 hours, then the average lifetime of the 10 lamps (and the complete population) will be about 20.000 hours ([21+5*168+4*50000]/10). But since this is not a realistic expectation, this value is of no use. Lewis [Lew96] states that for censored data with a constant failure rate the estimated MTTF as follows:

$$MTTF = \frac{\sum_{i=1}^{n} t_i + (N-n) * t_*}{n} \text{ with}$$

N=sample size,
n=number of failures,
t_i=failure time of item i and
t_*=ending time of the test.
In this case, this will result in a

$$MTTF = \frac{21 + 5 * 168 + (10-6) * 504}{6} = 479{,}5 \text{ hours.}$$

However, something that can clearly be seen with the bare eye but not with the webcam, is that the remaining four lamps also emit less light than a new one, therefore the four lamps do not have a lifetime of 50.000 hours but more like 400 hours. Now the estimated MTTF is calculated as follows:

$$MTTF = \frac{\sum_{i=1}^{n} t_i + (N-n) * t_*}{n} = \frac{21 + 5 * 168 + 4 * 400 + 0}{10} = 246{,}1 \text{ hours.}$$

The conclusion of this test is that the expected average lifetime (H_0 is $\mu = \mu_0$) is not correct. If the MTTF is approximately normally distributed with an expected value of 5.7 years, then:

$$E(X) = \mu = 5.7$$

$$\text{var}(X) = \sigma^2 = \text{unknown.}$$

For testing this distribution the following test-statistic is used : $T_0 = \frac{\overline{X} - \mu_0}{S / \sqrt{n}} = \frac{\overline{X} - 5.7}{S / \sqrt{10}}$, H_0 can be rejected if $t_0 < -t_{\alpha,n-1}$ (α is the significance, and n is the sample size).

If the results from the experiment would be that 1 lamp fails after 21 hours and 5 lamps fail after 168 hours of burning time, this would mean that 4 lamps are still in function after 168 hours. Those 4 are then assumed to be reliable as specified and burn for 50.000 hours before a failure occurs. This would result in an average MTTF in the sample of 479,5 hours.

If the variation of the total population is unknown and thus approximated by the sample variation (normal distribution) than, the test statistic $T_0 = \frac{\overline{X} - \mu_0}{S/\sqrt{n}} = \frac{0.055 - 5.7}{2.79/\sqrt{10}} = -0.0007$. Because $t_0 < -t_{0.001,9}$ (-0.0007 < -4.297), thus H_0 can be rejected with 99,9% confidence.

Possible explanations of results

In order to allow a better translation of product reliability to the underlying business processes, the rollercoaster curve is used (see section 1.2.2). A standard figure of the rollercoaster-curve which could be expected if the lamps were as reliable as advertised is shown in figure C.6.

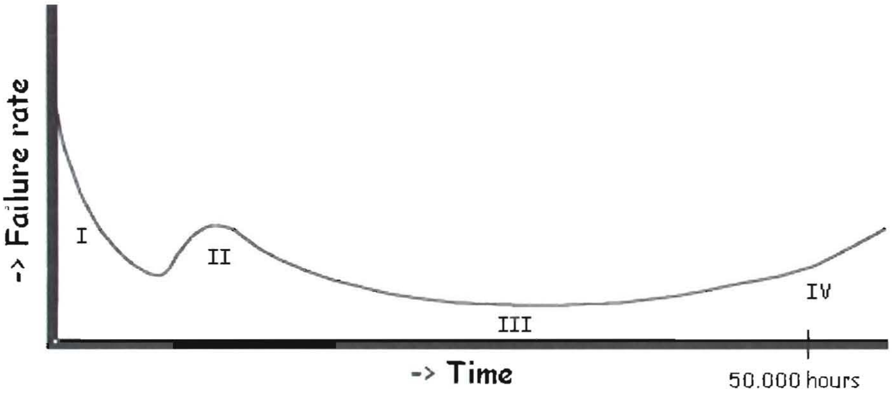

Figure C.6: The roller-coaster curve

There are three kinds of failures that are observed during the test:

- Discolouration of the LEDs
- Failure of LEDs in the lamp
- Degradation of the LEDs

These failures can be classified in several ways, to know which explanation is best, more information about the lamps is needed like the selection procedure of the lamps, the existence of subpopulations of lamps, etcetera. The most likely explanations are given below.

The discolouration of the LEDs can best be classified as a Class II failure. Although the lamps arrive out-of-spec (they emit yellow light instead of white light), it is expected that due to a problem during manufacturing a distinct sub-population of the Par 30 lamps shows this discolouration and is therefore a Class II failure.

The degradation of the LEDs is already visible after just one week of burning time. It seems that every lamp suffers from early degradation, this can clearly be seen by the bare eye if a new lamp is compared to the lamps that have burnt for some time. Besides that is can also be partially seen in the webcam images as can be seen in figures C.3, C.4 and C.5. Because all lamps show the degradation, there are two possible explanations. One is that the design of the lamps is so bad that their life time is extremely low, in this event the failures belong to the Class IV failures. However if the failures are the result of low quality components or if only a (big) subpopulation of the lamps suffers from the failures, then the failures belong to the Class II failures.

The failure of a number of LEDs within a lamp are actually a 'post-mortem failure'. Because upon arrival, lamp 7 showed a yellow light instead of white. Therefore the lamp has already 'failed' but after a few hours of burning some LEDs also stopped working at all. More information about this failure and the rate of occurrence is needed to be able to classify it correctly.

Conclusion

It is clear that the LED Par 30 lamps do not have an average lifetime of 50.000 hours. The test shows that this hypothesis can be rejected with at least 99,9% confidence.

Because it is not known exactly when the light intensity of the Par 30 LED lamps is too low an approximation has to be made. It is clear that after just one week the intensity of the light is significantly lower, therefore the Class II/Class IV failures already occur after 168 hours. This results in a different roller-coaster curve for the test lamps, an estimate is shown in figure C.7.

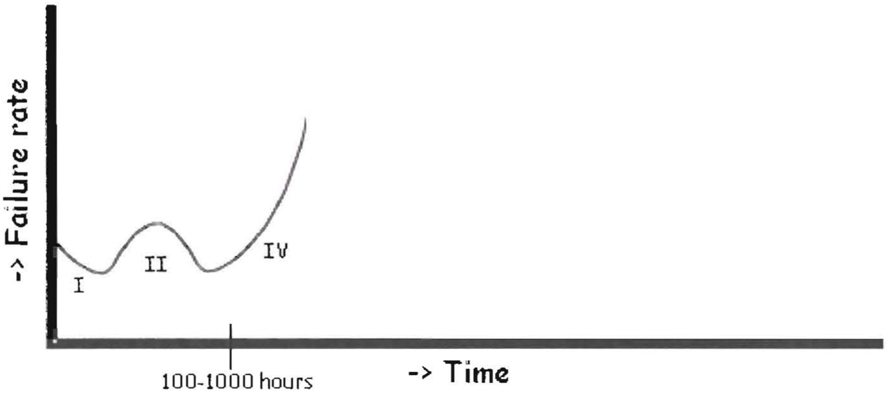

Figure C.7: The approximated roller-coaster curve for the LED lamps

The observations from the test can form the basis of further research to the causes of the different kinds of failures. However, more information about the underlying business processes is needed to perform this further research.

Appendix B: First test sample size

The time to failure (TTF) is assumed to be a random variable with a continuous distribution function. The failure rate of a complete group of lamps is most likely to resemble the rollercoaster curve [Luy00], see figure D.1. Because this kind of figures cannot easily be described by a known function an approximation of the figure is needed. If the failure rate of the lamps is assumed to be constant over time, then the TTF is exponentially distributed. This is a commonly used assumption in reliability literature. Another possible assumption is that the failure rate of the lamps is growing over time. This could mean that the TTF is normally distributed [Lew96].

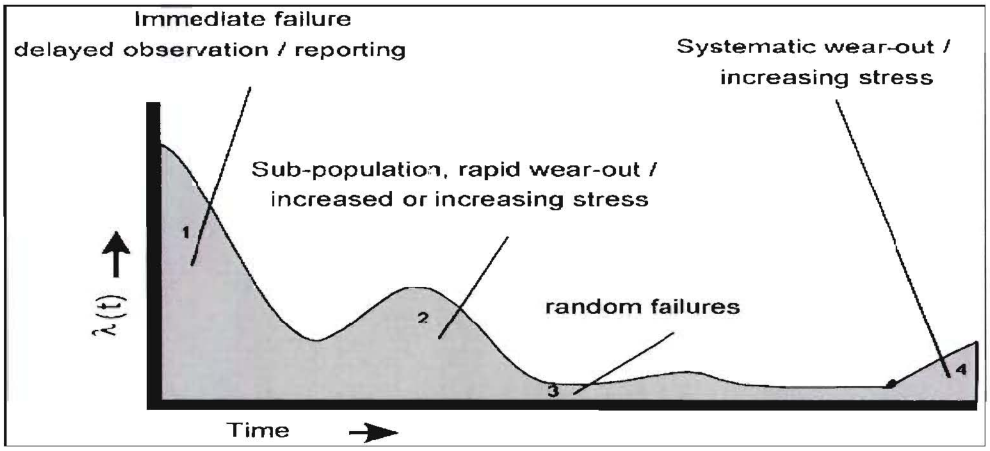

Figure D.1: The rollercoaster curve

The primary goal of the experiment is to check whether the average or expected time to failure is correct. For both possible distributions of the TTF, the minimum sample size that is needed to reject the H_0 hypothesis is calculated.

A secondary goal of the test is to determine a better approximation of the actual failure rate in order to help finding the cause of failures; for example early wear out due to wrongful use or systematic wear-out because the product quality degrades over time.

Calculations

If the time to failure (TTF) of LED lamps is approximately exponentially distributed with an expected value of 50.000 hours of burning time (about 5.7 years), then the average and variation of the distribution are:

$$E(X)=\frac{1}{\lambda}=\frac{1}{0.175}=5.7 \text{ years}$$

$$\operatorname{var}(X)=\frac{1}{\lambda^2}=\frac{1}{0.175^2}=32.5 \text{ years.}$$

For testing this distribution the following test-statistic is used: $Z_0 = \dfrac{\overline{X} - \mu_0}{\sigma / \sqrt{n}} = \dfrac{\overline{X} - 5.7}{\sigma / \sqrt{10}}$, H_0 can be rejected if $z_0 < -z_\alpha$ (α is the significance, so $1 - \alpha$ is the level of confidence).

If the TTF is approximately normally distributed with an expected value of 5.7 years, then:

$E(X) = \mu = 5.7$

$\text{var}(X) = \sigma^2 = \text{unknown}.$

For testing this distribution the following test-statistic is used : $T_0 = \dfrac{\overline{X} - \mu_0}{S / \sqrt{n}} = \dfrac{\overline{X} - 5.7}{S / \sqrt{10}}$, H_0 can be rejected if $t_0 < -t_{\alpha,n-1}$ (α is the significance, and n is the sample size).

For the sample sizes of 10, 20 and 30, calculations are performed for situations where 10%, 20%, 30%, 40% or 50% of the lamps fail, see appendix C [Con02], [Lew96] and [Mon99].

An example, using a realistic possible test result:
If the results from the experiment would be that 30% of the lamps fail after 200 hours of burning time (just over a week), this would mean that 70% lamps are still in function after 200 hours. Those 70% are then assumed to be reliable as specified and burn for 50.000 hours before a failure occurs. This would result in a MTTF in the sample of 4 years (about 35.000 hours).

If the variation of the total population is unknown and thus approximated by the sample variation (normal distribution) than, the test statistic $t_0 = -1.72$. Because $t_0 < -t_{0.1,9}$ ($-1.72 < -1.383$), H_0 can be rejected with 90% confidence.

If the variation of the total population is assumed to be equal to the square of the MTTF (exponential distribution) and therefore is known, the test statistic $z_0 = -1.31$ should be used. Because $z_0 < -z_{0.1}$ ($-1.31 < -1.28$), H_0 can be rejected with 90% confidence.

Conclusion

In the above example both approximations of the failure rate result in the same conclusion, the hypothesis can be rejected. Because this example is expected to happen based on the complaints from the field, a sample size of 10 lamps should be enough to conclude with high confidence (90%) that the high reliability stated by the manufacturer of the lamps is not true.

Appendix C: Calculations for possible sample sizes

Sample size 10

Time to 1^{st} failure	100	200	1000	2000	10000	20000	Confidence levels
Sample average	5,14	5,14	5,15	5,16	5,25	5,37	
Sample variation	3,24	3,23	3,13	3,00	2,09	1,17	
t_0	-0,99	-0,99	-0,99	-0,99	-0,98	-0,98	80%, >0.883
Variation = mean^2	26,40	26,41	26,51	26,62	27,57	28,79	
z_0	-0,35	-0,35	-0,34	-0,33	-0,27	-0,20	60%, >0.25

Time to 2 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	4,57	4,57	4,59	4,61	4,79	5,02	
Sample variation	6,49	6,46	6,26	6,00	4,17	2,35	
t_0	-1,40	-1,40	-1,40	-1,40	-1,40	-1,40	90%, >1.383
Variation = mean^2	20,87	20,89	21,06	21,27	22,99	25,23	
z_0	-0,78	-0,78	-0,77	-0,75	-0,60	-0,43	75%, >0.67

Time to 3 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	4,00	4,00	4,03	4,06	4,34	4,68	
Sample variation	9,73	9,70	9,39	9,01	6,26	3,52	
t_0	-1,72	-1,72	-1,72	-1,72	-1,72	-1,72	90%, >1.383
Variation = mean^2	15,99	16,02	16,24	16,52	18,82	21,91	
z_0	-1,35	-1,34	-1,31	-1,27	-0,99	-0,69	90%, >1.28

Time to 4 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	3,43	3,43	3,47	3,52	3,88	4,34	
Sample variation	12,98	12,93	12,52	12,01	8,34	4,69	
t_0	-1,99	-1,99	-1,99	-1,99	-1,99	-1,99	95%, >1.883
Variation = mean^2	11,76	11,79	12,04	12,36	15,06	18,82	
z_0	-2,09	-2,09	-2,03	-1,96	-1,48	-0,99	95%, >1.65

Time to 5 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	2,86	2,87	2,91	2,97	3,42	4,00	
Sample variation	16,22	16,16	15,64	15,01	10,43	5,86	
t_0	-2,23	-2,23	-2,23	-2,23	-2,23	-2,23	95%, >1.883
Variation = mean^2	8,18	8,21	8,47	8,81	11,73	15,96	
z_0	-3,14	-3,13	-3,03	-2,91	-2,10	-1,35	99%, >2.33

Sample size 20

Time to 1st failure	100	200	1000	2000	10000	20000	Confidence levels
Sample average	5,14	5,14	5,15	5,16	5,25	5,37	
Sample variation	3,24	3,23	3,13	3,00	2,09	1,17	
t_0	-1,39	-1,39	-1,39	-1,39	-1,39	-1,38	90%, >1.328
Variation = mean^2	26,40	26,41	26,51	26,62	27,57	28,79	
z_0	-0,49	-0,49	-0,48	-0,47	-0,38	-0,28	65%, >0.38

Time to 2 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	4,57	4,57	4,59	4,61	4,79	5,02	
Sample variation	6,49	6,46	6,26	6,00	4,17	2,35	
t_0	-1,99	-1,99	-1,99	-1,99	-1,98	-1,98	95%, >1.729
Variation = mean^2	20,87	20,89	21,06	21,27	22,99	25,23	
z_0	-1,11	-1,10	-1,08	-1,06	-0,84	-0,60	85%, >1.03

Time to 3 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	4,00	4,00	4,03	4,06	4,34	4,68	
Sample variation	9,73	9,70	9,39	9,01	6,26	3,52	
t_0	-2,44	-2,44	-2,44	-2,44	-2,44	-2,43	95%, >1.729
Variation = mean^2	15,99	16,02	16,24	16,52	18,82	21,91	
z_0	-1,90	-1,90	-1,85	-1,80	-1,40	-0,97	95%, >1.65

Time to 4 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	3,43	3,43	3,47	3,52	3,88	4,34	
Sample variation	12,98	12,93	12,52	12,01	8,34	4,69	
t_0	-2,82	-2,82	-2,82	-2,82	-2,82	-2,81	99%, >2.539
Variation = mean^2	11,76	11,79	12,04	12,36	15,06	18,82	
z_0	-2,96	-2,95	-2,87	-2,78	-2,10	-1,40	95%, >1.65

Time to 5 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	2,86	2,87	2,91	2,97	3,42	4,00	
Sample variation	16,22	16,16	15,64	15,01	10,43	5,86	
t_0	-3,15	-3,15	-3,15	-3,15	-3,15	-3,15	99%, >2.539
Variation = mean^2	8,18	8,21	8,47	8,81	11,73	15,96	
z_0	-4,44	-4,42	-4,28	-4,12	-2,97	-1,91	99%, >2.33

Sample size 30

Time to 1st failure	100	200	1000	2000	10000	20000	Confidence levels
Sample average	5,14	5,14	5,15	5,16	5,25	5,37	
Sample variation	3,24	3,23	3,13	3,00	2,09	1,17	
t_0	-1,71	-1,71	-1,71	-1,71	-1,70	-1,69	95%, >1.699
Variation = mean^2	26,40	26,41	26,51	26,62	27,57	28,79	
z_0	-0,60	-0,60	-0,59	-0,57	-0,47	-0,34	70%, >0.53

Time to 2 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	4,57	4,57	4,59	4,61	4,79	5,02	
Sample variation	6,49	6,46	6,26	6,00	4,17	2,35	
t_0	-2,43	-2,43	-2,43	-2,43	-2,43	-2,42	95%, >1.699
Variation = mean^2	20,87	20,89	21,06	21,27	22,99	25,23	
z_0	-1,36	-1,35	-1,33	-1,29	-1,03	-0,74	90%, >1.28

Time to 3 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	4,00	4,00	4,03	4,06	4,34	4,68	
Sample variation	9,73	9,70	9,39	9,01	6,26	3,52	
t_0	-2,99	-2,99	-2,99	-2,99	-2,98	-2,98	99%, >2.462
Variation = mean^2	15,99	16,02	16,24	16,52	18,82	21,91	
z_0	-2,33	-2,32	-2,27	-2,21	-1,72	-1,19	95%, >1.65

Time to 4 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	3,43	3,43	3,47	3,52	3,88	4,34	
Sample variation	12,98	12,93	12,52	12,01	8,34	4,69	
t_0	-3,45	-3,45	-3,45	-3,45	-3,45	-3,44	99%, >2.462
Variation = mean^2	11,76	11,79	12,04	12,36	15,06	18,82	
z_0	-3,63	-3,61	-3,52	-3,40	-2,57	-1,72	99%, >2.33

Time to 5 failures	100	200	1000	2000	10000	20000	Confidence levels
Sample average	2,86	2,87	2,91	2,97	3,42	4,00	
Sample variation	16,22	16,16	15,64	15,01	10,43	5,86	
t_0	-3,86	-3,86	-3,86	-3,86	-3,86	-3,86	99%, >2.462
Variation = mean^2	8,18	8,21	8,47	8,81	11,73	15,96	
z_0	-5,44	-5,42	-5,25	-5,04	-3,64	-2,34	99%, >2.33

Appendix D: Manual Illumination Data

13-12-2006

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	8040	7970	7940	8040	7983
B1	7510	7410	7370	7510	7430
B2	8080	7970	7970	8080	8007
B3	7450	7380	7350	7450	7393
B4	9050	8910	8900	9050	8953
B5	7670	7560	7480	7670	7570
B6	7610	7620	7470	7620	7567
B7	6410	6450	6360	6450	6407
A0	6880	6970	6680	6970	6843
A1	7490	7460	7440	7490	7463
A2	6940	6980	6920	6980	6947
A3	7940	7890	7820	7940	7883
A4	7800	7830	7610	7830	7747
A5	8030	7550	7570	8030	7717
A6	6960	7000	6950	7000	6970
A7	7810	7730	7740	7810	7760

20-12-2006

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	7480	7490	7490	7490	7487
B1	6350	6360	6400	6400	6370
B2	6700	6740	6710	6740	6717
B3	7310	7280	7300	7310	7297
B4	8540	8510	8470	8540	8507
B5	6050	6060	6040	6060	6050
B6	7210	7270	7130	7270	7203
B7	5820	5720	5820	5820	5787
A0	7320	7310	7260	7320	7297
A1	6630	6620	6600	6630	6617
A2	7220	7220	7110	7220	7183
A3	7160	7220	7170	7220	7183
A4	5800	5830	5820	5830	5817
A5	6340	6330	6390	6390	6353
A6	6680	6680	6780	6780	6713
A7	7460	7500	7480	7500	7480

19-1-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5950	6040	6060	6060	6017
B1	4720	4810	4840	4840	4790
B2	5330	5420	5430	5430	5393
B3	6130	6190	6200	6200	6173
B4	7230	7360	7380	7380	7323
B5	4250	4280	4310	4310	4280
B6	6230	6380	6320	6380	6310
B7	5150	5280	5270	5280	5233
A0	6570	6590	6600	6600	6587
A1	5410	5490	5490	5490	5463
A2	5150	5240	5300	5300	5230
A3	6250	6330	6320	6330	6300
A4	4470	4500	4510	4510	4493
A5	5000	5050	5110	5110	5053
A6	6260	6270	6270	6270	6267
A7	6790	6760	6740	6790	6763

25-1-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5680	5770	5840	5840	5840
B1	4570	4640	4650	4650	4650
B2	5070	5140	5130	5140	5130
B3	5890	5960	6010	6010	6010
B4	7220	7310	7340	7340	7340
B5	4190	4270	4300	4300	4300
B6	6410	6590	6680	6680	6680
B7	5060	5080	5110	5110	5110
A0	6080	6170	6230	6230	6230
A1	5460	5500	5540	5540	5540
A2	5740	5760	5750	5760	5750
A3	5910	5830	5870	5910	5870
A4	4240	4210	4240	4240	4240
A5	5250	5250	5240	5250	5240
A6	6190	6250	6290	6290	6290
A7	6910	7020	7050	7050	7050

29-1-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5870	5930	6010	6010	5937
B1	4690	4730	4810	4810	4743
B2	5240	5280	5330	5330	5283
B3	5930	5980	6050	6050	5987
B4	7200	7310	7360	7360	7290
B5	4220	4350	4410	4410	4327
B6	6850	6920	6980	6980	6917
B7	5300	5380	5460	5460	5380
A0	6180	6530	6520	6530	6410
A1	5060	5060	5130	5130	5083
A2	5420	5330	5510	5510	5420
A3	6220	6320	6320	6320	6287
A4	4210	4250	4270	4270	4243
A5	5070	5160	5140	5160	5123
A6	5750	5760	5800	5800	5770
A7	6750	6930	6830	6930	6837

29-1-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5960	5950	5970	5970	5960
B1	4810	4810	4810	4810	4810
B2	5330	5330	5370	5370	5343
B3	6050	6080	6080	6080	6070
B4	7410	7440	7450	7450	7433
B5	4410	4440	4420	4440	4423
B6	6960	6990	7000	7000	6983
B7	5440	5460	5440	5460	5447
A0	6410	6460	6510	6510	6460
A1	5110	5090	5080	5110	5093
A2	5460	5460	5470	5470	5463
A3	6370	6360	6370	6370	6367
A4	4260	4260	4260	4260	4260
A5	5200	5210	5200	5210	5203
A6	5850	5860	5780	5860	5830
A7	6830	6920	6930	6930	6893

31-1-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5990	5990	5990	5990	5990
B1	4710	4720	4730	4730	4720
B2	5410	5410	5430	5430	5417
B3	6190	6180	6170	6190	6180
B4	7480	7460	7460	7480	7467
B5	4470	4430	4470	4470	4457
B6	6340	6380	6370	6380	6363
B7	5570	5570	5560	5570	5567
A0	6490	6530	6540	6540	6520
A1	5400	5360	5350	5400	5370
A2	5180	5240	5200	5240	5207
A3	6290	6330	6310	6330	6310
A4	4250	4280	4270	4280	4267
A5	5270	5290	5330	5330	5297
A6	6130	6110	6100	6130	6113
A7	7060	7060	7080	7080	7067

2-2-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5970	6000	5990	6000	5987
B1	4820	5080	4850	5080	4917
B2	5330	5370	5370	5370	5357
B3	5930	5970	5990	5990	5963
B4	7470	7520	7510	7520	7500
B5	4410	4440	4450	4450	4433
B6	6690	6680	6710	6710	6693
B7	5500	5870	5610	5870	5660
A0	6690	6680	6690	6690	6687
A1	5210	5220	5250	5250	5227
A2	6250	6250	6310	6310	6270
A3	6390	6420	6400	6420	6403
A4	4190	4200	4400	4400	4263
A5	5320	5340	5340	5340	5333
A6	6210	6190	6220	6220	6207
A7	6930	6880	6880	6930	6897

6-2-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	6060	6110	6110	6110	6093
B1	4940	4710	4980	4980	4877
B2	5240	5280	5650	5650	5390
B3	5910	5890	5970	5970	5923
B4	7350	7390	7380	7390	7373
B5	4360	4420	4410	4420	4397
B6	6320	6320	6310	6320	6317
B7	5320	5300	5350	5350	5323
A0	6380	6380	6470	6470	6410
A1	5390	5410	5430	5430	5410
A2	5150	5130	5200	5200	5160
A3	6210	6190	6200	6210	6200
A4	4210	4200	4220	4220	4210
A5	5070	5260	5290	5290	5207
A6	5980	6090	6130	6130	6067
A7	6880	6930	6930	6930	6913

9-2-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	6030	6080	6080	6080	6063
B1	4910	4680	4950	4950	4847
B2	5210	5250	5620	5620	5360
B3	5880	5860	5940	5940	5893
B4	7320	7360	7350	7360	7343
B5	4330	4390	4380	4390	4367
B6	6290	6290	6280	6290	6287
B7	5290	5270	5320	5320	5293
A0	6350	6350	6440	6440	6380
A1	5360	5380	5400	5400	5380
A2	5120	5100	5170	5170	5130
A3	6180	6160	6170	6180	6170
A4	4180	4170	4190	4190	4180
A5	5040	5230	5260	5260	5177
A6	5950	6060	6100	6100	6037
A7	6850	6900	6900	6900	6883

15-5-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5320	5260	5250	5320	5277
B1	3828	3757	3808	3828	3798
B2	5000	5070	4920	5070	4997
B3	4450	4670	4590	4670	4570
B4	6740	6680	6670	6740	6697
B5	2041	2283	2050	2283	2125
B6	3836	3556	3546	3836	3646
B7	4660	4620	4670	4670	4650
A0	5580	5620	5780	5780	5660
A1	3507	3552	3467	3552	3509
A2	4480	4500	4570	4570	4517
A3	5390	5440	5330	5440	5387
A4	3563	3548	3501	3563	3537
A5	4930	4900	4880	4930	4903
A6	4480	4500	4570	4570	4517
A7	4750	4810	4760	4810	4773

15-5-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4810	4750	5090	5090	4883
B1	3600	3711	3595	3711	3635
B2	4490	4470	4820	4820	4593
B3	5110	5150	5130	5150	5130
B4	6600	6710	6570	6710	6627
B5	2122	2259	2144	2259	2175
B6	3782	3965	3428	3965	3725
B7	4880	4780	4880	4880	4847
A0	5320	5530	5160	5530	5337
A1	4240	4230	4260	4260	4243
A2	4760	4480	4550	4760	4597
A3	5420	5360	5660	5660	5480
A4	3600	3627	3634	3634	3620
A5	5020	5080	5060	5080	5053
A6	5160	5060	5200	5200	5140
A7	5900	5800	5640	5900	5780

23-5-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4460	4860	5000	5000	4773
B1	3415	3718	3497	3718	3543
B2	4550	4590	4510	4590	4550
B3	5270	5250	5520	5520	5347
B4	6760	6860	6490	6860	6703
B5	2948	3128	3198	3198	3091
B6	5490	5550	5690	5690	5577
B7	4990	4970	4910	4990	4957
A0	5070	4830	4510	5070	4803
A1	4280	4310	4480	4480	4357
A2	3996	4250	3857	4250	4034
A3	5390	5220	5330	5390	5313
A4	3351	3339	3386	3386	3359
A5	4760	5080	4780	5080	4873
A6	4850	4720	4880	4880	4817
A7	5720	6180	5820	6180	5907

1-6-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	5180	5360	5350	5360	5297
B1	3853	4050	3777	4050	3893
B2	4410	4640	4670	4670	4573
B3	5410	5460	5420	5460	5430
B4	6680	6540	6350	6680	6523
B5	3140	2801	3044	3140	2995
B6	4950	5020	4720	5020	4897
B7	4620	4650	4410	4650	4560
A0	4760	4640	4520	4760	4640
A1	3481	3393	3828	3828	3567
A2	3163	3393	3014	3393	3190
A3	5520	3029	5260	5520	4603
A4	3256	3360	3181	3360	3266
A5	4690	4850	5020	5020	4853
A6	4300	4340	4560	4560	4400
A7	5350	5790	5820	5820	5653

5-6-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4480	4380	4470	4480	4443
B1	3787	3780	3772	3787	3780
B2	4500	4420	4440	4500	4453
B3	5090	5110	5160	5160	5120
B4	6380	6360	6400	6400	6380
B5	2904	2881	2873	2904	2886
B6	3492	3392	3339	3492	3408
B7	4360	4380	4300	4380	4347
A0	3672	3669	3699	3699	3680
A1	4580	4530	4560	4580	4557
A2	3214	3176	3191	3214	3194
A3	4930	4870	4880	4930	4893
A4	3528	3509	3525	3528	3521
A5	4560	4570	4540	4570	4557
A6	0	0	0	0	0
A7	5820	5860	5800	5860	5827

11-6-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4950	4770	4850	4950	4857
B1	3818	3809	3815	3818	3814
B2	4510	4500	4510	4510	4507
B3	3872	3871	3860	3872	3868
B4	6360	6200	6250	6360	6270
B5	2228	2203	2293	2293	2241
B6	4760	4680	4710	4760	4717
B7	4210	4290	4310	4310	4270
A0	3486	3487	3386	3487	3453
A1	4500	4430	4440	4500	4457
A2	2793	2670	2771	2793	2745
A3	4980	5010	5010	5010	5000
A4	3507	3511	3509	3511	3509
A5	4100	4150	4010	4150	4087
A6	0	0	0	0	0
A7	5460	5460	5350	5460	5423

18-6-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4700	4680	4670	4700	4683
B1	3580	3564	3586	3586	3577
B2	4370	4400	4380	4400	4383
B3	4420	4470	4400	4470	4430
B4	6150	6130	6150	6150	6143
B5	2674	2680	2663	2680	2672
B6	3414	3576	3400	3576	3463
B7	3857	3897	3869	3897	3874
A0	3389	3347	3334	3389	3357
A1	4570	4550	4570	4570	4563
A2	2453	2482	2522	2522	2486
A3	5070	5040	5080	5080	5063
A4	3304	3330	3334	3334	3323
A5	2426	2406	2444	2444	2425
A6	0	0	0	0	0
A7	5650	5650	5640	5650	5647

25-6-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4490	4470	4470	4490	4477
B1	0	0	0	0	0
B2	4330	4370	4380	4380	4360
B3	4080	4080	4070	4080	4077
B4	6140	6240	6190	6240	6190
B5	3175	3107	3168	3175	3150
B6	3226	3276	3270	3276	3257
B7	3961	3971	3950	3971	3961
A0	4210	4280	4280	4280	4257
A1	4480	4480	4500	4500	4487
A2	2657	2651	2624	2657	2644
A3	4820	4850	4870	4870	4847
A4	3287	3287	3288	3288	3287
A5	3185	3196	3172	3196	3184
A6	0	0	0	0	0
A7	5190	5190	5190	5190	5190

2-7-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4350	4340	4290	4350	4327
B1	0	0	0	0	0
B2	4350	4370	4420	4420	4380
B3	4380	4380	4350	4380	4370
B4	6040	6010	6060	6060	6037
B5	2289	2280	2255	2289	2275
B6	3298	3269	3296	3298	3288
B7	3737	3704	3781	3781	3741
A0	3340	3347	3344	3347	3344
A1	3481	3460	3446	3481	3462
A2	2543	2563	2594	2594	2567
A3	4520	4580	4550	4580	4550
A4	3201	3201	3155	3201	3186
A5	2720	2707	2759	2759	2729
A6	0	0		0	0
A7	4360	4300	4350	4360	4337

18-7-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	4390	4380	4400	4400	4390
B1	0	0	0	0	0
B2	4330	4290	4340	4340	4320
B3	4670	4640	4670	4670	4660
B4	6080	6120	6100	6120	6100
B5	2098	1990	1945	2098	2011
B6	3052	3113	3095	3113	3087
B7	3697	3654	3700	3700	3684
A0	3732	3725	3765	3765	3741
A1	4280	4290	4290	4290	4287
A2	3676	3782	3787	3787	3748
A3	4440	4430	4440	4440	4437
A4	3033	3021	3041	3041	3032
A5	3121	3081	3068	3121	3090
A6	0	0		0	0
A7	4910	4920	4910	4920	4913

1-8-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	3580	3522	3565	3580	3556
B1	0	0	0	0	0
B2	4470	4470	4470	4470	4470
B3	4810	4840	4810	4840	4820
B4	5910	5920	5970	5970	5933
B5	1576	1595	1595	1595	1589
B6	3682	3763	3690	3763	3712
B7	3799	3710	3738	3799	3749
A0	3580	3545	3567	3580	3564
A1	3892	3922	3938	3938	3917
A2	2042	1994	2017	2042	2018
A3	4340	4270	4340	4340	4317
A4	3270	3253	3238	3270	3254
A5	2926	3004	2941	3004	2957
A6	0	0		0	0
A7	4770	4700	4800	4800	4757

13-8-2007

Lamp	Measurement 1	Measurement 2	Measurement 3	Maximum	Average
B0	3950	3855	3902	3950	3902
B1	0	0	0	0	0
B2	4380	4380	4380	4380	4380
B3	4810	4850	4840	4850	4833
B4	0	0	0	0	0
B5	2497	2558	2473	2558	2509
B6	3920	3956	3921	3956	3932
B7	3314	3331	3334	3334	3326
A0	3562	3591	3517	3591	3557
A1	3950	3928	3923	3950	3934
A2	2078	2082	2077	2082	2079
A3	4450	4470	4430	4470	4450
A4	3248	3238	3265	3265	3250
A5	2288	2323	2255	2323	2289
A6	0	0	0	0	0
A7	4540	4580	4550	4580	4557

Appendix E: Manual Illumination Data Summary

	13-12-2006	20-12-2006	19-1-2007	25-1-2007	29-1-2007	31-1-2007	2-2-2007	6-2-2007	9-2-2007	15-5-2007	15-5-2007	23-5-2007	1-6-2007	5-6-2007	11-6-2007	18-6-2007	25-6-2007	2-7-2007	18-7-2007	1-8-2007	13-8-2007	
Hours	0	168	888	1032	1132	1176	1224	1320	1392	3672	3678	3866	4079	4178	4321	4493	4664	4826	5210	5548,8	5835	Hours
B0	7983	7487	6017	5840	5960	5990	5987	6093	6063	5277	4883	4773	5297	4443	4857	4683	4477	4327	4390	3556	3902	B0
B1	7430	6370	4790	4650	4810	4720	4917	4877	4847	3798	3635	3543	3893	3780	3814	3577	0					B1
B2	8007	6717	5393	5130	5343	5417	5357	5390	5360	4997	4593	4550	4573	4453	4507	4383	4360	4380	4320	4470	4380	B2
B3	7393	7297	6173	6010	6070	6180	5963	5923	5893	4570	5130	5347	5430	5120	3868	4430	4077	4370	4660	4820	4833	B3
B4	8953	8507	7323	7340	7433	7467	7500	7373	7343	6697	6627	6703	6523	6380	6270	6143	6190	6037	6100	5933	0	B4
B5	7570	6050	4280	4300	4423	4457	4433	4397	4367	2125	2175	3091	2995	2886	2241	2672	3150	2275	2011	1589	2509	B5
B6	7567	7203	6310	6680	6983	6363	6693	6317	6287	3646	3725	5577	4897	3408	4717	3463	3257	3288	3087	3712	3932	B6
B7	6407	5787	5233	5110	5447	5567	5660	5323	5293	4650	4847	4957	4560	4347	4270	3874	3961	3741	3684	3749	3326	B7
A0	6843	7297	6587	6230	6460	6520	6687	6410	6380	5660	5337	4803	4640	3680	3453	3357	4257	3344	3741	3564	3557	A0
A1	7463	6617	5463	5540	5093	5370	5227	5410	5380	3509	4243	4357	3567	4557	4457	4563	4487	3462	4287	3917	3934	A1
A2	6947	7183	5230	5750	5463	5207	6270	5160	5130	4517	4597	4034	3190	3194	2745	2486	2644	2567	3748	2018	2079	A2
A3	7883	7183	6300	5870	6367	6310	6403	6200	6170	5387	5480	5313	4603	4893	5000	5063	4847	4550	4437	4317	4450	A3
A4	7747	5817	4493	4240	4260	4267	4263	4210	4180	3537	3620	3359	3266	3521	3509	3323	3287	3186	3032	3254	3250	A4
A5	7717	6353	5053	5240	5203	5297	5333	5207	5177	4903	5053	4873	4853	4557	4087	2425	3184	2729	3090	2957	2289	A5
A6	6970	6713	6267	6290	5830	6113	6207	6067	6037	4517	5140	4817	4400	0								A6
A7	7760	7480	6763	7050	6893	7067	6897	6913	6883	4773	5780	5907	5653	5827	5423	5647	5190	4337	4913	4757	4557	A7
Average	7540	6879	5730	5704	5753	5769	5862	5704	5674	4535	4679	4750	4521	4336	4214	4006	4098	3756	3964	3758	3357	Average

Appendix F: Calculations Best Guess Method AEL

Without burn-in

L70 Calculations

A4 / L70	A7 / L70
75 = 168a+b 58 = 888a+b 58-b = 888a a = (58-b)/888	73 = 4493a+b 67 = 4664a+b 67-b = 4664a a = (67-b)/4664
75 = 168(58-b)/888+b (75-b)/168 = (58-b)/888 888(75-b) = 168(58-b) 66600-888b = 9744-168b 56856 = 720b b = 79 a = -0,02	73 = 4493(67-b)/4664+b (73-b)/4493 = (67-b)/4664 4664(73-b) = 4493(67-b) 3440472-4664b = 301031-4493b 39441 = 171b b = 230,65 a = -0,035
70 = -0,02t+79 t = (70-79)/-0,02 t = 379,8	70 = -0,035t+230 t = (70-230)/-0,035 t = 4578,5

L50 calculations

B5 / L50	B3 / L50
58 = 1392a+b 28 = 3672a+b 28-b = 3672a a = (28-b)/3672	100 = 0a+b b = 100 65 = 5835a+b a = (65-100)/5835 a = -0,006
58 = 1392(28-b)/3672+b (58-b)/1392 = (28-b)/3672 3672(58-b) = 1392(28-b) 212976-3672b = 38976-1392b 174000 = 2280b b = 76,3 a = -0,013	
50 = -0,013t+76,3 t = (50-76,3)/-0,013 t = 2000	50 = -0,006t+100 t = (50-100)/-0,006 t = 8335,7

With Burn-in

A2 / L50	B2 / L50
35 = 5549a+b 65 = 5210a+b 65-b = 5210a a = (65-b)/5210	85 = 5835a+b 100 = 1032a+b 100-b = 1032a a = (100-b)/1032
35 = 5549(65-b)/5210+b (35-b)/5549 = (65-b)/5210 5210(35-b) = 5549(65-b) 182350-5210b = 360685-5549b -178335 = -339b b = 526,1 a = -0,09	85 = 5835(100-b)/1032+b (85-b)/5835 = (100-b)/1032 1032(85-b) = 5835(100-b) 87720-1032b = 583500-5835b -495780 = -4803b b = 103,2 a = -0,003
50 = -0,09t+526,1 t = (50-526,1)/-0,09 t = 5276,5	50 = -0,003t+103,2 t = (50-103,2)/-0,003 t = 17042

L70

A2 / L70	B2 / L70
t = 5276,5	70 = -0,003t+103,2 t = (70-103,2)/-0,003 t = 10638

Appendix G: Degradation analysis by J. Sari

Josephine Sari performed an analysis of the GU10 High Power LED Lamps together with LED Tube lights (subject of the Master's thesis of Yiu Man Kan [Kan07]) to test a proposed theorem on bivariate and multivariate failure mechanisms [Sar07]. She developed an alternative reliability quantification model for bi-/multivariate constant stress degradation test data which suits this degradation tests of LED lamps.

The High Power LED Lamp test data was used for the analysis of the multivariate constant stress degradation test (CSDT). In the analysis it was assumed that there was a lighting system that consisted of 4 lighting locations. Two of the locations consist of 8 samples of GU10 High Power LED lamps, both halves of the test board (the A and the B lamps respectively) and the following assumptions were used:

- Each set of samples is assumed to have its own degradation failure mechanism, which is the degradation of the light output. This mechanism is considered as one performance characteristic of the system.
- The system is considered fail if the light output of at least one of the LED light sets degrades to its critical light output value (L50)
- The system is assumed to be arranged as a lighting system which is operated at ambient temperature of 25° C, and the degradation failure mechanism may not be independent of each other. Therefore, dependence analysis is needed.
- The CSDT test that has been performed can provide sufficient data needed for the reliability assessment of the system.

There are 16 high power LED lamp samples that have been tested at 25° C ambient temperature and the samples are labelled as A0..A7, B0..B7. Half of the samples represents performance characteristic 3, PC3 (B0..B7) and the other half represents the fourth performance characteristic, PC4 (A0..A7). In the original measurement times, these samples are tested for 0-, 168-hour and several other measurement times until the 4080-hour of operating time. This is the final measuring time if the measurement is stopped before the catastrophical failures occurred. As explained in section 4.2, the readings show probable human error during the experiment, which makes the degradation path does not reflect their supposedly physical degradation process. Therefore for some measurement times, that are close to each other with higher possibility of measurement errors, the average of the readings are used. Based on these modified observations, the cumulative degradation data of PC3 and PC4 is calculated and plotted. These are shown below. The same plots without using an average over several measurement periods are shown in appendix H.

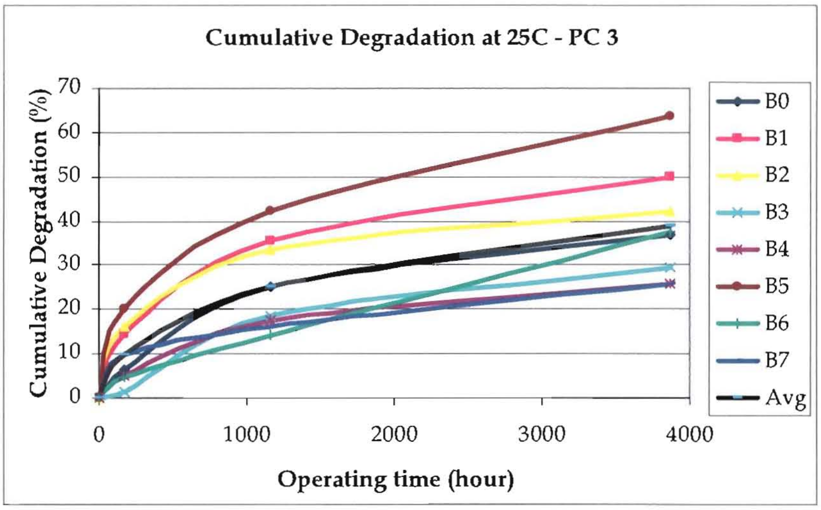

Figure I.1: PC3 (B lamps) cumulative degradation curve

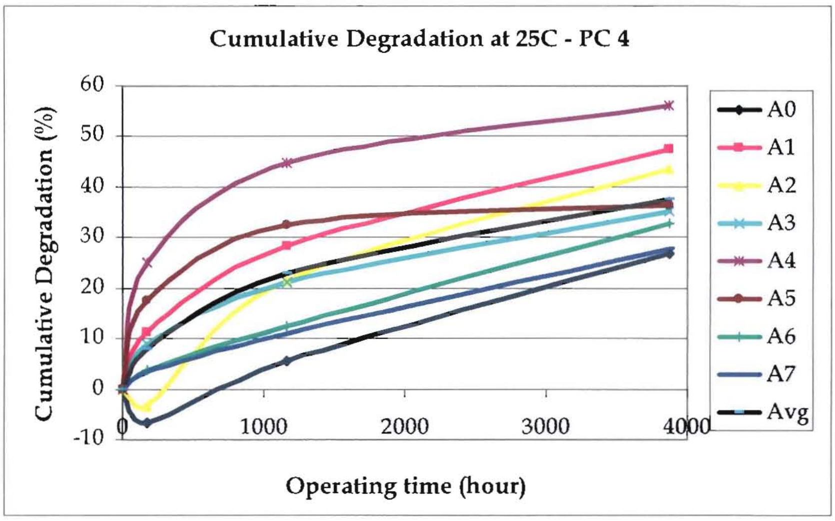

Figure I.2: PC4 (A lamps) cumulative degradation curve

Since the data points that can be used to model the third and fourth PCs are now lesser, consequently lesser unknown variables can be estimated if the efficiency of the estimation is to be maintained. Therefore, normal distribution with two parameters (μ and σ) will be used to model the marginal degradation data distribution of these two PCs. It is also assumed that the standard defenition (σ) of the marginal degradation data of PCs 3 & 4 is not a function of time.

Only the proposed multivariate CSDT Model 1 can be used to model and analyse the data. To demonstrate the ability of the proposed multivariate CSDT Model 1 to model multivariate degradation data which follows different marginal degradation distribution functions; PCs 3 & 4 with normal marginal degradation distribution assumption will be analyzed together with PCs 1 & 2 with inverse Gaussian marginal degradation distribution assumption. These are the LED tube lights from a second

Master's Thesis only additional modelling and analysis of the stage 1 of multivariate CSDT model 1 is needed to assess the marginal degradation data of PCs 3 and 4.

The results of the stage-1 of multivariate CSDT model 1 for the fixed effect of the PCs 3 and 4 are presented below.

Performance Characteristic	Distribution Parameter	Regression Function/Estimation
3	U3	0.048 – 2.7842737*ln(t) + 0.904*(ln(t))2
	O3	9.997679
4	U4	0.903 – 4.41*ln(t) + 1.06*(ln(t))2
	O4	9.900535

Table I.1: The results of stage-1 multivariate CSDT Model 1 for PC 3 and 4

	50%	
	PC3	PC4
Sample	U=9926.15; o=391.478	U=9683.83; o=237.135
1	8859	9461
2	9023	9562
3	8811	9431
4	9379	9778
5	9725	9984
6	9685	9962
7	8822	9438
8	9506	9853

Table I.2: Predicted TTF data (hours) of performance characteristic 3 and 4 with critical value

For PCs 3 and 4, normal distribution will be used to represent the distribution of their predicted marginal time-to-failure data. The estimated distribution parameters are also listed above. Normal distribution assumption is chosen to demonstrate that the analysis can be done with the model when the data has different marginal distribution functions.

Assuming that exchangeable Frank copula is suitable to model the multivariate predicted time-to-failure data, the value is predicted. This results in a value of 3.65 which is approximately equal to Kendall's tau 0,361. This corresponds to the general dependence effect of the 4-variate degradation failure.

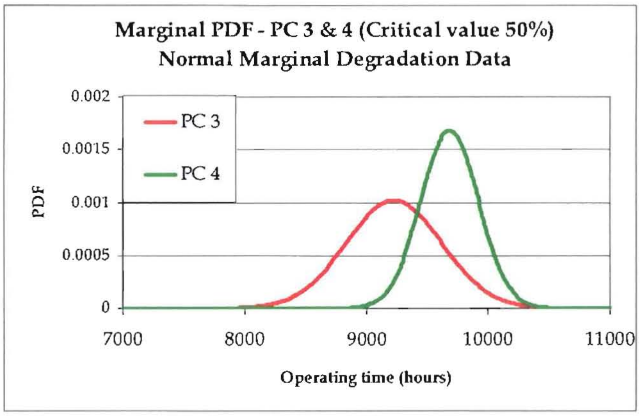

Figure I.3: Marginal PDF of PCs 3 & 4

The marginal probability distribution functions of PCs 3 & 4 are plotted above. This figure shows that the marginal PDF of PCs 3 & 4 are far at the right side of PCs 1 & 2. This supports the conclusion taken before that marginal reliability estimates are significantly higher. Therefore, the first and second failure mechanisms may have stronger influence on the system reliability. The adjusted system PDF is presented below. It shows that the peak of the failure probability is much closer to the first and second PCs than to the third and fourth PCs.

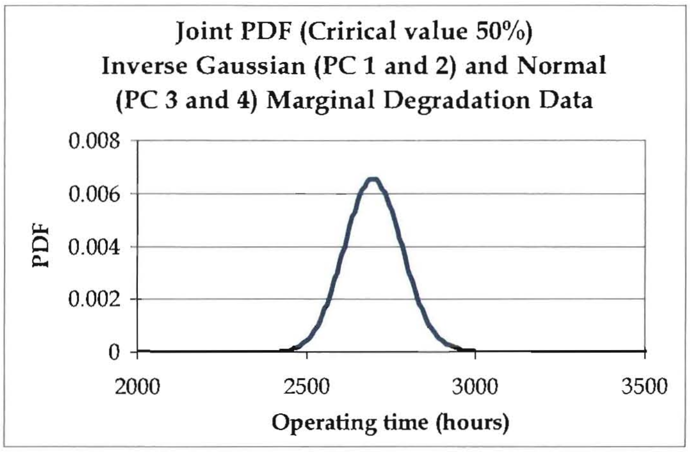

Figure I.4: Joint PDF of the multivariate degraded system

Meanwhile, the hazard rate of the multivariate degradation data also shows similar conclusion to the previous paragraph. The degradation data of the LED lamps system reflects part of the third and fourth phases of the roller-coaster curve. This shows that the main failure mechanism in the system is aging. This information can be used to plan and analyze the policy of LEDNed.

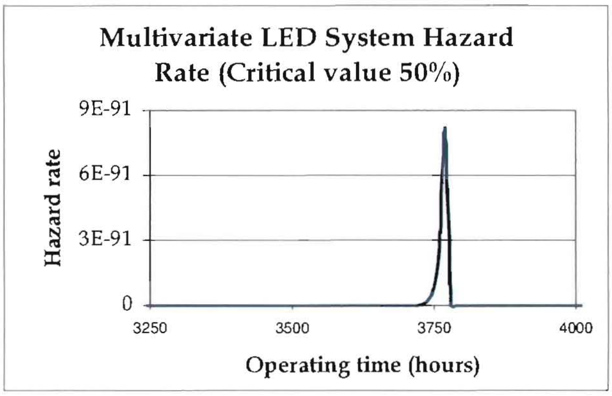

Figure I.5: Hazard rate of the multivariate degraded system

These analyses are helpful to understand the behaviour of the lamps and compare it to the LED tube lights. However the goal of these analyses is to show how a certain kind of degradation analysis can be done and to show how a system works. In order to do this a lot of the original data is filtered away and is therefore not very accurate in in this analysis and therefore additional analyses are needed to determine the degradation pattern of the GU10 High Power LED lamps in detail.

This is also because of the lamps that showed the catastrophical failures, they should be taken out of the analysis because they may show different behaviour even before they brake down. There may be some production flaw present for example

Appendix H: Degradation plots with original data