Design for availability : creating value for manufacturers and customers

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Abstract

This research introduces a newly developed continuous improvement methodology called Design for Availability that uses principles of Lean Sigma and Design for X to cost-effectively optimize the availability of capital goods, i.e. systems used in the production of other end-products or -services, throughout their entire lifetime. The absence of such a methodology in the literature is remarkable because many users of capital goods increasingly insist on high system availability levels against lower lifetime costs. Against this background this study develops an analytical framework that allows manufacturers to determine the current status of system availability and associated lifetime costs, and to identify opportunities to create additional value for both the manufacturer and its customers. The applicability of this Design for Availability framework is tested through a case study at a global manufacturer of capital goods in the food processing industry. The results show that applying the Design for Availability framework can provide substantial benefits for the manufacturer as well as its customers, as long as a number of critical key success factors are taken into account during implementation, such as organizational commitment to Design for Availability, good leadership and communication, and creating system availability and lifecycle awareness.

Keywords: Continuous improvement, Design for X, system availability, lifecycle costs

1. Introduction

To meet the ever-increasing requirements of customers, manufacturers of capital goods, i.e. systems used in the production of other end-products or -services, have adopted continuous improvement methods such as “Lean Production” and “Six Sigma” (Bhuiyan and Baghel, 2005). Lean Production, often entitled simply as "Lean", is a procedure of which the main objective is to eliminate waste in core business processes by concurrently reducing supplier, customer, and internal variability (Shah and Ward, 2007). Six Sigma seeks to improve the quality of process outputs through the reduction of defects and variability in core business processes, and is based on statistical methods (Bhuiyan and Baghel, 2005). Recently, Lean and Six Sigma have been integrated to create Lean Sigma which simultaneously exploits the benefits of Lean Production and Six Sigma principles (Arnheiter and Maleyeff, 2005). For manufacturers of capital goods to execute Lean Sigma, Huang (1996) suggests the implementation of Design for X practices to cost-effectively improve a system. The “X” stands for system characteristics such as manufacturability, maintainability, reliability, and supportability. These characteristics relate to business processes occurring throughout the system’s lifetime (i.e., the system’s design, production, sales, maintenance, and use), and should be addressed early in the system’s development (Smith and Knezevic, 1996). Usually, one Design for X practice is applied at a time and it seems difficult to choose an appropriate practice for the problem at hand (Huang, 1996).

Nowadays, many users of capital goods insist on increasing system availability against minimized costs (Kumar et al., 2000), in which availability is defined as the time that a system is available for use in relation to the total time that the system is required to be in operation (e.g., Birolini, 2003; Blanchard et al., 1995; Thompson, 1999). This means that the manufacturer should not only focus on its own core business processes, but should also deal with those processes that occur when the system is in use. Therefore, this research introduces Design for Availability that uses the principles of Lean Sigma and Design for X to cost-effectively optimize the availability of capital goods throughout their entire lifetime. In search of this optimization, Design for Availability, as Lean Sigma, minimizes variability and reduces defects in the manufacturer's core processes, and eliminates any activity that does not add value to the end-user (Arnheiter and Maleyeff, 2005; Bhuiyan and Baghel, 2005; Naslund, 2008). However, Design for Availability differs from Lean Sigma in that it does not merely create customer value by producing low cost standardized systems, but also by connecting the manufacturer and its network to aim for better service throughout the entire lifetime of a sold system (Stabell and Fjeldstad, 1998). Lean Sigma implements only those Design for X practices that address the manufacturer's core business processes, whereas Design for Availability combines many, if not all, Design for X practices to create value to the customer.

Against this background the objective of this research is to introduce Design for Availability as a new continuous improvement methodology. We achieve this objective by presenting a framework that manufacturers, together with their customers, can apply to obtain capital goods with a high level of availability against lowered lifetime costs (Section 2). The applicability of this framework is tested through a case study at a global manufacturer of high value capital goods in the food processing industry (Section 3). Before concluding, we also outline the success factors for applying the Design for Availability framework (Section 4).

2. Design for Availability Framework

Design for Availability is a continuous improvement methodology that allows manufacturers and their customers to cost-effectively produce and use capital goods that meet high system availability requirements. A crucial step in the implementation of Design for Availability is the analysis of the current status of system availability and its lifetime associated cost. To this end we have developed an analytical Design for Availability framework that will be described below.

2.1. System Availability Analysis

Availability is the measure of the degree to which a system is in an operational and committable state when a production run is called for at a random moment in time (Blanchard et al., 1995). Availability can be expressed by the following equation (Smith and Knezevic, 1996):

$$A = \frac{MTTF}{MTTF + MTTS + MTTR} \qquad (1)$$

where MTTF, MTTS and MTTR represent the Mean-Time-To-Failure, Mean-Time-To-Repair and Mean-Time-To-Support respectively. MTTF is defined as the average life of a non-repairable system or the average time before the first failure of a repairable system occurs (Kumar et al., 2000). MTTS covers the period from a failure report until the start of a reactive (corrective) maintenance action, performed to restore the functionality of a system after the loss of system performance or after system failure (Kumar et al., 2000). MTTR is the time it takes to bring the system back to its satisfactory working condition (Thompson, 1999).

To help manufacturers, in conjunction with their customers, to constantly improve the availability of their product systems we outlined system availability principles by conducting an extensive review of the literature on MTTF, MTTS and MTTR. The outline, shown in Figure 1, not only distinguishes MTTF, MTTS, and MTTR, but additionally shows that system availability is dependent on the manufacturer's design and development activities, categorized under “Design”, as well as on its after-sales activities when the system is already operational at the customer, categorized under “Operations”. The availability principles will be explained in more detail hereafter.

<< Insert Figure 1 about here >>

2.1.1. Mean-Time-to-Failure

MTTF refers to the ability of a system to remain functional under given operating conditions and can be improved by increasing: (1) system reliability (e.g., Birolini, 2003; Huang, 1996; Kumar et al., 2000; Thompson, 1999) and through; (2) reliability-centered maintenance (e.g., Arts et al., 1998; Blanchard et al., 1995; Negri and Galli, 1997; Oyebisi, 2000).

(1) System Reliability

System reliability is a design parameter indicating the ability of a system to remain functional for a specified time under given operating conditions (Kumar et al., 2000) and requires the fulfillment of so-called simplicity-clarity-unity requirements (Huang, 1996). Simplicity implies that the number of parts in a system should be minimized given the system’s performance requirements. Although system simplicity automatically decreases if performance requirements increase, the simplest system design should always be obtained. If the simplicity requirement is not fulfilled, system reliability will be reduced. Next, clarity encourages the lack of system ambiguity as a system should carry out a single, clear-cut action, facilitating the prediction of system reliability. Finally, unity denotes that each part of the system should equally contribute to system accuracy, preventing the system to have a weak link, and contributing to system reliability. The fulfillment of simplicity-clarity-unity requirements prevents the system from failing, increasing its MTTF. Apart from system simplicity-clarity-unity, system reliability also requires a critical and analytical consideration of the conditions under which the system will operate (Oyebisi, 2000). To this end, designers need to test newly developed systems in their operating environment, preferably at the customer's site, by applying failure identification methods such as Failure Mode, Effect and Criticality Analyses (FMECA) and Fault Tree Analysis (FTA) to maximize reliability. FMECA is a methodology to examine how system failures can occur and what the effects are of these failures on system performance and safety (Blanchard et al., 1995). FTA is a top-down procedure in which the undesired event, i.e. a critical system failure, is represented in a causes-to-effects chart, showing logical relationships between causes and their single or multiple consequences (Birolini, 2003). Applying failure identification methods will give designers the opportunity to remove the cause of system failures, increasing its MTTF.

(2) Reliability-Centered Maintenance

Reliability-centered maintenance is a systematic approach for selecting and employing applicable and effective maintenance activities for a system taking failure consequences into account. Applicable implies that if the maintenance task is executed, it will either realize the prevention or cutback of a failure, or the detection of a hidden failure (Kumar et al., 2000), increasing the MTTF of a system. To attain maintenance task effectiveness it is important to monitor the maintenance actions that are performed and, if necessary, remove deficiencies. Reliability-centered maintenance considers proactive (preventive) maintenance only (Blanchard et al., 1995). Proactive maintenance actions are designed to minimize the risk of system failures. They are planned, scheduled and executed before a breakdown occurs, and contribute to better system performance.

2.1.2. Mean-Time-To-Support

MTTS is closely related to system downtime at the customer caused by the loss of system performance or failure. Reactive maintenance, and thus MTTS, can be optimized by improving: (1) the fault discovery process (e.g., Blanchard et al., 1995; Kumar et al., 2000; Oyebisi, 2000); (2) the commercial and technical service (e.g., Blanchard et al., 1995), and: (3) the availability and geography of field service engineers, tools, and spares and repairs (e.g., Birolini, 2003; Smith and Knezevic, 1996; Thompson, 1999).

(1) Fault Discovery Process

The fault discovery process refers to the procedure through which the cause of a system failure is quickly identified, which reduces MTTS. Failures must be traced back to the initial "symptom" at the system level (Blanchard et al., 1995). This tracing process can be facilitated by means of FMECA and FTA, condition monitoring, labeling system parts, and minimizing the number of parts. As before, FMECA and FTA are both failure identification methods, providing information about the cause and effects of system failures. Condition monitoring, on the other hand, is a device to (remotely) inspect or examine a system in order to provide data and information about its condition at any instance of operating time (Kumar et al., 2000). The purpose of labeling parts is to easily identify and register which part of the system has failed. Finally, minimizing the number of parts in a system refers to system simplicity, one of the three main reliability requirements. A complex system makes failure identification hard and delays customer support.

(2) Commercial and Technical Service

To allow for effective commercial and technical service it is necessary to document the details about the system's failure and make this information available to all concerned and involved (Blanchard et al., 1995). Thus, accelerating the fault discovery process by gathering information about the system's failure is one aspect that allows for more timely customer support. Such information needs to be documented to ensure even more effective customer support in the future. Besides details about the cause and effects of failures, information about the customer (e.g., name, address, etc.), the usage situation (e.g., human behavior, environment, etc.), and the relevant reactive maintenance action (e.g., tools, spares/repairs, etc.) should be systematically documented and analyzed. This sequence of activities facilitates the accumulation of knowledge essential to satisfactorily support customers. As a final aspect, process management will allow for improved customer support. Registering details about the customer support process itself (e.g., task descriptions, people/departments involved, etc.) facilitates the fine-tuning of the process, to pass on customer support related tasks, and to gear the customer support process with other business processes.

(3) Availability and Geography

Finally, it is necessary for the manufacturer to have sufficient field service engineers available, at the right location, with the right knowledge, tools and spare/repair parts to provide customer service and support in such a way that system downtime is minimized (Smith and Knezevic, 1996). The manufacturer is advised to set up a basic logistic support strategy including models for the distribution of spare/repair parts, field service engineers, and tools, taking into account service levels, fill rates, expected demand, and priorities (Birolini, 2003).

2.1.3. Mean-Time-To-Repair

MTTR indicates the ability of a system to be maintained, retained or restored and is dependent on (1) the ease of system disassembly (e.g., Birolini, 2003; Blanchard, 1995; Huang, 1996; Kumar et al., 2000; Thompson, 1999), (2) the management of maintenance actions (e.g., Birolini, 2003; Blanchard, 1995; Thompson, 1999), and (3) the composition of spare/repair packages (e.g., Birolini, 2003; Blanchard et al., 1995; Kumar et al., 2000; Smith and Knezevic, 1996).

(1) Disassembly

The difficulty and duration of maintenance actions is to a large extent determined by the complexity of the system. A system built with a lot of electronics and non-standard parts that are hard to reach is more difficult to disassemble and repair than a system with standard parts, tools and fasteners. Providing systems with advanced electronics makes it possible to better control the system and to evade inaccuracies of human actions. However, it also increases system complexity and impedes the efficiency of maintenance actions. In addition, the number of parts in a system, especially when non-standard, increases system complexity. Minimizing the number of (non-standard) parts in a system allows field service engineers to get easily familiar with maintenance procedures and to reduce MTTR. Finally, system complexity can be reduced through modularization, a method that specifies decoupled interfaces between system parts through one-to-one mapping from functional elements in the system to system parts (Ulrich, 1995).

(2) Maintenance Actions

Initially, the management of maintenance actions is an activity that is carried out in the design phase of a system. Designing simple systems, as well as developing maintenance training and detailed manuals can improve MTTR. Aside from the expertise that field service engineers have developed from accumulated maintenance experience, training will refine the maintenance skills that are necessary to perform efficient maintenance actions. In case the maintenance actions are carried out by the customer, such skills can be provided through similar maintenance training and detailed usage instructions.

On the other hand, the management of maintenance actions is achieved when the system is already in use at the customer. Decisions about whether to replace or to repair a broken part, and whether to repair on site or of site, can influence the MTTR (Birolini, 2003). Besides, monitoring maintenance actions and, if necessary, dealing with deficiencies increases maintenance effectiveness and MTTR.

(3) Spare/Repair Packages

Providing customers with spare/repair packages containing the right and sufficient number of parts is crucial for a system to be repaired immediately after failure. Yet, it is unnecessary to provide the customer with too many spare/repair parts resulting in redundant inventory costs (Smith and Knezevic, 1996). Failure identification methods, such as FMECA and FTA, can facilitate the accurate composition of spare/repair packages since the time, causes, and effects of failures will be revealed. Still, defining the appropriate spare/repair parts can be difficult because customers can easily modify the system, whether or not with parts from the original manufacturer. Keeping up with such modifications in the formulation of spare/repair packages is therefore required to optimize MTTR.

2.2. Life Cycle Cost Analysis

The ability of a manufacturer to effectively compete on system availability is also determined by the system's associated lifetime cost (Asiedu and Gu, 1998). Kumar et al. (2000) propose two important measures to assess a system's cost effectiveness, namely Total Cost of Ownership (TCO) and Life Cycle Cost (LCC). TCO includes the lifetime cost related to the acquisition and use of one particular system and are borne by the customer (Kumar et al., 2000). LCC, however, focuses on system lifetime cost borne by both the manufacturer and customer (Blanchard et al., 1995). Therefore, LCC seems most appropriate to use in conjunction with Design for Availability because it focuses on customer processes as well as on processes internal to the manufacturer that affect system availability.

System LCC can be broken down into four main categories (Kumar et al., 2000), as shown in Figure 2, namely the design and development costs (D); the production and assembly costs (P); the operation, service and maintenance costs (M); and the removal and disposal costs of the system (R). The design and development costs include the costs related to research and development, related management functions, engineering design, development and tests, and design documentation (Blanchard et al., 1995; Kumar et al., 2000). The production and assembly costs comprise manufacturing and assembly, facility construction, and initial logistic support costs (Blanchard et al., 1995; Fabrycky and Blanchard, 1991). The operation, service, and maintenance costs contain customer operations of the system in the field, keeping the system up to an acceptable standard through service and maintenance, and sustaining maintenance and logistic support throughout the system life cycle (Blanchard et al., 1995; Fabrycky and Blanchard, 1991; Kumar et al., 2000). Finally, the removal and disposal costs of the system are the estimated value of a system at the end of its expected life, including demolishing cost, recycling or reusing cost, and salvation value (Kumar et al., 2000).

<< Insert Figure 2 about here >>

The design and development costs as well as the production and assembly costs are usually borne by the manufacturer. However recently, the customer is more often involved in the design and development of systems as a result of which the customer might also bear part of the design and development costs. The operation, service, and maintenance costs are mostly borne by the customer unless the manufacturer offers full service contracts. The costs related to the removal or disposal of product systems is generally borne by the customer. Except for the costs related to the removal of the system, LCC is dependent on the system availability requirements set by the customer (A_0):

$$LCC(A_0) = D(A_0) + P(A_0) + M(A_0) + R \qquad (2)$$

The relationship between LCC and system availability is complex because changes in system availability can increase certain LCC components and lower others. Moreover, certain LCC components are dependent on the system's cumulative production volume

(CPV) in that the costs can be spread out over more units while others are not. Figure 3 summarizes the association between the main principles of system availability and its LCC.

<< Insert Figure 3 about here >>

To illustrate how certain LCC components respond to changing system availability, the following examples should be considered:

(1) Design and development costs

Improving MTTF through the fulfillment of simplicity-clarity-unity requirements (reliability) in the design of a new system is likely to increase the design and development costs. However, these costs can be spread out over the number of units sold of that new system. Making up the right amount of suitable spare/repair packages decreases MTTR and also MTTS through the availability of spare/repair packages, however, might raise the design and development costs per system batch because designers need to consider the composition of such packages.

(2) Production and assembly costs

Improving MTTF, MTTS, and MTTR through the minimization of the number of system parts will reduce the production and assembly costs per system since fewer parts and spare/repair parts have to be produced. Optimizing MTTF and MTTS through the incorporation of condition monitoring, however, will increase system complexity which negatively impacts MTTR and the production and assembly costs per system. In conclusion, changes in MTTF, MTTS, and MTTR can either decrease or increase the production and assembly costs.

(3) Operations, service and maintenance costs

Improving MTTF through reliability-centered maintenance will reduce the downtime of a system, and thus its operation, service and maintenance costs. Compounding sufficient and suitable spare/repair packages will, as already mentioned, positively influence a system's MTTS and MTTR (downtime), and as a result decrease its operation, service and maintenance costs. However, Figure 3 also shows that the service and maintenance costs might increase. For instance, as a result of employing field service engineers so that all customers over the world get serviced within a certain time span (minimizing MTTS), many service engineers might be waiting longer than working. However, all field service engineers will be waiting to get paid, increasing the service and maintenance costs. Moreover, this increase in service and maintenance costs is dependent on the CPV of a system in that the costs can be spread out over more units.

These examples show that the relationship between LCC and system availability is far from straightforward.

3. The Case Study

Case studies are argued to be very valuable at all stages of the theory-building process, but especially at the stage at which theories are tested (Flyvbjerg, 2006). This study tests the application of the analytical framework of Design for Availability through a single case study at a global manufacturer of capital goods in the food processing industry, fictitiously called Food Delight & Co (FD&Co). This manufacturer is chosen because the customers of FD&Co have increasingly high system availability requirements. First, they emphasize after sales support which means that FD&Co needs to control the availability level of their systems during their lifetime. Second, fixed-price service agreements and guarantees on system lifetime costs and performance in contracts have become the standard which means that the service and maintenance costs will increasingly be borne by FD&Co. Finally, due to concentration tendencies, the bargaining power of its customers has increased which raises system performance requirements. Given these developments it is not surprising that the management team of FD&Co is interested in determining the status of system availability (Section 3.2.) and lifetime costs in order to identify opportunities for improvement (Section 3.3.).

3.1. Data Collection and Analysis

Data to determine the current status of system availability at FD&Co were collected via eleven open ended person-to-person interviews (see the Appendix) with employees involved in all phases of the system's lifecycle (e.g., design, production & assembly, and service). Interviews were conducted over a period of four months with each interview taking about one hour. The intention was to discover the respondent's familiarity and experience with system availability, and specifically focused on gaining understanding about which principles of system availability, outlined in Figure 1, are applied at FD&Co and which ones not. The interviews were transcribed and the respondents were given the opportunity to validate the transcripts.

Methods triangulation was used to look at the consistency of findings arising from several different data collection methods (Yin, 2003). For example, the company's web site was visited to search for information about FD&Co's customer support process. Technical drawings, the program of requirements, and company standards were accessed to certify information about system designs (e.g., reliability, assembly, spare/repair packages, etc.). Company specific software and databases, such as SAP and product lifecycle management software, contributed to the validation of the customer support and maintenance process. If ambiguities remained, source triangulation was used through additional interviews with employees until no dubiety was left (Yin, 2003).

3.2. System Availability Analysis at FD&Co

A thorough analysis of the information obtained from the interviews and other data sources revealed which principles of system availability FD&Co applies in order to satisfy customers' system performance requirements. The results are discussed below and illustrated in Figure 4, with the implemented principles printed in **bold**.

<< Insert Figure 4 about here >>

3.2.1. MTTF

The findings show that FD&Co has well developed reliability-centered maintenance by drawing up system specific maintenance schedules. Moreover, the company supplements reliability-centered maintenance with continuous system modifications to improve system performance. To put a finishing touch on reliability-centered maintenance, FD&Co should observe maintenance actions in order to identify deficiencies and improve the effectiveness of maintenance actions. On the other hand, the results reveal that system reliability can be improved. For instance, FD&Co does not track any failure rates and the designers do not specifically focus on simplicity-clarity-unity requirements. Consequently, failure identification becomes impracticable even though FD&Co has appropriate software at its disposal to apply FMECA and FTA.

3.2.2. MTTS

The results reveal that FD&Co has a well developed customer support process. The company records details about the entire support and maintenance process which prevents the loss of important information. If FD&Co would gather, analyze and use information about the customer and system failures, and make this information easy accessible to all employees, the customer support process would even be better. Additionally, the availability and geography of field service engineers, tools, and spare/repair parts is well managed. By means of five service areas and sufficient offices, the company attempts to support its customers as quickly as possible taking into account geographical dispersion. Nonetheless, FD&Co could perform better if it would have more field service engineers available, especially because customers put increasingly high value on after sales service. Also fault discovery methods are still weakly developed at FD&Co. Only few of its systems are equipped with condition-monitoring techniques, the company does not apply any failure identification methods, designers do not focus on simplicity requirements, and FD&Co does not structurally label all of its parts for identification.

3.2.3. MTTR

The results further show that FD&Co has formulated design requirements in which main system repair times are stipulated. Because repair times increase with system complexity, designers consider the ease of maintaining systems throughout their development. Also, the company is aware that well-trained field service engineers deliver added value to FD&Co as well as to the customers. Customers are increasingly conscious of the contribution of skilled personnel and are willing to pay for maintenance training provided by FD&Co even though they are well-informed through complete manuals. This increasing popularity of training leads to new feedback to trainees which in turn leads to improved training. Finally, FD&Co has thoroughly examined whether to replace or to repair a certain broken part, and whether to repair on site or in a general repair station. On the downside, it was found that throughout the design and development of a system, the ease of disassembling the system is of less importance to the designers of FD&Co. Designers do not focus on system simplicity requirements, modularization, standardization of parts, and the minimization of disassembly tools. Additionally, due to the absence of failure identification methods, the company cannot optimally compose spare/repair packages and customers might have too many or too little spare/repair parts on stock.

3.3. LCC Analysis: Improving System Availability against Reduced LCC

According to FD&Co customers in the food processing industry demand 99.9 percent system availability. Supplementing the principles of system availability that are implemented by FD&Co with those that are not provides the company with opportunities to decrease system LCC at the 99.9 percent level of system availability. A paired comparison procedure with managers from FD&Co was conducted to identify which non-applied system availability principles would accomplish the largest reduction in LCC. This procedure yielded three key improvement opportunities: (1) the application of condition monitoring techniques, (2) tracking failure rates, and (3) improving maintenance management.

(1) Applying Condition Monitoring Techniques

Utilizing condition monitoring techniques will improve the fault discovery process at FD&Co, reducing the MTTS of systems. Additionally, the manufacturer can use condition monitoring tools as testing device, to collect failure rates, or to predict and avoid upcoming failures (condition-based maintenance), all increasing system reliability and thus MTTF. Although the application of condition monitoring techniques increases the cost related to engineering design (fitting condition monitoring to systems) and manufacturing (system complexity), LCC will decrease through a significant reduction of downtime costs caused by improved MTTF and MTTS. As FD&Co already utilizes condition monitoring techniques on a limited number of systems, the company is familiar with their implementation and should not yet worry about obtaining new software.

(2) Tracking System Failure Rates

Tracking system failure rates has several benefits. First, FMECA and FTA become a lot more feasible because failure rates are required as input parameters for such analyses. These analyses contribute to the fault discovery process of the manufacturer and give designers the opportunity to better execute reliability requirements, both leading to a significant reduction in downtime costs and thus LCC of FD&Co's systems. Second, the formulation of preventive maintenance schemes is facilitated through the availability of system failure rates. Without having details about failure rates, the preventive maintenance schemes at FD&Co can comprise too many or too little preventive maintenance actions. Lowering the amount of preventive maintenance actions and eliminating redundant spare/repair parts at the customer's site will reduce its systems' LCC. Expanding the amount of preventive maintenance actions (mostly cheaper than corrective maintenance) and spare/repair packages will severely reduce downtime situations at FD&Co's customers through increased MTTF and reduced MTTR. Besides, preventive maintenance can be done in the hours that the system is not operating.

The costs related to tracking failure rates are limited. The only costs that FD&Co bears are the cost related to collecting historical system failure data or the acquirement of an external failure rate database (design and development costs) which are once-only and can be spread out over the expected sales of more than one system type.

(3) Improving Maintenance Management

Carrying out maintenance actions as prescribed is necessary to attain the customer required availability level. The profitability of FD&Co's customers decreases over time if system availability degrades because of bad maintenance. Supervising maintenance actions, selling service contracts, sending trained field service engineers or providing training sessions to customers will help FD&Co to achieve high-quality maintenance. Although costs emerge because of additional field service engineers or the development and provision of training, LCC will reduce through a significant reduction of system downtime at the manufacturer's customers. Applying tools that show what the price of poor maintenance is, which are already available at FD&Co, can help the manufacturer to persuade its customers of the added-value of service contracts and training.

4. Success Factors in Using the Framework

The case study has tested the application of the Design for Availability framework and shows that the framework is a useful tool for manufacturers to identify opportunities for improvement after determining the current status of system availability and its lifetime costs. However, inwardly focused cultures, a limited degree of trust, lack of teamwork, and a lack of leadership at the manufacturer could hinder the successful use of the framework (Kotter, 1996). For that reason, we conclude this study by recommending manufacturers to take into account the following key success factors necessary to overcome previous mentioned barriers.

4.1. Vision and Strategy

Creating a vision and strategy is essential to trigger the use of the Design for Availability framework (Kotter, 1996). This starts with top management commitment to Design for Availability. Usage of the framework requires that it is implemented with a systematic, holistic understanding of the organization (Naslund, 2008). Tasks related to the use of Design for Availability should be integrated into the regular work of individual employees (Bhuiyan and Baghel, 2005). Besides, the corporate culture must emphasize the importance of customer satisfaction without jeopardizing the company's competitive advantage, and support improvement efforts with regard to system availability (Jha et al., 1996).

4.2. Good leadership

Another prerequisite for using the framework is the mutual commitment of employees to the organization's aims and objectives with regard to system availability and or lifecycle cost. The management team should clearly define and communicate the aims and benefits of using the framework and create a thorough understanding of system availability (Irani and Sharp, 1997). Good leadership also entails the articulation of the connections between the application of the framework and organizational success, and rewarding the employees who made the wins possible (Kotter, 1996).

4.3. Communication

To determine opportunities for improvement in system availability it is especially important to create life cycle awareness, i.e. to involve all parties caught up in system lifetimes (e.g., researchers, designers, field service engineers, the sales department, and customers) and to discuss opportunities to decrease LCC without harming system availability (Jha et al., 1996). This free flow of information about system availability allows managers to find ideas in unexpected places and pushes them to combine fragments of information (Irani and Sharp, 1997). Ideas can appear because of maintenance experience, technological developments, market turbulence, system modifications for a particular lead customer, and so on. As Bhuiyan and Baghel (2005) state: "People learn from their own and from other's experience, both positive and negative." The manufacturer should gather and manage all relevant information, and make this information easily available throughout the organization. This is referred to as product lifecycle management (PLM) (Saaksvuori and Immonen, 2008). PLM prevents information redundancy and the accumulation of out of date information and will facilitate the search for opportunities to cost-effectively influence system availability.

4.4. Training

In using the analytical framework the manufacturer will always indentify possibilities to cost-effectively improve system availability. Sometimes, more than one such opportunity will appear. Therefore, it is necessary to clearly describe a decision-making process to guide a team in deciding which opportunity adds most value to the manufacturer and/or the customer (Bhuiyan and Baghel, 2005). "Investment in training at all levels is money well spent (Jha et al., 1996)."

5. Conclusion

For years, manufacturers of capital goods have been adopting continuous improvement methods to meet the ever-increasing demands of customers. Nowadays, users of capital goods request increasingly high system availability levels against minimized system lifetime costs. Therefore, this research has developed a new continuous improvement methodology "Design for Availability" to economically optimize the availability level of capital goods. Design for Availability is different from other continuous improvement methodologies in that it does not only comply with the manufacturers' core business processes, but also with processes occurring when the system is already installed at the customer.

The analytical framework developed in this study specifies the principles of system availability and system lifetime costs, which manufacturers can apply in their search for opportunities to cost-effectively improve system availability. The application of this framework is tested through a single case study at a manufacturer of capital goods in the food processing industry. Results show that a thorough analysis of system availability and lifetime costs enabled the identification of improvement opportunities for that manufacturer and its customers. In spite of this contribution, results must be interpreted with the following limitations in mind. First, the outline of the system availability principles might not be all-embracing. Clearly, academics and practitioners should critically review and supplement the outline where necessary. Second, the applicability and relevance of the analytical framework is demonstrated through a single case study of a manufacturer in the food processing industry. Although studying a single manufacturer reduces concerns about internal validity, there is no doubt that the use of multiple manufacturers would enhance external validity. However, we chose to emphasize internal validity over generalizability, as our study is the first to apply the Design for Availability framework. Finally, this case study addresses only a rather short period of time. In the eight months at FD&Co, this study was able to provide the manufacturer with the three most important opportunities to reduce LCC while maintaining system performance requirements, however, could not capture the actual implementation of those opportunities. Since the use of continuous improvement methodologies by definition requires a sustained period of time before its impact can really be felt (Bessant et al., 1994), future researchers are suggested to apply a longitudinal approach.

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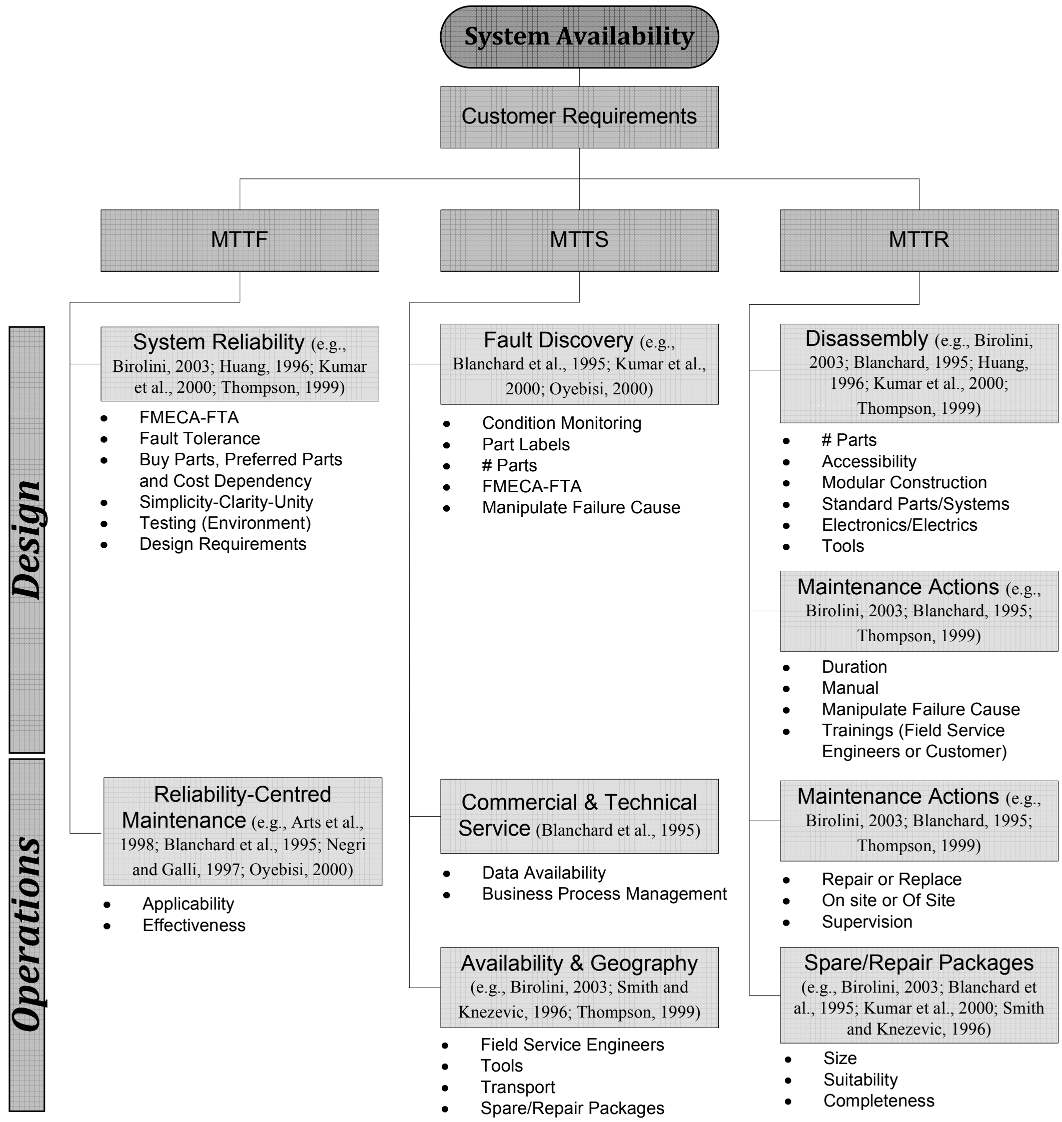

Figure 1. System availability analysis

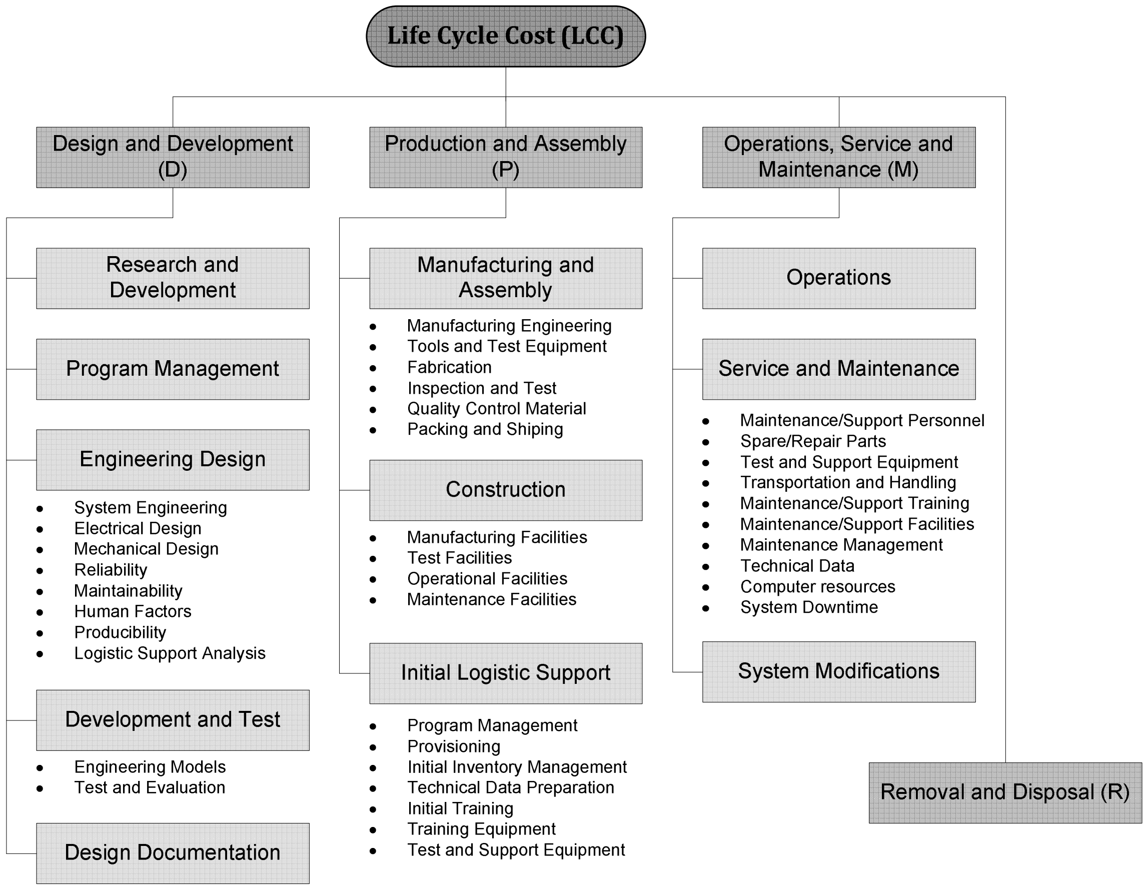

Figure 2. LCC breakdown structure (based on Blanchard et al., 1995)

System Availability \ LCC			Design and Development (D)		Production and Assembly (P)		Operations, Service and Maintenance (M)	
			Small CVP	Large CVP	Small CVP	Large CVP	Small CVP	Large CVP
MTTF	*Design*	System Reliability	↑ ↑	↑	↑ or ↓	↑ or ↓	↓	↓
MTTF	*Operations*	Reliability Centered Maintenance	↑ ↑	↑			↓	↓
MTTS	*Design*	Fault Discovery	↑ ↑	↑	↑ or ↓	↑	↓	↓
MTTS	*Operations*	Commercial & Technical Service Availability & Georgaphy	- ↑ ↑	- ↑	- ↑ or ↓	- ↑ or ↓	↑ ↑ or ↓ ↑ ↑ or ↓	↑ or ↓ ↑ or ↓
MTTR	*Design*	Disassembly Maintenance Actions	↑ ↑ ↑ ↑	↑ ↑	↑ or ↓ ↑	↑ or ↓ ↑	↑ or ↓ ↓	↑ or ↓ ↓
MTTR	*Operations*	Maintenance Actions Spare/Repair Packages	↑ ↑ ↑ ↑	↑ ↑	- ↑ or ↓	- ↑ or ↓	↑ ↑ or ↓ ↓	↑ or ↓ ↓

Note: 'CPV' cumulative production volume, ' ↓ ' decrease of LCC element , ' ↑ ' moderate increase of LCC element, ' ↑ ↑ ' large increase of LCC element

Figure 3. Lifecycle cost analysis for the main system availability principles

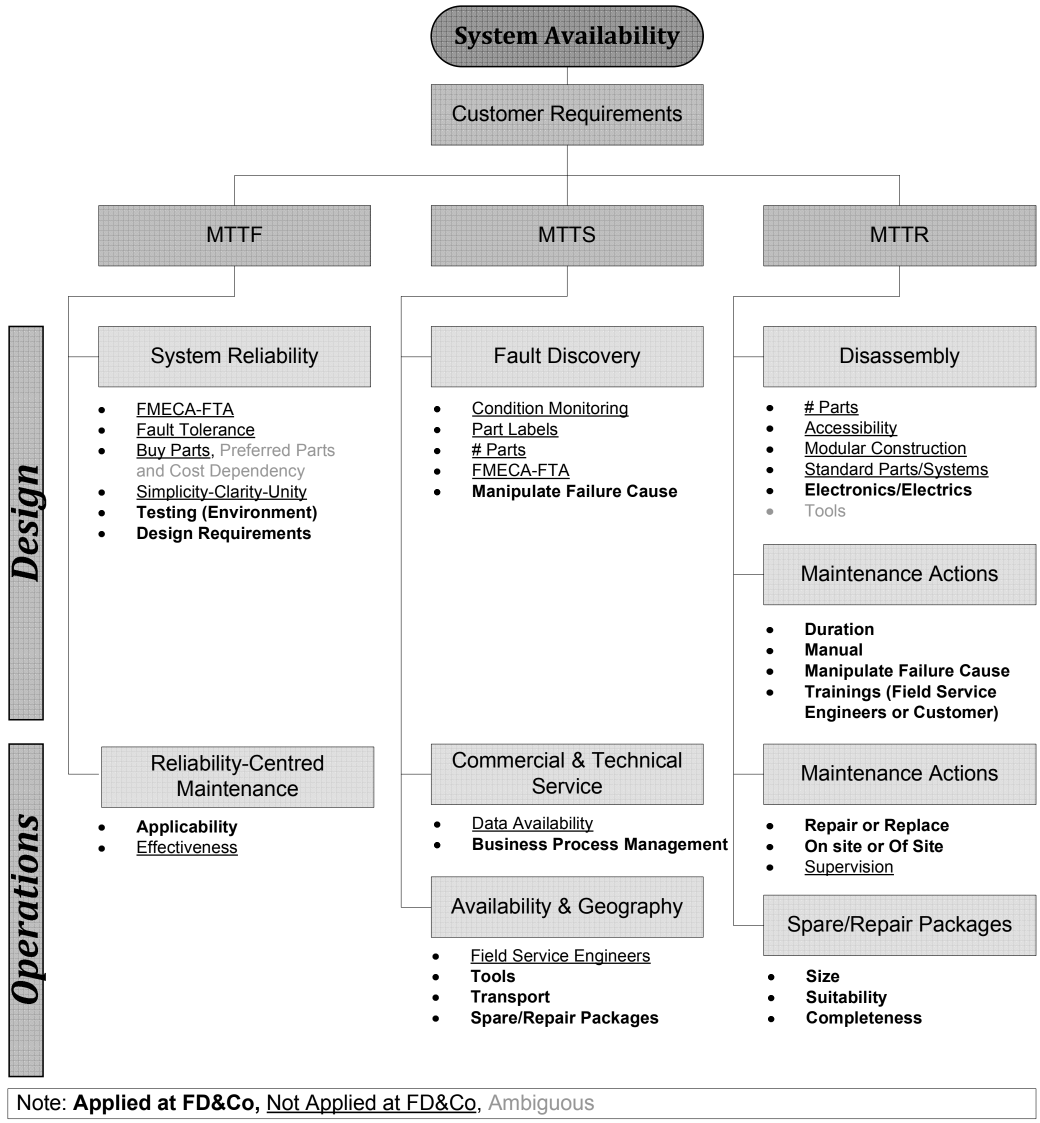

Figure 4. Implemented system availability principles at FD&Co

Appendix: Interviews about System Availability

Subject	Respondent
· System Reliability · Fault Discovery · Disassembly · Maintenance Actions	· Senior Product Specialist · Engineering and Development Manager
· Reliability-Centered Maintenance · Commercial and Technical Service · Availability and Geography · Maintenance Actions · Spare/Repair packages	· Structural Group Service
· Maintenance Actions (manuals, training)	· Coach Technical Information · Technical Trainer
· System Reliability	· Coach Mechanical Design Engineering
· Commercial and Technical Service · Availability and Geography · Spare/Repair Packages	· Service Manager
· Commercial and Technical Service · Availability and Geography	· Service Coordinator · Service Area Managers
· Fault Discovery · Disassembly · TCO/LCC	· Coach Innovation Engineering
· Validate Information	· Service Manager

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