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Framework for Robust Design and Reliability Methods to Develop Frugal Manufacturing Systems

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Abstract

Emerging markets are rapidly growing. Manufacturing systems in these markets have to be cost-effective but still of high quality. In addition they are often exposed to harsh conditions e.g. climate, infrastructure and lack of knowledge. Consequently, local conditions as well as reliability and robustness methods must be explicitly taken into account during the development process to successfully develop high quality yet cost-effective manufacturing systems for these specific markets. This paper shows different views on robustness and reliability to overcome the geographical and cultural distance of emerging markets for industrial equipment manufacturers from industrialized countries. In addition, framework conditions for robust design and reliability methods are derived in order to develop frugal manufacturing systems, aiming to improve sustainable usage in emerging markets.

Keywords: robustness; robust design and reliability methods; frugal manufacturing systems; BOP markets

1. Introduction

The global business world is increasingly influenced by the continuing economic growth in emerging markets [1]. High growth rates and an enormous market size with a large customer base in the middle class make emerging markets very attractive for companies in industrialized countries [2]. Other reasons are the growing demand and the rising purchasing power of the population [3]. In the emerging markets, a cumulative population growth rate of 95% and a real cumulative gross domestic product (GDP) growth rate of 70% are expected by 2030 [4]. Emerging markets already account for 36% of global GDP, while the OECD estimates that the consolidated GDP of today's emerging markets will account for 60% of world GDP in 2060 [5,6]. Due to the enormous dominance of the bottom of the pyramid (BOP) class in emerging markets, there is one of the largest sales potentials for companies worldwide [7].

There are several companies that have already identified this potential. One of them, the Chinese world market leader for household appliances Haier, is increasingly securing major market shares in the emerging markets, focusing on the strategy to satisfy these customers and the local aspects of the market. In the past, Haier has defined 70 customer segments for the domestic market of China alone, in order to be able to develop products that are precisely suited to the exact needs of each customer segment [7]. Other large enterprises, such as General Electric, Siemens, Logitech and Philips, have also recognized the trend in the emerging markets and are already aligning part of their product architecture with local customers and conditions [8]. Such product solutions are described by Roland Berger as frugal innovations which are functional, robust, user-

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friendly, growing, affordable and adapted to local conditions [9].

Emerging markets offer companies the opportunity of a large sales market, but at the same time they also create new challenges in the development and the life cycle of these frugal manufacturing systems (fms). The problem with developing fms is adapting the value chain to the local conditions and requirements of the target market [10]. In emerging markets the economic context is often coined by low income, shortage of resources, lack of qualified workforce, poor infrastructure, climate, supply chains etc. [11]. Several studies have already identified development trends in mechanical and plant engineering. Besides a shifting demand to growth markets outside Europe, this study shows the increasing relevance of the service business in internationalized markets and also the current deficit of companies from industrialized countries. The competition has a lead in service, maintenance and repair, they are cheaper and faster [12,13,14]. However, it is difficult for small and medium-sized companies from industrial countries to establish a good service business, because of the high investment on resources and the predominantly small numbers of units and sales in these countries. From this it can be deduced that reliable and robust manufacturing systems which need rather simple or no maintenance are required. This poses a major challenge for product planning and development, as fms demand low initial costs and low total cost of ownership [1]. The approach presented in this paper is, aims at an efficient development of fms and a generally improved sustainable use in emerging markets.

2. Frugal manufacturing systems in the context of reliability and robustness

2.1. Frugal manufacturing systems

Frugal manufacturing systems are machines, equipment and devices that meet the requirements of price-sensitive customers in industrialized countries and the fast-growing emerging markets. The word FRUGAL was used by Roland Berger as an acronym and assigns six properties of a frugal product: functional, robust, user-friendly, growing, affordable and local [1].

Functional means mainly the concentration on the core functionalities. The frugal product works efficiently with as few components as possible and fulfils its main task [8]. Robustness is generally defined over the lifetime. A frugal product is robust if it has a long lifetime and is insensitive to influences such as extreme weather conditions, dirt, fluctuating power supply or improper handling [10,15,16]. Another property is user-friendliness, which is determined by the lack of qualifications/knowledge in emerging markets. A frugal product must be developed in such a way that it can be put into operation and used by a low-skilled worker [17]. Growing means the success of the product on the market and the design of the product for growing markets in order to increase profitability with increased turnover and profit [2,8]. In order to achieve a high sales volume, the frugal product must be affordable. Affordable means that frugal products are worthwhile, useful, efficient and cost-effective for the customer [1]. However, adaptation to local environmental, infrastructural or regulatory conditions is also crucial for success. The acronym frugal refers to adaptation to the market as local [18].

2.2. Definition of reliability and robustness

Reliability describes the performance of a product component or product system in a given time interval under specified conditions during or after an application, so that the product always remains usable during its specified or expected lifetime [19]. The reliability of technical components or systems is thus defined as the probability with which the system is in a functioning state at a certain point in time or during a time interval under defined boundary conditions [19]. Therefore, reliability has a direct time reference. Several manufactured products that have been correctly manufactured and assembled are all intact at the time of their first use, so the reliability is 100%. As the lifetime increases, the probability of failure increases and vice versa the product reliability decreases. Therefore, a reliability statement is only meaningful with a direct reference to time, i.e. at a certain point of its life cycle. In contrast to availability, reliability considers only the period prior to the first failure. If the product can be repaired and thus returned to a functional condition, a mere consideration of reliability is not representative. In order to describe the complete failure behavior of such products and therefore the availability of the product, not only the reliability but also the repair distribution must be known [19]. The repair distribution describes the probability with which the product can be repaired or completely replaced in a certain time interval [19]. Especially for manufacturing systems, an availability analysis is essential in order to avoid downtimes through smart maintenance concepts and thus increase productivity.

Reliability or availability thus describe the probability with which a product is intact at a certain point in time, but do not make any statements about the quality of functional performance in the period under consideration. This relationship makes it possible to distinguish reliability from robustness. The robustness of a product or a process describes the ability to perform a function with a consistently high quality even under the influence of disturbance parameters, i.e. the product does not react sensitively to the influence of disturbance [20]. From a statistical point of view, robustness is defined as the ability of a product or process to perform its function at the target level with minimal variance. If robustness is put in context with reliability, one can speak of robust and reliable products if the product does not fail during its required lifetime and always performs its function under the defined environmental and boundary conditions at the target level with minimal variance. Kemmler introduces the "robust reliability" theory as the probability that a product or process will maintain its required functionality with minimal variance during its entire lifetime despite all internal and external disturbances [21]. Figure 1 shows the relationships between robustness and reliability depending on lifetime.

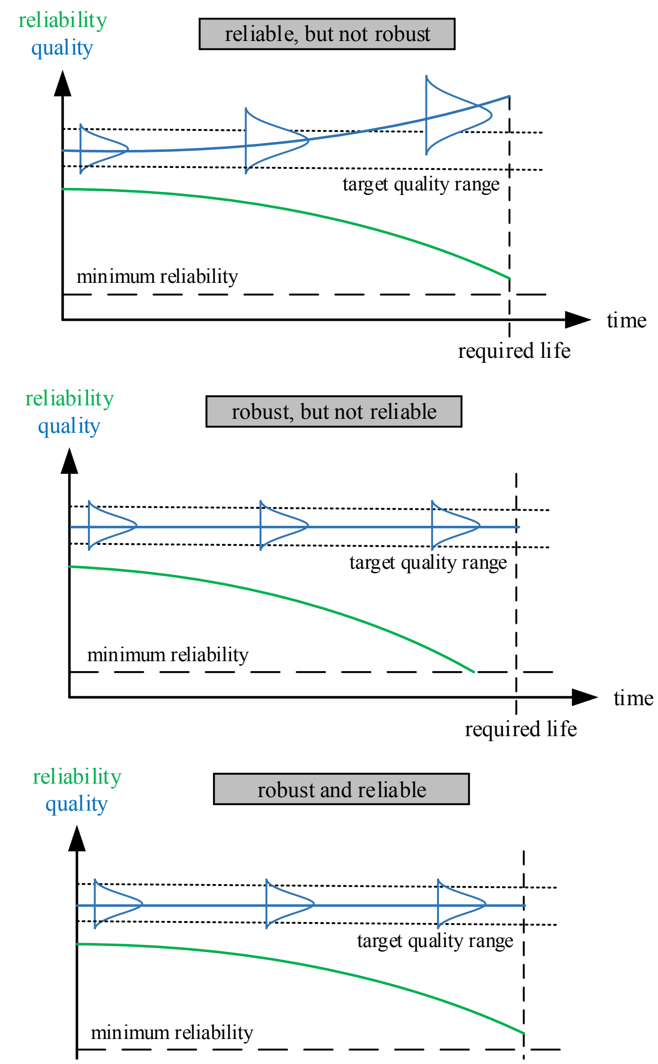

Fig. 1. The relationships between robustness and reliability.

2.3. Context and objectives

Aim of this paper is a framework to develop reliable and robust manufacturing systems in a frugal context. This means to meet the demands of low costs, high quality and high availability at the same time. In order to reduce the investment costs of fms, the focus must be on the essential core functions and locally available service components. This causes development costs, which should be as low as possible and, therefore, are the central conflict in the development of this framework. Ensuring reliability and robustness usually requires cost-intensive tests in order to determine the relationship between lifetime and reliability or the effect of disturbance variables on quality. Tests in the development process are mostly based on cost-intensive prototypes, which increase the total costs for development. For this reason, alternative methods must be used to offer a possibility for a fundamental assurance of reliability and robustness with a low development budget. Since no completely new machine can be developed with a low development budget, this framework is derived from an already existing manufacturing system. Accordingly, a frugal system structure is to be derived from an already existing system structure.

3. Reliability and robustness framework for frugal manufacturing systems

The framework for reliability and robustness for frugal manufacturing systems is divided into four phases, see Figure 2. The first phase comprises the analysis of the local conditions and provides the basis for the following steps. In the second phase, the functions and the structure of the already existing system are analyzed. In the third phase the system structure is optimized regarding its reliability. The fourth phase concentrates on the process structure which is analyzed and evaluated regarding robustness and thus the achievement of target values.

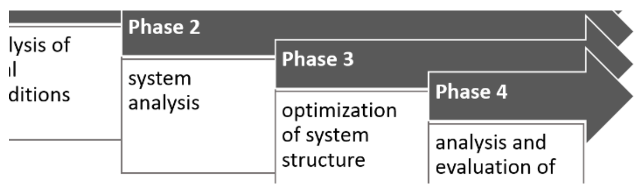

Fig. 2. Overview of the framework for reliability and robustness for frugal manufacturing systems.

3.1. Phase 1 - Analysis of local conditions

First of all, a consistent understanding of frugal, reliability and robustness and its context is essential for the approach, which was established in Chapter 3. From this, the necessity of target values (quality, performance and variance) can be derived, which will be considered in phase two and three. Therefore, customer demands and expectations must be identified, since they are the factors for success of frugal products [22,23,24]. Consequently, the focus of product innovation needs to be put on the customer. Furthermore, the degree of his or her appraisal of functionality needs to be accounted for.

For the analysis and optimization of reliability, the identification of possible disturbance variables is also relevant. There is a different understanding of disturbances in the literature. According to Stricker and Lanza, a disturbance consists of a cause and an effect, they occur unintended or unplanned, unexpectedly and unpredictably or with an unknown time of occurrence. As a result, various disturbances can occur in a production system, such as equipment malfunctions, lack of staff, incorrect operation, etc. [25].

In the context of fms further disturbances of the system environment have to be considered. Some standards, such as DIN EN 60721-1, deal with the classification of environmental influences and are intended for electrical engineering products [26]. Various environmental influences and the associated environmental influencing variables are recorded here. The influences resulting from the following local environmental conditions are considered here:

- air as the surrounding medium,
- water as surrounding medium,

- construction to which the product is connected,
- other external influences [26].

The fms must be able to maintain the previously defined target values despite possible disturbances and environmental influences, or it needs to be restorable with minimal effort. For this purpose, the system should change into modified states during the various disturbances, which is referred to as adaptability. The necessary reaction time divides the kinds of adaptability: operational, tactical and strategic. [27] The approach in this paper deals in particular with known disturbances in the system environment and the strategic response capability by considering them in product planning and development. The most important aspects in phase 1 are:

- identification and definition of target values (quality, performance and dispersion)
- record customer satisfaction (value of the functionality)
- determination of relevant disturbance variables in the local target market

3.2. Phase 2 – System analysis

The approach in this paper is based on the assumption that a similar or predecessor product exists, which is first analyzed regarding its components and functions. Hereby, the core functions [6,28] and the help functions that enable them are of high importance. Secondary functions play only a subordinate role, because otherwise the fulfilment of the substantial cost reduction may not be achieved.

The existing product is, therefore, analyzed with regard to its functions and components. This analysis is divided into four steps:

- collect: all components (consideration of the abstraction level, if necessary, on assembly level)
- structure: here, the assignment of core / main functions, auxiliary functions and auxiliary functions takes place
- create system structure: present mutual assignments and connections of the functions, but do not create their realization in the real object
- create coordination matrix: so that the relation between functions and real object becomes apparent.

3.3. Phase 3 - Optimization of the system structure regarding reliability

The basic objective of this step is to adapt the system structure in such a way that a low-cost, technologically simple machine is developed which is just as reliable as a high-end machine. In order to achieve this goal, complexity has to be reduced, either by completely removing components or by using simpler components to perform the function. In this context, "simple" can be understood as a technologically simpler and, therefore, more cost-efficient solution. This could be, for example replacing a high-strength aluminum alloy with a simple structural steel. If complex components are now replaced by simpler components, it can be assumed, that there will be a reduction in reliability and thus in the availability, which is the price to be paid for complexity reduction. In order to compensate reduction in availability, the next step may be to make the components as easy to maintain and repair as possible. Thus, effective and efficient repair or maintenance activities increase availability by minimizing downtime. In this context, easy maintenance or repair is understood as the possibility that components can be maintained, repaired or replaced quickly and easily without advanced expertise. The basic prerequisites to achieve easy maintainability are easy access to the relevant components and adapting the necessary know-how for servicing or maintenance to the respective target market. Also the use of locally available technologies, tools and materials and the availability of spare parts must be guaranteed. Fig. 3 shows the procedure for the optimization of the system structure regarding reliability.

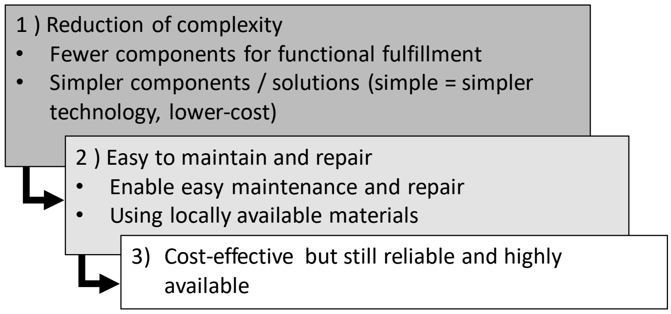

Fig. 3. Stages of frugal and reliable optimization.

In the first step of optimization, all components that contribute to the core function are evaluated regarding their complexity. A simple subdivision into the categories "high complexity" and "low complexity" seems appropriate in order to not unnecessarily complicate the already qualitative method. Before the actual implementation of the complexity reduction, it is important to identify optimization potential that is as risk neutral as possible. For this purpose, those "highly complex" components, whose influence on the quality of the functional execution are least significant are identified in a pairwise comparison. This approach ensures that components which do not or only slightly affect the quality of the manufacturing system are optimized first. This decouples robustness from reliability in a targeted manner, so that optimization steps initially only affect reliability and do not unwillingly influence robustness as well. Once the optimization potential with the lowest risk has been identified, alternatives that are functionally simpler, can be developed. The new system structure results in a new classification of the components regarding their complexity, see Figure 4.

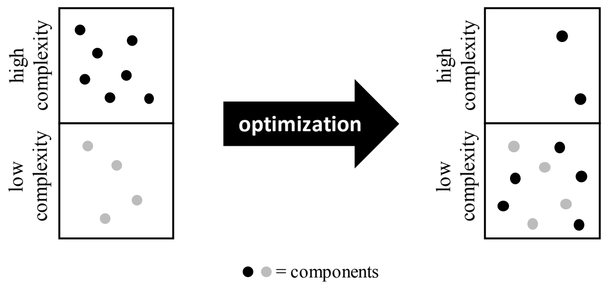

Fig. 4. Reduction of complexity.

It can be assumed that some complex structures will always be preserved, since replacing all complex components by simpler ones will hardly ever be feasible. Therefore, the optimization passes into the second step. Simpler and more cost-efficient components often lead to a lower reliability, which inevitably results in lower availability. Since the reliability itself can only be quantified by costly life tests, quantification is deliberately omitted by only considering vague relations. In order to compensate the lower reliability and maintain availability, intelligent maintenance concepts have to be developed that enable the simple components to be repaired or replaced quickly and easily. In this case, also components, that are not easily maintainable, will remain, see Figure 5. This conflict of objectives results in the following design strategy:

- Area I: durable design
- Area II: durable design
- Area III: enable maintenance
- Area IV: Enable maintenance if cost-effective, otherwise durable

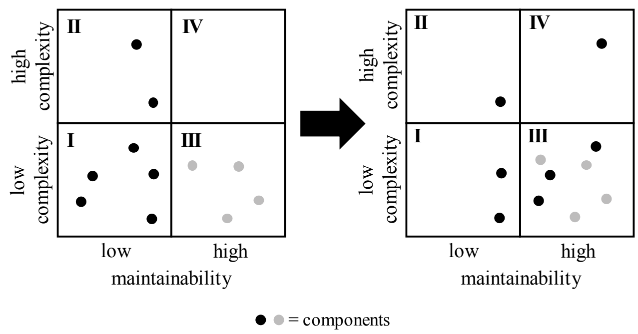

Fig. 5. Optimization of maintainability.

Finally, an availability comparison between the initial structure and the newly developed frugal system structure can be carried out using petri net simulation [29]. However, this requires estimates of the reliability distribution and the repair behavior of all components.

Besides the necessary functions for the machine additional auxiliary functions can increase the customer satisfaction. From the viewpoint of reliability and affordability, auxiliary functions should be regarded carefully. It does not mean to abandon all of them, but to choose those which fulfill the frugal approach and could be integrated as “furnish up” functions.

3.4. Phase 4 - Analysis and evaluation of process structure

To ensure the robustness of the machine, the effect of the control and disturbance parameters on the target variables and respectively the quality must be quantified. If these effects are known, the control parameters can be set to where the influence of the disturbance parameters on the target variable becomes minimal. A further objective in the robustness phase is to check whether the quality objectives of the system structure developed in phase 3.3 can still be achieved. If the quality is not achieved, the system structure must be adapted in an iterative process.

For an analysis of robustness all parameters are classified in the first step, for which the representation or classification in a p-diagram according to Taguchi has proven to be useful, see Figure 6 [30].

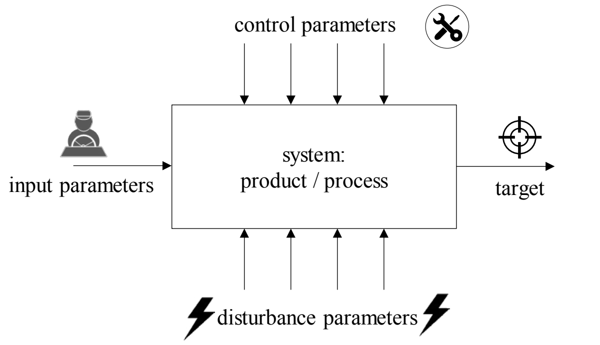

Fig. 6. Classification of parameters using the p-diagram.

The effects of the parameters on the target variable can only be determined by Design of Experiments (DoE), whereby real experiments or simulations can be used, since simple estimations are not sufficient in this phase. Although some experts are very well able to estimate influences on the mean value, the influence of variance is often difficult to capture physically and, therefore cannot be described, which is why empirical data is essential. For the planning and execution of real tests, with which statistically reliable results can be easily determined, the Taguchi test plans are suitable. [30]. With increasing computing capacities, Robust Design Optimization or Design for Six Sigma has been further established, in which the effects are calculated with simulation models in combination with special test plans for deterministic simulation models [31].

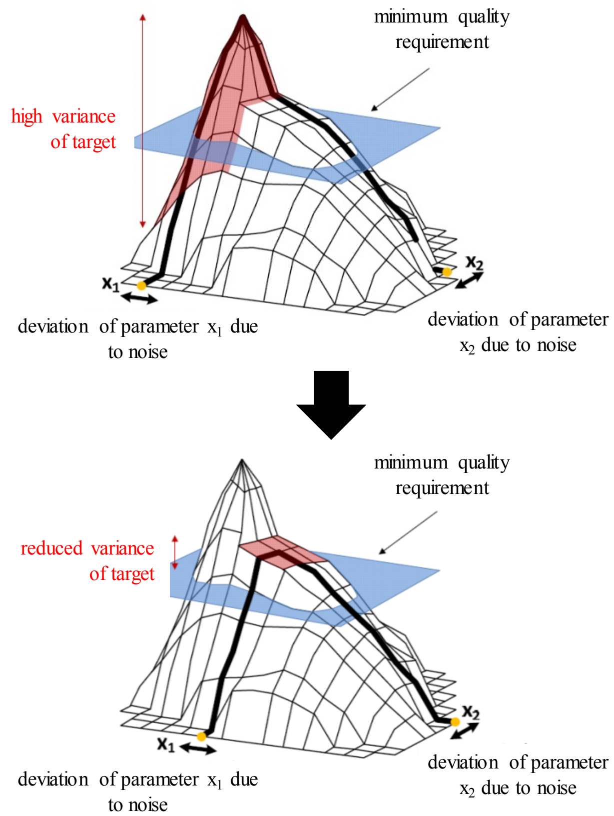

Fig. 7. Identification of a robust optimum.

The results are setting levels for all control or process parameters that result in a minimum scatter of the target variable even under the influence of the disturbances, see Figure 7.

4. Conclusion and outlook

The framework shown in this paper can be used to derive frugal manufacturing systems for emerging markets from existing high-end solutions. The four-level framework structure guarantees a systematic approach and requires only minimal financial expenditure for the development of frugal manufacturing systems. Nevertheless, the demands for robustness and reliability are taken into account in order to guarantee high-quality products. The main focus is the two-stage optimization of the system structure from a perspective to reduce complexity and maintenance effort. The loss in reliability due to the use of simpler components is offset by the integration of simple maintenance and results in a cost-efficient machine with similar availability to the high-end solution.

The developed framework is now to be validated on a packaging machine. Therefore an industrial partner could be won for the validation of the framework, specifically a module of a packaging machine.

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