The Risks Of Applying Qualitative Reliability Prediction Methods: A Case Study

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SUMMARY & CONCLUSIONS

The fast technological innovation of the past decades contributed to an increasing complexity in products. This increased product complexity together with four different business drivers (time, profitability, functionality and quality) have an important influence on the reliability strategies used within companies. New methods are necessary to predict reliability in product design [1]. In current business processes qualitative reliability prediction methods are often applied to estimate the reliability risks present in products and processes. An example of a popular qualitative reliability prediction method is the so-called Failure Mode and Effects Analysis (FMEA). Many successful implementations of the FMEA method are described in literature from various professional fields. On the other hand, several setbacks of the traditional FMEA approach are described in literature. Most of these drawbacks result from the qualitative analysis approach. Nevertheless, the FMEA reliability prediction method is probably the most implemented method in practice. Present-day companies do not seem to take notice of the drawbacks of qualitative reliability prediction methods as described in literature. A convincing reason for this is the fact that no proven alternatives exist for these qualitative methods. Therefore the goal of this paper is to illustrate the risks of applying qualitative reliability prediction methods in practice and make suggestions for improving the application of these methods. This illustration is based on a complete reliability prediction approach named ROMDA. This ROMDA approach adopts FMEA to predict product reliability and will be presented in the second section. Subsequently this ROMDA approach is applied in a practical situation after which the reliability predictions are evaluated. Based on this evaluation, general conclusions and recommendations are described in order to improve the application of qualitative reliability prediction methods in practice.

1. *INTRODUCTION*

Manufacturers of high volume consumer products are currently working under strong pressure, because they have to deal with four different and often conflicting, business drivers [1]:

1. Time: does the product reach the market at the required moment in time?
2. Profitability: is the difference between product cost and product sales price adequate?
3. Functionality: is the product able to fulfill its intended functions?
4. Quality: does the product fulfill its intended purpose?

Recently, time-to-market has become a central point in many industries [2]. In order to keep up with competitors, it has become essential for companies to introduce more products to the market in a shorter time. Companies that succeed in developing and marketing new products faster than competitors can obtain many advantages, including gaining a large market share and higher profit by commanding premium prices. As a result, product development processes should bring good products to the market much faster than before. Brombacher states that "the challenge for manufacturers has become to maximize product profitability by minimizing time-to-profit" [1]. In order to minimize time-to-profit, many companies are looking for methods and techniques to accelerate the product creation process.

The fast technological innovation of the past decades contributed to an increasing complexity in products. The complexity of the technical content of products is increasing, but also the diversity and the variety of these products. Companies have to deal with this increasing product complexity in their product creation processes by delivering products that satisfy customer requirements [2]. These trends together with earlier mentioned business drivers time, profitability, functionality and quality also have an important influence on the reliability strategies used within companies.

The best way to make products reliable is to thoroughly test all possible product-customer combinations for an extended period of time before releasing a product to the market [1]. This process of extensive testing has become too time consuming and expensive. As mentioned before, the complexity of consumer products is rapidly increasing as a result of higher customer requirements. Nevertheless, customers expect the same or even higher product reliability levels. Customers have high expectations because technology has become less transparent to them. Customers often do not realize the complexity behind the systems they use, and therefore, they do not see the difficulties that come with the complex systems and just expect them to work [3]. As a result, the current interest in product complexity, cost reduction, time-to-market reduction and reliability assurance offers new challenges and opportunities in the field of reliability. New methods are necessary to predict reliability in product design [1]. In current business processes qualitative reliability prediction methods are often applied to estimate the reliability risks present in products and processes.

A method to perform qualitative reliability predictions is the Failure Mode and Effects Analysis (FMEA). The goal of the FMEA is to anticipate, identify and avoid failures in the operation of new systems and products while the systems or products are still on the drawing board [4]. Many successful implementations of the FMEA method are described in literature from various professional fields [5], [6], [7]. On the other hand, several drawbacks of the traditional FMEA approach are described in literature [8],[9]. Most of these drawbacks result from the qualitative analysis approach. Examples of these setbacks are: subjective approach of risk ranking, impossibility to distinguish between failure modes with equal risk priority numbers and inclination towards group thinking. Nevertheless, the FMEA reliability prediction method is probably the most implemented method in practice. Present-day companies do not seem to take notice of the drawbacks of qualitative reliability prediction methods as described in literature. A convincing reason for this is the fact that no proven alternatives exist for these qualitative reliability prediction methods.

Therefore, the goal of this paper is to illustrate the risks of applying qualitative reliability prediction methods in practice and make suggestions for improving the application of these methods. This illustration is based on a complete reliability prediction approach, named ROMDA [10] that adopts FMEA to predict product reliability. Nevertheless, other reliability prediction approaches could also have been applied to illustrate these risks. In section 2 a more extensive description of this ROMDA approach is given. Subsequently, in section 3, this ROMDA approach is applied in a practical situation after which the reliability predictions are evaluated. This paper finishes by describing conclusions and recommendations in order to improve the application of qualitative reliability prediction methods in practice in section 4.

2. *THE ROMDA APPROACH*

The theoretical reliability prediction and improvement concept was introduced in the paper "A Method for Reliability Optimization through degradation Analysis and Robust Design" [11]. The concept attempts to establish a relationship between product reliability and product design, and investigates failure of products with respect to a dominant performance characteristic, where performance characteristic is defined as a measure expressing how good a product fulfils its function. The concept expresses the performance characteristic, that characterizes the reliability of the product, as a function of the dominant design parameters (= physical product parameter that can be influenced by the designers). The dominant design parameters degrade over time. These degradation profiles are superimposed on the design parameters in the functional or mechanistic model, by which the degradation of the performance characteristic as a function of time and the design parameter values can be explained. The degradation of the performance characteristic is then used to derive reliability characteristics (e.g. mean time to failure (MTTF), variance time to failure (VTTF)) of the stipulated performance characteristic.

In essence, this approach can be used to establish the behavior of the statistical properties of the 'time to failure' of the performance characteristics given the statistical properties (like the mean and the variance) of the design parameters at time t=0 and their degradation models.

Three main degradation profiles could exist, namely:

1. Shift in the mean values of the designable parameters (linear or nonlinear over time)
2. Change in the variance of the designable parameters (linear or nonlinear over time)
3. A combination of both a shift in the mean value and a change in the variance of the designable parameters (linear or nonlinear over time)

The performance characteristic is statistical of nature and degrades over time due to the effects of degradation of the dominant design parameters. The performance characteristic is linked to the dominant design parameters by a functional, or mechanistic, relationship. When failure limits are known, a translation can be made to a failure rate curve. (e.g. the roller-coaster failure rate curve of K.L. Wong [12]).

A general schematic approach of the proposed ROMDA concept to predict and improve (optimize) reliability in a robust way is summarized in the following subsections.

2.1 *Design Parameters and Performance Characteristic*

The first step is the identification of the critical (dominant) design parameters of the performance characteristic under study. This performance characteristic must degrade or deteriorate over time. Hence, it has to be possible to explain the degradation of the performance characteristic through the physical degradation of the dominant design parameters. This first step forms the basis of the ROMDA concept since in this step the main causes of degradation of the performance characteristic over time are identified. The suggested approach for the identification of these critical design parameters is performing a Failure Mode and Effect Analysis (FMEA) [10]. During such an FMEA the main causes of performance degradation over time are identified and rated based on the common FMEA rating factors: probability of occurrence, severity and detectability. The design parameters that score highest on the overall FMEA score (multiplication of the three rates) are indicated as being critical. These critical design parameters are the point of departure for the remainder of the ROMDA approach.

2.2 *Time-dependent Degradation Model*

The next step is to obtain a time-dependent stochastic model of the degradation of these critical design parameters. The suggested approach for acquiring this model is to perform an accelerated life test (ADT) in which the degradation behavior of the design parameters is monitored over time. Subsequently, the stochastic models of the design parameters are introduced into the performance characteristic/design parameter mechanistic (functional) relationship to obtain a stochastic time and design parameter dependent model for the performance characteristic under study.

2.3 *Reliability Characteristics*

Lastly, this model of the performance characteristic with respect to certain chosen specification limits can be used to obtain reliability characteristics, like the mean time-to-failure (MTTF) and variance of time-to-failure (VTTF). Optimization methods, like Robust Design, can be employed to improve or optimize these reliability characteristics by setting the nominal value of the design parameters at certain values (parameter design). The goal of this optimization method is to maximize the nominal values and to minimize the variance values of these reliability characteristics.

Earlier application of the ROMDA concept in [10] has illustrated the ability to predict and optimize reliability based on the concepts' results. The resulting model made it possible to monitor product's performance and predict future failure behavior. However, the case study described in the next section is based on another application of the ROMDA concept and demonstrates the possible risks of applying qualitative methods like FMEA for reliability prediction.

3. *CASE STUDY: PAPER FEED MODULE*

In this case study the ROMDA concept has been applied on a paper-feed module of a certain type of professional copier. This section describes a summary of the several steps taken. For more detailed information about all phases of the concept the reader is referred to literature [13]. This section finishes with a discussion on the implications of the results of this case study for the application of a qualitative method for reliability prediction.

3.1 *The High Capacity Feeder*

The paper-feed module stores the blank paper sheets in paper trays and delivers these sheets on request to the first stage of the copy process. The paper-feed module as part of the total copier is displayed in figure 1. This figure shows that the paper-feed module can be divided into three module units: the High Capacity Feeder (HCF), the paper trays, and the manual sheet input.

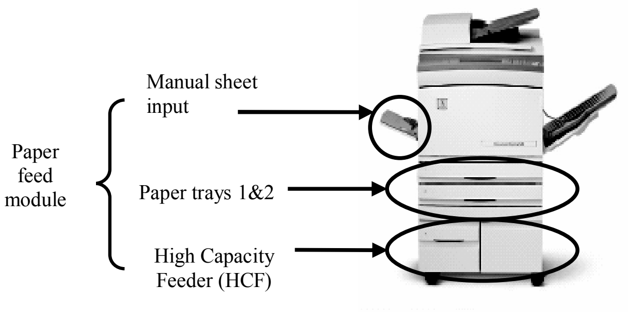

Figure 1 Copier with paper-feed module

The case study presented in this section is concerned with the High Capacity Feeder module unit. Due to existent time constraints, not all module functionalities could be dealt with during this research project. Within the HCF several functions can be distinguished like the paper elevation function, the paper grip function and the paper transport function. This case study will only focus on the paper elevation function of the HCF.

3.2 *The Elevation Function*

The paper lift's task is to elevate the paper up to the right level at the right moment. The elevation level is determined by a paper level sensor. The paper mechanically presses this sensor when it reaches the right level. The right moment implies that the paper lift should reach the right paper level in time. If the paper lift reaches this right paper level too late, the copier will come to a standstill and an error message will be displayed. The elevation speed is the relevant parameter that defines whether the paper lift will reach the right paper level in time. Since the elevation distance is constant, this elevation speed can be replaced by elevation time (t_E). Elevation time can be defined as the time required to lift a certain amount of paper over a fixed distance. This elevation time may be considered as a good indicator of the elevation performance and will therefore be used as a performance characteristic for this function.

3.3 *Identification of the Critical Design Parameters*

In order to identify critical design parameters for the elevation function an FMEA was performed. Since the main concern of ROMDA is the prediction of functional degradation over time, a forth rating factor was added to the three original factors (probability of occurrence, severity and detectability) namely, time dependence. This extra factor helps to discriminate between degradation failure modes and time independent failure modes. The scales used to perform this FMEA are:

- Probability of occurrence: 1-5 (1 being a failure mode with low frequency, 5 a failure mode with high failure frequency)
- Severity: 1-5 (1 being a failure mode with low impact, 5 a failure mode with high impact)
- Detectability: 1-5 (1 being a failure mode that is easy to detect, 5 a failure mode that is difficult to detect)
- Time dependence: 1-2 (1 being a time independent failure mode, 2 a time dependent failure mode)

The FMEA was executed for the HCF module unit on basis of these rating factors. The FMEA team consisted of experts on both the HCF module and the FMEA method. As a result, this FMEA team can be contemplated as being suitable [14]. The time dependent failure mechanisms from the FMEA concerning this elevation function are a degradation of the elevation motor causing a decrease in motor speed (lowering of the number of revolutions). And a more difficult rotation of the axle in the gear shaft, wear in the cable system and a resistance rise in the slide bearings of the elevator brake system contributing to a torque increase in the elevation mechanism.

In other words, these failure modes make it mechanically more difficult to lift an elevator plate loaded with a certain amount of paper. Based on these results, the design parameters of the elevation function are determined. These design parameters are:

- motor speed (number of revolutions);
- torque in elevation mechanism

3.4 *Experimental Set Up*

The elevation time (t_E) is measured by using the encoder wheel at the end of the motor axle. The number of revolutions of this encoder wheel corresponds with the number of revolutions of the motor (exit) axles. The encoder wheel contains 20 spokes that successively pass a sensor. As a result this sensor generates 20 electrical pulses per rotation. By adding up the time between these electrical pulses, the rotation time of the axle can be calculated. Since the elevation distance is constant and one axle rotation corresponds to a fixed elevated distance, (a multiplication of) this rotation time can be used as a measure for elevation time. To be able to test the influence of the design parameters "motor speed" (v_m) and "torque in elevation mechanism" (T_E) on the "elevation time" (t_E), the values of these design parameters need to be varied. The motor speed can be varied by placing different tensions (Volts) on the lift motor. A higher tension corresponds to a higher motor speed. The torque in the elevation mechanism can be varied by placing different weights on the lift plate. A higher weight corresponds to a higher torque in the elevation mechanism. As a result, it is expected that when motor speed decreases and torque in elevation mechanism increases, elevation time will decrease.

The experiments are performed by using the Design of Experiments (DOE) technique. The ranges of the design parameter settings are described in the specifications of the HCF and the lift motor. The nominal weight on the lift plate corresponds to two packs of paper that is 5 Kg. The minimal weight placed on the lift plate is no weight in case of an empty paper tray. The maximal weight on the lift plate corresponds to four packs of paper that is 10 Kg. It is physically impossible to store more paper on the lift plate. The nominal tension placed on the lift motor is according to specification 24,5 Volt. The minimal and maximum tension placed on this motor are consecutively 21,6 Volt and 26,2 Volt. Beyond these specification limits, the HCF is not able to function properly anymore. An overview of these ranges is given in table 1. The design factor levels in the screening experiment are determined to be the minimal, nominal and maximal levels of the design parameter (see table 1). This results in the screening design presented with all possible combinations of motor speed (minimal, nominal and maximal) and torques (minimal, nominal and maximal). This screening design is replicated three times, resulting in 27 runs. In order to prevent systematic measurement failures in the design, the runs are completely randomized. The 27 runs could not be performed in one day. As a result, the blocking factor "day" was introduced in order to investigate the influence of the factor day on the elevation time measurements. These results are analyzed using X- and R- control charts and ANOVA to determine whether "motor speed" (tension) and "torque in elevation mechanism" (load) have a significant influence on the performance characteristic "elevation time".

	limits		
	minimal	**nominal**	**maximal**
Motor speed (Tension)	21,6 V	24,5 V	26,2V
Torque in elevation mechanism (Load)	0 KG	5,0 Kg	10,0 Kg

Table 1 Ranges of Design Parameters

The R control chart of the screening experiment showed that the measurements are in control. In order to measure the change in performance characteristic due to the various settings of the design parameters, the X control chart should be out of control, which indicates the possibility of measuring this setting variation. The X chart of this experiment showed that, also this criterion is met. The ANOVA of this experiment shows that the effect of the design parameters motor speed (tension) and torque in elevation mechanism (load) have a P-value equal to zero. It is important to remark that the P-value of the interaction effect between tension and load is rather low indicating a significant interaction effect.

Based on the results from this screening experiment, it can be concluded that motor speed and torque in the elevation mechanism do have a significant influence on the elevation time of the paper lift in the HCF module unit.

Based on the FMEA results, the motor speed is expected to decrease over time. On the other hand, the torque in the elevation mechanism is expected to increase over time. As a result of these changes in design parameters, the performance characteristic elevation time is expected to increase over time.

3.5 *The degradation test*

For the execution of this degradation test, two new modules (consisting of trays and motors) are used. During the degradation test, all measurements (elevation time, motor speed and torque) are replicated three times to be able to measure the measurement variability. For the execution of the degradation test on the elevation function, a so-called compressed-time test was selected [15]. At the start of the degradation test, it was uncertain how fast the module would degrade over time. Therefore, the first four days the degradation test cycle was only 3 to 4 hours long. Between these test cycles, measurements were performed.

Since the execution of one measurement cycle takes about three hours, two measurements per day are performed with this 3- or 4-hour cycle. After these four days, a 6-hour test cycle was started in order to unburden the people performing the measurements, as the 6-hour test interval only requires one measurement cycle per day. After eight days, a 16-hour test cycle was started followed by a 21-hour test cycle two days later.

This gradual transition to longer test periods was executed in order to speed up the degradation process. The complete degradation test has run 200 hours.

During the fifth 21-hour cycle, both modules broke down. The modules were unable to lift the required weights during the motor speed measurements and produced strong cracking sounds under normal operating conditions. At this point, it was decided to end the degradation test and to analyze the modules together with the acquired data.

The R chart of the elevation time versus degradation test hours indicated that the elevation time measurements are stable and predictable. Only the measurement results at 200 hour are out of control for both modules. These out of control points are the result of the break down of both modules.

However, the X chart of elevation time versus degradation test hours indicated that no well-defined degradation pattern can be recognized for the elevation time of both modules. No significant rise in elevation time can be established and both modules show different elevation time behaviors. These results make it impossible to model the degradation behavior of the performance characteristic elevation time. Based on this parameter behavior, the breakdown of the two modules cannot be predicted. These results suggest that the performance characteristic elevation time should be replaced by another performance characteristic that does predict the module failure behavior.

The X charts of the design parameter motor speed at 0 Nm load and at 0,8 Nm load versus degradation test hours showed a clear decrease in motor revolution time for both modules. This corresponds to an increase in motor speed. This conflicts with the expectancy of declining motor speed over time. With hindsight, the process of carbon brush wear can explain this increase in motor speed. As a result of carbon brush wear, the contact surface of the carbon brushes increases eventuating in a longer current supply to the motor. This longer current supply to the motor causes this decrease in revolution time. The second X chart shows an approximately constant motor speed over time for both modules. Only after 200 hours, as an immediate result of the module break down, motor speed drops to zero. Based on this parameter behavior, the breakdown of the two modules cannot be predicted.

Based on the FMEA results, the HCF load was expected to increase over time, and as a result, the period time of the HCF was expected to decrease over time. However, the X charts of the design parameter torque in the elevation mechanism versus degradation test hours showed a rather constant load level for both HCF modules. With the exception of two peaks in HCF load, which could not be technically explained afterwards.

Since the breakdown of the modules could not be explained by the degradation of the design parameters and the behavior of the performance characteristic demonstrated no clear degradation path, further investigation was required to reveal the root cause of the module failures. The strong cracking sounds that were produced by the modules under normal operating conditions came from the gearbox of the lift motor. On that account, it was decided to disassemble these lift motors and to investigate the several components. This investigation resulted in the detection of three defects inside the lift motor gearbox:

1. The wear down of gearwheels; as a result the constant friction between the various gearwheels, the length of the gearwheel spokes decreased. See figure 2a.
2. The wear down of the gearwheel axles; as a result of the rotation of the gearwheel axles in the fixation shafts, the diameter of these gearwheel axles decreased.
3. The wear down of the fixation shafts; as a result of the rotation of the gearwheel axles in the fixation shafts, the diameter of these fixation shafts increased. See figure 2b.

This degradation process of the lift motor's gearbox results in a continuous increase of the play between the various gearwheels. At a certain play-level between the gearwheels, the gearwheel transmission becomes irregular due to the difference in friction at different positions of the gearwheels. Ultimately, the gearwheel transmission fails due to lack of connection between the various gearwheels. In this degradation test, this gearwheel transmission failing expressed itself as an instant failure mechanism since motor speed and elevation time does not change due to an increase in gearwheel play.

Based on these degradation test results, it can be concluded that the dominant failure mechanism was not identified in the FMEA process. The behavior of the dominant failure mechanism is not visible in the degradation profiles of the performance characteristic elevation time and the design parameter motor speed.

As a result, these performance characteristic and design parameters cannot be used to describe the degradation behavior of the complete paper feed module.

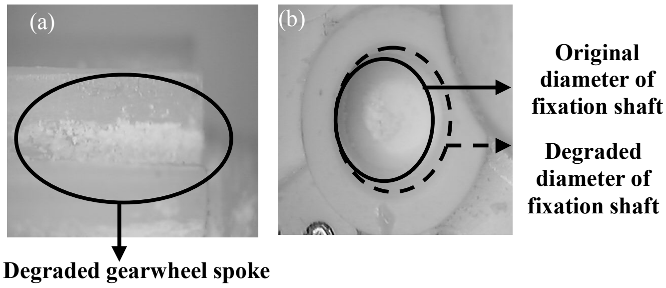

Figure 2 Degradation of the motor gearbox [13]
(a): decrease in spoke length
(b): increase in fixation shaft diameter

In order to come to a time dependent degradation model of the elevation function a new FMEA should be performed. This FMEA should identify design parameters that describe the degradation of the gearbox based on the results of the earlier performed experiments. Furthermore, there should be searched for a performance characteristic that describes the degradation of the paper feed module due to increases in gearwheel play. Subsequently, the screening experiments and degradation tests should be executed once more.

4. *CONCLUSIONS AND RECOMMENDATIONS*

The FMEA process performed at the beginning of this case study, resulted in the identification of two design parameters. The significance of these design parameters was confirmed by performing a screening experiment. However, the results of the degradation test indicated that the dominant failure mechanism is not visible in the degradation profiles of the performance characteristic and the design parameter. In other words, the results of this degradation test indicated that the dominant failure mechanism was not identified in the FMEA process. Using all the results from this degradation test, a new FMEA should be performed. Subsequently, the screening experiments and degradation tests should be executed once more, followed by the process of model formulation and optimization. All in all, a time-consuming and therefore costly process.

Based on the results of this case study, it can be concluded that the application of qualitative reliability prediction methods like FMEA in real life business processes may cause problems. Based on the FMEA results, wrong decisions can be made within companies concerning e.g. product quality and safety. In a worst case scenario, this may cause life threatening situations in which products do not comply with safety norms. In this case study, the results of erroneous FMEA outcomes were relatively restricted, namely higher project cost and longer project duration.

The possibility of erroneous FMEA results can be attributed to the qualitative nature of this method. Instead of applying quantitative data about known failure mechanisms, experienced engineers are used to indicate main causes of product failure. Although these engineers are very skillful in designing these products and solving problems within them, this does not automatically mean that these engineers will come up with all relevant failure mechanisms. Therefore, a new approach is suggested in which the FMEA results are compared with error field data or product service data from a comparable, or the same product [16].

The new approach consists of two paths that are performed in parallel. On the one hand, the time dependent FMEA process is executed as described above. On the other hand, field errors of a comparable or the same product are presented in a Pareto in order to indicate the main causes of failures. For the dominant failure mechanisms a fault tree analysis is performed which in the end results in the main time-dependent causes of product failures. The results of both paths are compared and combined to come to the root causes of failure.

A restriction for using error field data or service data is that it can only be used for a derivative product development processes as defined in [2]. These development processes should be able to provide relevant service information from predecessors. Service information can give a quantitative estimation of the dominant failure, if sufficient statistical information is available. Furthermore, when the engineering information is also able to provide quantitative information, estimations can be made about the dominance of the root-causes of failures. Therefore, by using service information a quantitative motivation can be made for the determination of the performance characteristic and the critical design parameters.

It is important to remark that the application area of this extended approach is wider than just for ROMDA concept. Other decision processes based on qualitative reliability prediction methods could also be supported by such a root cause analysis of service data. Nevertheless, more research is required in order to investigate the opportunities and limitations of applying this approach in practice.

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