MEASURING SERVICE OUTCOMES FOR ADAPTIVE PREVENTIVE MAINTENANCE

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Abstract

Services account for an increasing share of economic activity in the western world. As part of this, preventive maintenance (PM) service volumes are constantly growing as a result of a growing (and aging) asset population and maintenance outsourcing. While the pursuit of improved service productivity is in the interest of both firms and nations, the challenges of measuring service performance, and more specifically service outcomes, persist. This paper presents an outcome-based measure for fleet PM, which has far-reaching implications considering service productivity and performance measurement.

We develop a *statistical process control* based measure that utilizes data typically available in PM. The measure is grounded in reliability theory, which enables generalization of the measure within PM services but also outlines the limitations of its application. Finally we apply the measure in a PM field service process of a servitized equipment manufacturer. Based on actual maintenance records we show that the service provider could reduce their service output by at least 5–10% without significantly affecting the aggregate service outcome.

The developed measure and control process form the basis for *adaptive preventive maintenance*, which is expected to facilitate the transition towards outcome-based contracts through complementing *condition-based maintenance*. One of the key benefits of the approach is that it provides a cost-effective way of revealing the scarcely studied phenomenon of service overproduction. Based on our case, we conclude that there are significant

productivity gains in making sure that you meet required standards for service output but do not exceed them.

Keywords: service performance; Statistical Process Control; outcome measurement; preventive maintenance; design science.

1 Introduction

The global engineering assets base is growing and aging in an era where the pursuit of economic efficiency is driving both firms and governments to outsource their maintenance functions. This is creating a constantly growing demand for comprehensive maintenance services. In answering to this demand, the maintenance service provider is paid to restore and sustain engineering asset availability through corrective maintenance and preventive maintenance (PM). The nature of PM services implies long-term contracts, with a relationship-based business logic (Brax, 2005; Johnsen et al., 2009; Oliva and Kallenberg, 2003). Further, as the decisions and actions of the maintenance service provider have a direct effect on asset availability, the service provider is bound to accept liability, at least to some extent. This introduces outcome-based elements to contracting (Eisenhardt, 1989a), which may ultimately lead to business logics where the maintenance service supplier is paid for equipment availability (Baines et al., 2009; Hypko et al., 2010a; Ng et al., 2009; Oliva and Kallenberg, 2003). As service provider income is then tied to the service outcome, service operations management becomes more challenging. In effect, the pursuit for productivity is complemented by the pursuit for effectiveness (Djellal and Gallouj, 2013), which consequently raises the bar for operational performance measurement. This challenge, recognized by academics and practitioners alike (Oliva and Sterman, 2001; Selviaridis and Norrman, 2014; Viitamo and Toivonen, 2013), is what we address in this paper.

When moving towards more outcome-based contracts, the cost of quality (cf. Schiffauerova and Thomson, 2006) is reallocated from the customer to the service provider. This is the case for both below optimal quality (under-service), where the service supplier incurs penalty costs or loses performance bonuses, and above optimal quality (over-service), where the service supplier would have achieved the same outcome with less resources or inputs. The latter is exceptionally challenging in PM, where the created customer value equates to sustained equipment availability. In other words, the customer does not experience the value of the service as the service action is performed but rather it is experienced between the performed service actions. For the customer the actual service delivery can be a nuisance as the equipment may be unavailable during service delivery. This implies that mitigating over-service in the case of PM translates to postponing service actions as much as reasonable, while avoiding equipment failure resulting from under-service. In other words, it is a balancing act along the thin line between under- and over-service. The service operations challenge thus becomes one of optimal service timing, with respect to deployed resources and created value.

Currently the challenge of optimal service timing in PM is tackled in two principally different ways. In what could be characterized as *design-based preventive maintenance* (DPM) the manufacturer of the equipment estimates the proper service timing based on reliability estimates, calculations and simulations (Murthy et al., 2008). While this is a cost-effective way of determining service timing, it cannot account for the full spectrum of operational environments that the equipment may be subjected to, implying a likely bias toward over-maintenance. On the other hand, in *condition-based maintenance* (CBM), PM timing is based on the monitoring and prediction of equipment deterioration. While this method typically enables optimal service timing, it is not applicable for all maintainable technologies. Further, considering older equipment, the required sensors and other infrastructure typically need to be retrofitted. The question is whether something could exist between these two extremes which is more accurate and optimal than DPM while allowing wider implementation and less costs and effort than CBM. We seek to provide such an alternative through measuring and consequently learning from service outcomes, represented by equipment availability in the context of PM.

While equipment availability as such is fairly easy to measure, the performance measurement challenge lies in measuring availability in a way that supports service action timing. While it is fairly easy to measure how efficiently maintenance actions are performed (e.g. the time it takes a technician to perform a maintenance action), PM effectiveness is a more challenging concept. This is because the service provider will know neither how much the PM action will postpone the inevitable failure nor when the next PM action should be performed. Postponing failure is essentially the service outcome and it determines the equipment availability. Thus we answer the question: *How can PM service performance be measured in a way that facilitates control of service outcomes?*

We answer this question by designing (van Aken, 2004; Holmström et al., 2009) a statistical process control (SPC) based measure, building on principles derived from reliability theory. This measure, untypically for SPC, essentially measures the customer process instead of the service supplier's process, making it an indirect measure of value-in-use. Hence, the developed measure could also be seen as a manifestation of *service-dominant logic*, where it is not the service supplier process but the customer process which is the basis for performance measurement (Ng et al., 2009; Vargo and Lusch, 2004; Vargo et al., 2008). Further, due to the customer focus of the measure, we can also measure distributed service production with a conceptual service process (implying multiple concurrent process instances), whereas traditional SPC applications have been limited to centralized (service) production with a single, continuous concrete process.

Due to the statistical basis of the measure, its applicability lies mainly in the PM of groups or fleets of similar equipment. Consequently, the control of service outcomes is also exerted on a fleet level. In other words, the design complements the service operations management of single pieces of equipment with managing fleets of equipment, introducing a systems perspective to service provision, as proposed by Ng et al. (2009). Further, the developed measure, along with the outlined method for the control of service outcomes that we call *adaptive preventive maintenance* (APM), provides the sought "middle ground" alternative to DPM and CBM. Through being more optimal than DPM, while involving less implementation costs and effort than CBM, APM also lowers the bar for the transition towards outcome-based contracts through a cost-efficient reduction and quantification of outcome uncertainty (Eisenhardt, 1989a). Thus this work aims at contributing to a more productive society by maximizing service effectiveness rather than efficiency.

This introduction is followed by a review of previous research into the role of outcomes in performance measurement and how this is related to SPC application in service operations. In section 3 we describe the design methodology employed by the research along with a description of the case company. In section 4 we describe the development of the measure and related control process, including the measure's foundation in reliability theory. In section 5 we demonstrate and evaluate the measure in the case context (consisting of three embedded cases). Finally, in sections 6 and 7 we discuss the implications for theory and practice, and outline the limitations of the research, ending with concluding remarks.

2 Measuring service outcomes

The customer perspective has had a legitimate role in performance measurement since the influential article by Kaplan and Norton (1992). However, few works have outlined *how* the customer perspective should be included, let alone *what* should be measured (Neely et al., 2000). The customer perspective is also central regarding preventive maintenance (PM), because performance measurement has to focus on the customer process, as PM is performed to sustain equipment availability. Customer satisfaction typically figures in frameworks and practice, in some situations even to the extent that it is presented as the only measurable outcome (cf. Brown, 1996). However, regarding PM, measuring only customer satisfaction is problematic because it does not solve the underlying problem of the attributability of outcomes to service actions as it is dependent on the customer appreciating the technical consequences of the delivered service (Woodruff, 1997). An alternative outcome measure frequently appearing in different frameworks is customer value. The problem with customer value as a measure~~,~~ is that it is hard to define precisely (Parasuraman, 1997)~~,~~ and while being an antecedent to customer satisfaction (Woodruff, 1997) it also suffers from the same dilemma of service outcome attributability.

A possible avenue to overcoming the challenges regarding different measures of customer perspective is to measure quality. The customer perspective is also, at least to some extent, captured by the concept of quality (Neely et al., 1995). Despite this, the relationship between customer satisfaction, quality and value is somewhat ambiguous (Reeves and Bednar, 1994). However, quality can more easily be translated into concrete measures (Parasuraman et al., 1985). Service quality has also been tied to service co-creation by Lillrank and Liukko (2004), who note that variance in quality depends on the heterogeneity of the processes which produce the service. Grönroos (2000) defines service quality as a construct with two different components valued by the customer: the functional quality, which addresses *how the service was delivered*, and the technical quality, which addresses *what was delivered*. Within these components, the customer-perceived quality is determined by the difference between expected and experienced quality (Parasuraman et al., 1985). Related to this, we should also consider Reeves and Bednar's (1994) dual definition of quality as both *conformance to requirements* and *fitness for use*. Further, Neely et al. (1995, p. 85) define the "cost of quality" concept as "a measure of the extra cost incurred by the organization because it is either under- or over-performing" (cf. Schiffauerova and Thomson, 2006). This definition suits the PM context well, where performance depends on maintaining high quality through avoiding over- or under-delivering the service. Considering the dual nature of quality as defined by Grönroos (2000), this paper focuses solely on technical quality, namely *what is delivered*.

The applicability of SPC is dependent on how well the process is defined (Oakland, 2008). Lillrank and Liukko (2004) divide service processes, based on their heterogeneity, into non-routine, routine and standardized. Reflecting this against Reeves and Bednar's (1994) definition of quality, we could expect that standardization formalizes process requirements, which enables measurement of *conformance to requirements*. On the other hand, if the delivered service value can be objectively expressed and measured, SPC can be applied to measure and control *fitness for use*. PM provides such a context as – in Grönroos's (2000) terms – technical quality is objectively expressed as availability and cannot exceed 100%.

While SPC has been suggested as a suitable tool for measuring and improving service quality (Mefford, 1993) and more specifically maintenance quality (Duffuaa and Ben-Daya, 1995; Ridley and Duke, 2007), it has not been widely adopted by practitioners (Mason and Antony, 2000). Implementations reported in academia are consequently far from abundant, with the exception of implementations in healthcare where SPC has been reported to have been used in several different applications (Thor et al., 2007). While there are a number of implementations reported within the PM context, they tend to be factory-centric (Jacob and Sreejith, 2008; cf. MacCarthy and Wasusri, 2002), that is to say dealing with a single "customer" process and a heterogeneous installed base. Further, the reported implementations typically deal with quality in terms of product quality, rather than service quality (Chan and Wu, 2009; Panagiotidou and Nenes, 2009; cf. Yeung et al., 2007). In contrast, this paper focuses on service performance and quality in fleet-centric operations, implying multiple concurrent and independent customer processes served by fairly homogeneous equipment. The potential value of SPC in fleet maintenance has been recognized (Xie et al., 2002), and despite there being a few reported implementations (eg. Vassilakis and Besseris, 2010), the authors were unable to find any previous implementations in field services, which is the context of this paper.

3 Methodology

In this study we take a design science approach (van Aken, 2004; Holmström et al., 2009), through which we develop and evaluate a solution for measuring PM outcomes. We present the developed SPC-based measure as a design artefact that can be used to improve PM performance (van Aken, 2004). We claim that in a given PM context, due to given mechanisms, the implementation of the presented artefact (the developed measure) will result in the desired outcome (Denyer et al., 2008) of improved performance. Thus the key attributes for evaluating the validity of this research lie not in the number of replications in different settings but rather in the detailed exploration, explication and description of the context dependent mechanisms (van Aken, 2004) through which the artefact is observed to produce outcomes. This empirical process, based on a mix of qualitative and quantitative data, is described in the following part of the paper. As stated by van Aken (2004, p. 226) “a design-science is not concerned with action itself, but with knowledge to be used in designing solutions, to be followed by design-based action”.

3.1 The design science process

As illustrated in figure 1 below, the design science approach can be described as an iterative six step process (Peffers et al., 2007, pp. 52–56), based on which the remainder of this methodology section is structured.

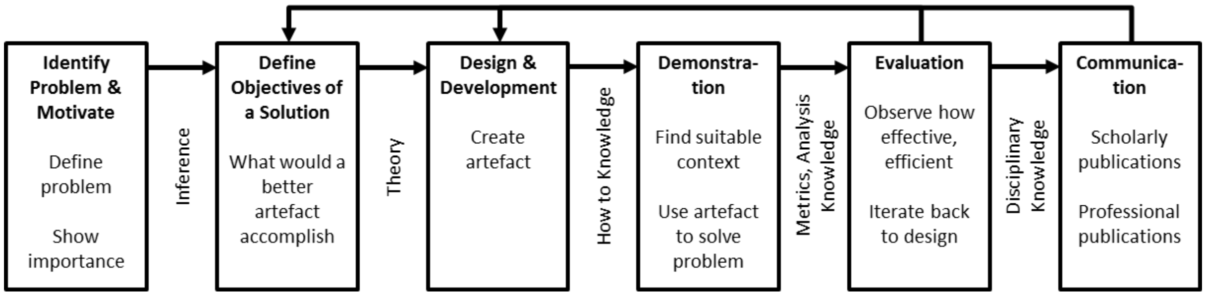


Figure 1. The design science research process, adapted from Peffers et al. (2007, fig. 1).

The study was conducted in close co-operation with the case company from the very beginning, starting with problem identification and eventually progressing through solution development to demonstration of the solution. As something inherent to design science, what eventually became the object of study (the SPC-based measure) did not exist at the outset of the research. In more traditional methodological terms the research could be characterized as a single case study, methodologically justified by the uniqueness (and novelty) of the phenomenon and the exploratory nature of the research (Siggelkow, 2007; Yin, 2009). However, in the demonstration phase of the study we highlight the embedded nature of the case study (Yin, 2009) as we demonstrate the developed measure in three different (embedded) cases, based on data from three European countries. For each country we were also able to perform separate analysis based on the technologically different main components of the studied equipment, while controlling for environmental and operational variables.

The design science approach produces designs which are constructed through a combination of iterative research and prior knowledge of context dependent mechanisms. The question of design transferability thus becomes one of context similarity with respect to mechanisms relevant to the design, and testing the design in different contexts is done to explore variation in intended and unintended outcomes. The three embedded cases in the demonstration phase enabled evaluation of the measure in similar problem contexts with slight differences (e.g. in service base composition, data quality and service organization). While the analysed cases provide sufficient context variation for demonstration and evaluation of the measure, as with any exploratory research aiming at theory development, further testing in more varied contexts is required. The aim of this further research is then to reveal further context dependent mechanisms, determining the contextual limitations of the applicability of the design, eventually leading to a saturation of findings (Eisenhardt and Graebner, 2007; Eisenhardt, 1989b).

While Peffers et al. (2007) assume that the design science process starts with a problem for which a solution is developed, Holmström et al. (2009) note that an equally viable starting-point for the process is that of a solution for which a suitable problem needs to be found. The latter was the case in this study, where the case company saw untapped potential in the installed/service base information that the company possessed. As the "pre-solution" in this case offered merely the means for creating the actual solution, we find Peffers et al. (2007) process fully applicable beyond the first step suggested by Holmström et al. (2009). Continuing with the first step in Peffers et al. (2007) process (figure 1), a solvable problem was then sought, first in terms of service process efficiency but then converging towards service process effectiveness, wherein an appropriate problem was eventually found and theoretically framed. As the problem and the means for creating the solution (the installed base information possessed by the company) were both known, the solution objectives were defined as to "control and eliminate over-maintenance", which concluded the *"problem identification and motivation*" and *"define the objectives for a solution*" phases (Peffers et al., 2007, pp. 52–55). During these phases we conducted and recorded three semi-structured interviews with key company personnel, each lasting for 1.5–2 hours, which were subsequently transcribed. Further we arranged three workshops lasting 1.5–3.5 hours and two shorter discussions where potential problems and solution objectives were discussed and preliminary solution designs iterated. Additional data was gathered in the form of a field observation of a service technician lasting 3.5 hours and from a wide variety of company internal documentation, including maintenance process descriptions.

The "*design and development*" and "*demonstration*" phases (Peffers et al., 2007, p. 55) involved less case company interaction. For design demonstration during these phases the case company supplied three sets of service records consisting of the complete records and equipment specifications for a total of 2640 individual pieces of equipment in three European countries, covering a time span of 24–30 months. The supplied data was cleaned in order to remove new and incoming equipment, which left 2504 equipment service histories to be analysed. The data was then further cleaned through the removal of service events conducted for reasons other than maintenance and the removal of service events with missing data. During these phases we also arranged two workshops with key company representatives, each lasting 1.5–2.5 hours, where data related issues were discussed and the design was iterated.

In the "*evaluation*" phase (Peffers et al., 2007, p. 56), we were able to show that the service base was on average over-maintained, which confirmed the suspicions amongst the interviewed company personnel. However, the implementation of the control part of the measure was not possible with the current configuration of company IT systems, which meant that a further implementation effort was needed (and subsequently taken on by the company) in this respect. All in all, we can still say that the devised design artefact reached the objectives set for the design by making over-maintenance visible through the new measurement approach. Additionally, the data upon which the solution draws and the mechanisms which serve as a foundation for the measure were so explicit that we argue that the limits of design transferability to other similar contexts can be quite confidently discussed. To sum up, the first five phases (Peffers et al., 2007) described above allow us to formulate theoretical propositions related to service performance measurement (Holmström et al., 2009).

And finally, this paper constitutes the sixth and final "*communication*" phase (Peffers et al., 2007, p. 56), where we describe this process of theorizing (Weick, 1995).

3.2 Case selection and description

The industry in which the case company operates ranks among the frontrunners of servitization (Vandermerwe and Rada, 1988), and within this industry the case company is one of few leading global companies. The company is a capital goods manufacturer with over half a century of experience in providing after sales services, including PM field services. The company is considered as a benchmark in effective field services, and half of the company's total generated revenues come from service sales. The equipment manufactured by the company typically has a supporting role in customer operations and is not operations critical. Further, in most countries the service of the equipment is regulated by national or industry institutions as the customer is usually different from the end-user and has limited competences in maintaining the equipment on its own.

The case company has a global service base of approximately a million individual pieces of equipment. The underlying technologies for this type of equipment are fairly similar between different manufacturers, which enables the company to serve both its own and competitor's makes, and vice versa. The (business-to-business) service market for the equipment is fairly competitive with both global and local players, which means that tendering for services and modernizations is frequent. This also has implications for the information used by the developed measure (cf. Hypko et al., 2010a) as equipment service histories may be fragmented and equipment information outdated. In the following section we present how the measure is developed based on reliability theory, while its empirical application is outlined in section 5.

4 Developing the measure based on reliability theory

In this section we describe the development of the design artefact (Peffers et al., 2007), which in our case is the method for PM performance measurement. We first present the theory-grounded design propositions (DPs) (Denyer et al., 2008) based on which it is designed. In doing this we mainly draw upon the tenets of reliability theory. Here, reliability is essentially an antecedent of the demand for PM. After this we describe the design which is developed based on the DPs. Thus we outline relevant constructs and justificatory knowledge, followed by a description of form and function, and the principles of implementation, all of which are key components in theorizing through design (Gregor and Jones, 2007).

4.1 DPs

As the purpose of PM is to prevent failures from happening, the need for PM is determined by how often the equipment would fail without the maintenance actions. This is a probabilistic problem in the sense that we cannot know exactly when the equipment will fail (Murthy et al., 2008). This is despite the fact that a timespan can typically be specified within which the equipment will eventually fail and perhaps also variations in the failure rate during this time span. This leads us to the first DP:

DP1: A measurement method for PM outcomes needs to accommodate a probabilistic phenomenon.

The reliability of equipment can be illustrated through *the rate of occurrence of failures* (Murthy et al., 2008), also referred to as the *hazard rate* (Klutke et al., 2003) or *failure rate* (Bennett and Jenney, 1980; Wu and Clements-Croome, 2005), which is a measure of the probability of the equipment, or a part thereof, failing during a given moment of its lifetime. In this paper we use the term failure rate due to its brevity. Klutke et al. (2003) note that standard reliability texts typically describe a conceptual distribution of the failure rate, known as the bathtub curve (figure 2). Conceptually, the distribution conveys the idea that there are three distinct phases in the life of equipment (Klutke et al., 2003): first, an "early failure" or "infant mortality" (burn-in) period, where the failure rate decreases over time; second, a "random failure" (useful life) period where the failure rate is constant over time; and third, a "wear-out" period, where the failure rate increases over time.

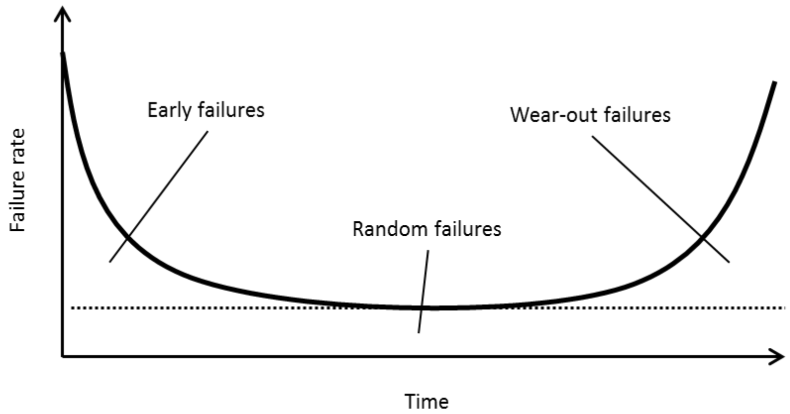


Figure 2. The bathtub curve.

Klutke et al. (2003) question this distribution, especially the part on early failures, and note that some authors advocate a rollercoaster curve (cf. Wong and Lindstrom, 1988), where the early failure stage is modelled slightly differently. Without making a case for either of these early failure conceptualizations, we instead highlight that there are three different failure types. In reference to types of probabilities, random failures are common-cause failures, while both early failures and wear-out failures are special-cause failures. Further we note that PM is primarily intended to prevent wear-out failures (Murthy et al., 2008). From this we can derive our next DP:

DP2: A measurement method for PM outcomes needs to distinguish special-cause failures (wear-out & early failures) from common-cause failures (random failures).

Early failures could be caused, for example, by problems with the sub-standard quality of manufactured parts, out-of-specifications usage or the operational environment. Random failures could be caused by (as per definition) random events in the interaction of the equipment with its environment, for instance the accidental exposure of mechanical parts to dust and rocks or the temporary over-heating of a bearing. Wear-out failures can be caused by, for example, increased friction-related damages resulting from insufficient lubrication and cleaning. While reliability is inherently an attribute of technology, we can expect both the usage of the technology and the environment in which the technology is used to affect its reliability profile (Murthy et al., 2008; Tinga, 2010), which leads to the following DP:

DP3: A measurement method for PM outcomes needs to control for technology, usage and environment variables.

The bathtub conceptualization depicts the failure rate as a function of time, relative to equipment commissioning, in which PM can be modelled as a reduction of the failure rate (wear-out failures) (Wu and Clements-Croome, 2005), effectively prolonging the expected lifetime of the equipment (Murthy et al., 2008). However, we note that there is a complementary way of modelling PM in terms of reliability improvement, as we are not explicitly interested in equipment-specific reliability but rather reliability provided as a service. Here PM is modelled as a reduction in the relative age of the equipment (Doyen and Gaudoin, 2004; Wu and Clements-Croome, 2005), which implies that time should be viewed as a relative, rather than absolute, measure (Doyen and Gaudoin, 2004). This leads to the next DP:

DP4: A measurement method for PM outcomes needs to view time as a relative measure.

Based on these DPs we may now outline the design and function of a performance measure for managing PM outcomes.

4.2 Measuring PM outcomes

The service operations management challenge addressed in the empirical study is about the timing of PM interventions. In other words, maintenance should be performed before the wear-out phase is initiated (see figure 2) in order to minimize the number of breakdowns. However, playing it too safe by timing maintenance very early will lead to an excessive maintenance rate and consequently equipment being under maintenance excessively often. In other words, equipment availability is maximized when the PM intervention takes place just before the wear-out phase is initiated. While the task of optimizing maintenance in this respect seems fairly trivial, it becomes problematic when failures are infrequent (Percy and Kobbacy, 2000) because this would mean that an empirically based failure-rate distribution may be unattainable. However, as long as the conditions set by DP3 (the design needs to control for technology, usage and environment variables) are met, we can aggregate the failure information of sufficiently homogeneous equipment pools. Provided these equipment pools are large enough, we ultimately arrive at an empirically-based failure-rate distribution for the pool of equipment, according to DP1.

When considering DP1 (the design needs to accommodate a probabilistic phenomenon) and DP2 (the design needs to distinguish special-cause failures from common-cause failures), we note that there already exists a performance measurement method that satisfies both, namely SPC (MacCarthy and Wasusri, 2002; Oakland, 2008). However, SPC has its origins in manufacturing and despite more recent service implementations (cf. MacCarthy and Wasusri, 2002; Thor et al., 2007), we were unable to find previous implementations which would satisfy DP4 (the design needs to view time as a relative measure). Thus, in devising the design we need to take SPC a step further, by introducing the relative perspective on time (also referred to as *event time* (Ancona et al., 2001) to SPC.

As we are interested in the outcomes of the PM service, we assume that any reduction in the relative equipment age will take place as a direct result of the equipment being subjected to maintenance actions. Considering DP4, it is then natural that we measure outcome timings in relation to the service provision event. Further, as long as the constraints set by DP3 hold, we can (based on DP1) also aggregate service events. This reduces the population needed for a viable empirical failure-rate distribution of the maintained equipment pool, which is now measured relative to the last service event.

However, the introduction of relative time to a measurement method designed for absolute time creates a problem. As we can expect the length of the aggregated maintenance intervals to vary, we have a declining population of intervals. In other words, as we are interested in the occurrence of failures, there will be fewer intervals (where failures – be they common- or special-cause – may potentially occur) the further away we move from the relative starting point (the last maintenance action). However, as we are interested in the rate of failures rather than the absolute number of them, the problem is remedied through incorporating a correction factor for the distribution of failures (see step 5, below), which compensates for the declining population of intervals as we move further away from the relative starting point. This also leads to diverging control limits and warning limits in the control chart (figure 3).

The procedure for constructing the measure is outlined in the steps below, and figure 3 offers a conceptual illustration of the resulting control chart:

1. Extract maintenance intervals from maintenance service data, delimited by maintenance events.
2. Exclude intervals between service visits if the visits are not for maintenance purposes as no reduction in relative equipment age took place.

3. Group data based on similar technology/usage/environment, creating a pool of similar equipment.

4. Plot data relative to the maintenance action as the starting point through aggregating the grouped intervals, so that the control chart displays the number of failure events (the *y*-axis) and time since the previous PM event (the *x*-axis). The number of PM events can also be plotted (as is done in the measure samples presented in this paper) as they convey the accuracy of service timing.

5. Scale the absolute number of failures to correspond to the failure rate through multiplying the absolute number by a correction factor, accounting for the intervals which have already ended (either by equipment failure or by the next PM visit).

6. Plot the mean value (C), the upper control limit (UCL) and lower control limit (LCL), the upper warning limit (UWL) and lower warning limit (LWL), and scale the limits by the correction factor. The warning and control limits can be derived from variations in the number of failure events at any given time and could be expected to be normally distributed, implying a warning limit at two standard deviations and a control limit at three standard deviations.

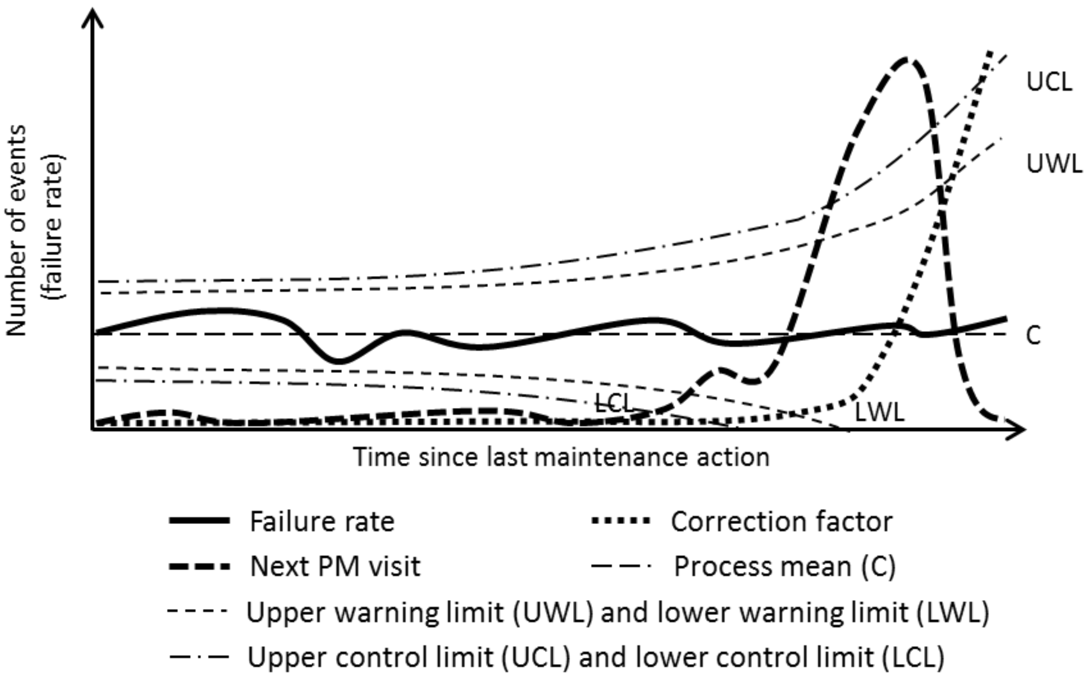


Figure 3. Conceptual illustration of the measure.

Based on DP2 we can expect the shape of the resulting failure rate distribution to reveal whether the failures identify themselves as wear-out failures which were not prevented or as random failures. In the case of over-maintenance we should observe a constant rate of random failures and in the case of under-maintenance there should be a rising average failure rate at the far end of the distribution. Further, if a significant number of maintenance events involve part replacement, there may also be indications of infant mortality at the beginning of the failure rate distribution. In other words, we are able to separate between failures which were unpreventable and failures which can be attributed to failed prevention (i.e. imperfect service quality).

4.3 Managing PM outcomes

As we are aggregating the maintenance intervals of similar equipment, the measure conveys the failure behaviour of the pool of equipment being aggregated rather than the failure behaviour of any single piece of equipment. Consequently any optimization of service timing based on the control chart will not be done for a single piece of equipment but rather for the pool of equipment, and hence on a fleet level. This means that while the PM timing for individual pieces of equipment will theoretically be likely to be sub-optimal, on an aggregate level the timing will be optimized.

The process for managing PM outcomes based on the developed measure consists of the following three phases:

1. *Learn* – In this initial phase, failure information is gathered and accumulated over time and for similar equipment. Collecting more information leads to reduced relative variance in the failure rate. Once enough information has been gathered (what is enough should be evaluated on a case-by-case basis), aggregating it and constructing the designed measure will confirm whether the aggregated pool of equipment is being under- or over-maintained.

2. *Adapt* – If the pool of equipment is over-maintained then the PM intervals should be gradually prolonged (increasing the maintenance frequency) while keeping a close eye on the evolving failure rate distribution. Once the maintenance intervals have been sufficiently prolonged, the UWL and UCL will be breached repeatedly, indicating the first (statistically significant) signs of wear-out failures. At this point we have passed the optimal interval, and based on the revealed failure rate distribution we can tell what the optimal interval is and subsequently revert to it. If the pool of equipment is under-maintained to begin with, then the maintenance interval should be shortened. However, in this case gradual adjustment is not necessary as the optimal interval should be visible, based on the initial failure rate.

3. *Control* – Once the pool of equipment is being maintained at the optimal interval, the failure rate is monitored for changes in reliability. In cases where reliability growth (cf. Meth, 1992; Murthy et al., 2008) can be expected in the pool of equipment (in a way

which cannot be controlled through technology-related information), it may be beneficial to periodically revert to the *adapt* phase.

5 Empirical demonstration and evaluation of the developed measure

The developed measure was demonstrated and evaluated based on maintenance event records supplied by the case company. The records consisted of maintenance events and technical data for 2504 individual pieces of equipment. The data allowed analysis of not only each model, but also of their main components separately, providing the opportunity to control for technology. Further, the data also allowed control of the other factors required by DP3 (discussed in the previous section); namely usage and the operational environment.

The maintenance events were recorded by the date of occurrence in the data. However, when constructing the measure, the events and failure rates were converted to events per week instead of events per day in order to secure non-zero rates. In order to determine the proper control and warning limits, the weekly failure rates were analysed based on absolute (calendar) time. As depicted in figure 4, the real weekly failure rate seemed to be normally distributed, which justified using standard deviations as control and warning limits. With these specifications, control charts were built for each country, each main-component and the respective operational conditions.

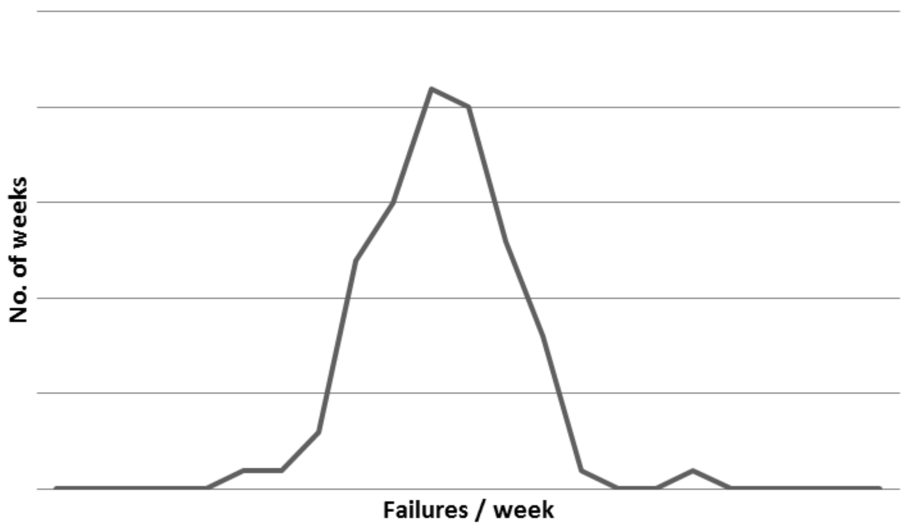


Figure 4. The observed weekly failure rate that seems normally distributed.

When crafting the charts we noted that the visual clarity of the charts was compromised in the region where the correction factor grows larger as it is approaching infinity. Due to this we limited the control charts to >10% of the interval population remaining. This was only done for improving the visual clarity of the control charts and does not affect the results. While the correction factor is included in the conceptual illustration of the measure (figure 3), we have left it out in the result sample charts for reasons of clarity.

Based on the analysis of all the main components, for all three countries, we could see no clear indication of under-maintenance because there were no signs of wear-out failures in the graph (see figure 5 for a representative sample). Further, as the failure rate cannot be expected to rise dramatically in a short period of time, we could safely assume, based on the absence of wear-out failures and the width of the distribution for the next PM event, that the PM interval could be prolonged by at least 5–10% without significantly increasing the aggregate failure rate. Relating this to figure 5, in visual terms, this means that the peak of PM events is moved 5–10% further away from the vertical axis (through gradually prolonging the average maintenance interval), revealing an equally small new section of the failure rate profile.

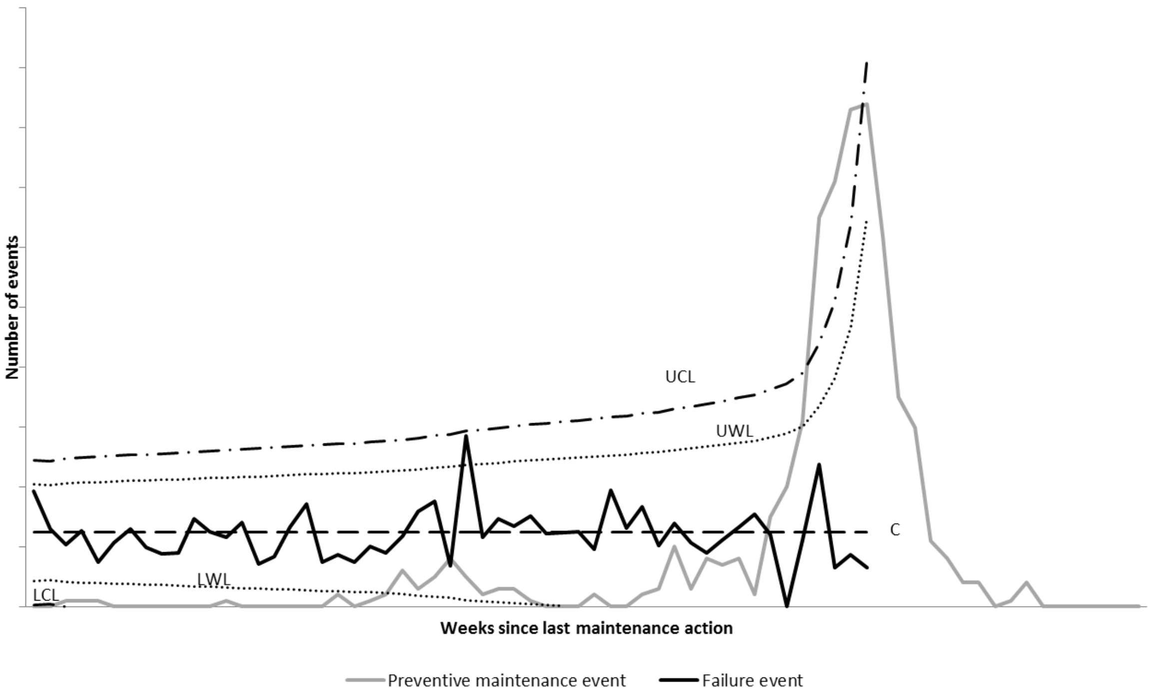


Figure 5. The measured outcomes for a main component.

This finding was supported by interviews conducted with case company key personnel, who shared a suspicion that the service base was currently being over-maintained, while definitive proof thereof had been lacking. From an operational perspective the change of maintenance interval would imply a corresponding reduction in the required service resources for providing the PM. This is simply because of maintenance being carried out less often. In practice, however, the potential savings are slightly less, as the same resources typically provide the corrective maintenance service.

We also found that for one type of main component the PM actions actually seemed to induce some failures as the failure rate was higher directly after the PM event compared to when more time had passed (see figure 6). While this was especially evident in one country (figure 6), there were indications of a similar, but weaker, trend in the other countries also. The root cause for this was not confirmed during the study, but when confronted with these results, the interviewees had some suspicions regarding a prescribed step in the PM process.

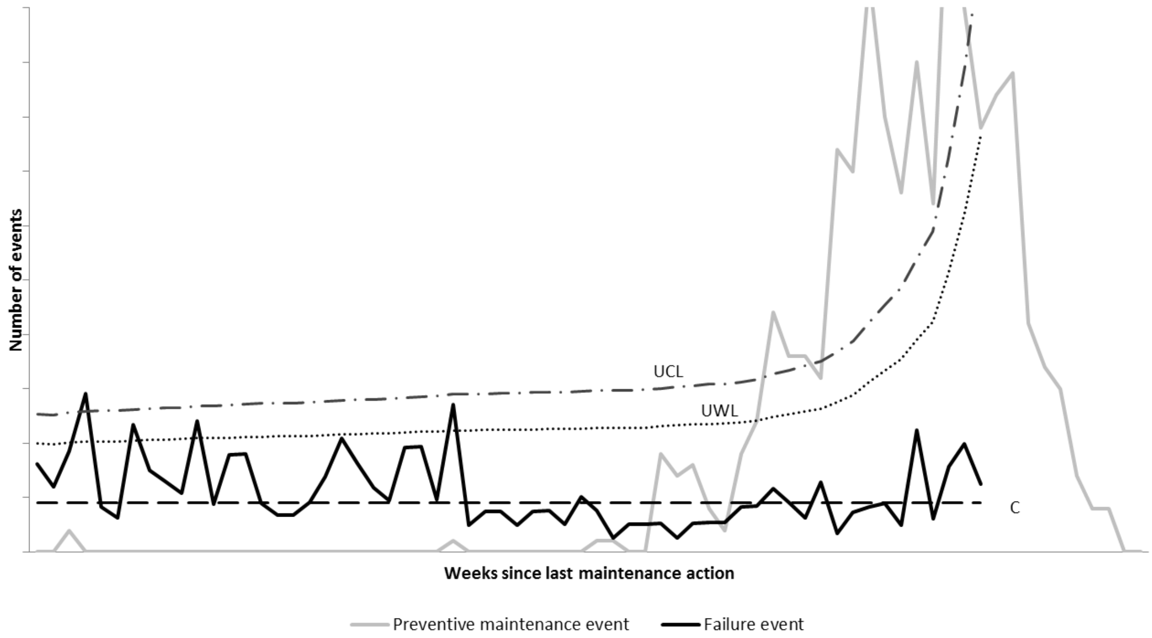


Figure 6. The measured outcomes for a main component, showing signs of maintenance induced failures.

Note that in figure 6 the process mean and control limits have been calculated based on the latter two thirds of the failure rate distribution in order to highlight the falling trend of the failure rate.

The three embedded cases displayed similar results; however, we also observed some differences. The varying service base composition and size meant that the pools of equipment varied in size; however, this did not have a notable impact on the reliability of the measure as this was compensated for by the time span of the data (i.e. for smaller pools, the data was available from a longer period). Related to the service base composition, there were some differences in technology, usage and environment, which were reflected in the rate of random failures which varied to some extent between countries. A final observation, which can also be seen when comparing figures 5 and 6, is that there were differences in service timing accuracy between countries. While this barely affects the measure, a wider distribution of service visits could be beneficial considering the adaptation process. To sum up, the differences in measurement results between countries were so minute that aggregating data from different countries would probably be feasible as long as technology, usage and environment can be controlled.

As something inherent to the design science approach, there also emerged some unexpected issues with implementation, related to organizational legacy. The first issue was with established conceptions of performance which were built on maximizing output while maintaining outcome, resulting in a strong emphasis on resource utilization. In prolonging the PM intervals, the relative share of PM is reduced while the relative share of corrective maintenance grows. As PM allows better planning and preparation, a relative reduction in PM also equates with a reduction in resource utilization. This means that implementing the measurement method and PM optimization process also has broader implications for how operational performance should be measured in the case company. The second issue was that the gradual increase in the maintenance interval suggested by the outcome management process was not possible to achieve as designed as the case company service scheduling systems only allowed coarse adjustment. Neither of the issues affected the relevance of the measurement approach as the prime objective of the design (revealing over-maintenance) was still met. However, the issues were problematic in the sense that they were not rectifiable through design iteration during the conducted study. Next we will discuss the results of this study, along with their significance and limitations.

6 Discussion

While as a method SPC has a long history of development and application (cf. Bersimis et al., 2007; MacCarthy and Wasusri, 2002; Stoumbos et al., 2000; Thor et al., 2007; William and Douglas, 1999; Woodall, 2000), we claim this study brings something new to the table (as summarized in table 1). First of all, in this study we measure the (technical) outcome of a conceptual maintenance process, where the data illustrates rates of outcomes – whereas in most SPC charts each data point represents a single output or outcome. The process here is conceptual in the sense that several aggregated process instances may occur simultaneously – that is to say, the same (conceptual) process happens at the same time in different places. The conceptual process also implies that we use a relative perspective on time (event time) which allows us to examine the correlation between the maintenance action and the outcome. This differs clearly from typical SPC approaches that use an absolute perspective on time (clock time), or another equally ordered and sequential perspective (data-points to the left of a specific point, per definition, have been generated before the specific point). In our case we also aggregate several "outcome periods", which are of different lengths; this is rectified through a correction factor which consequently leads to diverging control limits.

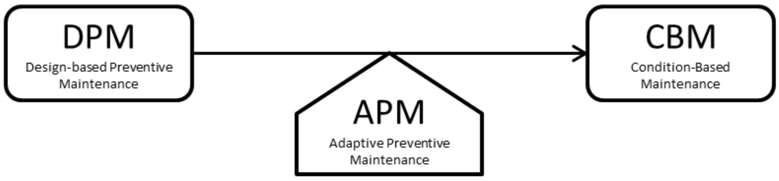
	The typical prior SPC application in manufacturing	**The typical prior SPC application in services**	**The SPC application presented in this paper**
Measured variable(s)	Mainly throughput and output related variables	Mainly throughput and output related variables	An outcome related variable
Measured process	The manufacturer's production process	The service supplier's production process	The customer's production process
Measurement purpose	To identify and remove special-cause failures	To identify and remove special-cause failures	To find the threshold for the emergence of special-cause failures
Measured value	The value potential / embedded value	Co-created value	Value-in-use
Perspective on time (cf. Ancona et al., 2001)	Absolute, clock time	Absolute, clock time	Relative, event time
Type of process	A single manufacturing process in centralized production (a concrete process)	A single service process in centralized production (a concrete process)	Aggregated similar service process instances in de-centralized production (a conceptual process)
Object of process control	The control of a single process	The control of a single process	The control of the aggregate process
Control principle	To control input and transformation based on output	To control input and transformation based on output	To control output based on outcome

Table 1. The developed SPC measure compared to previous SPC measures in manufacturing and services.

In contrast to previous SPC applications, where the measurement is output for the purpose of controlling the input or transformation, the developed design measures outcomes for the purpose of controlling output. This means essentially that the developed measure here does not utilize SPC of the service supplier process but rather SPC of the customer process. This answers to a call of research to measure value-in-use (Nudurupati et al., 2011), motivated by the increasing importance of product related services (Lovelock and Gummesson, 2004) and the transition from product- to service-dominant thinking (Vargo and Lusch, 2004; Vargo et al., 2008). Further, from a quality control perspective, this application of SPC is not only (or even primarily) intended to limit the costs incurred by special causes, but rather to limit the costs incurred by their absence, thus providing a concrete measure for the holistic measurement of the cost of quality and the identification of over-service or over-maintenance.

The strong theoretical foundation of the developed measure secures a good generalizability, but it also dictates the limitations. While this general SPC-based measurement method is basically applicable to any population within the limits of statistical significance, certain requirements on data availability arise from the reliability theory. Depending on factors influencing the failure rate, we could expect that applying this measure would require being able to at least control for technology, equipment usage and environment. However, the bottom line is that the service information required for the measure is quite simple and could be expected to be available to any maintenance service provider, providing no decisive advantage for the servitized original equipment manufacturer (OEM) (cf. Oliva and Kallenberg, 2003; Ulaga and Reinartz, 2011).

Further, in this study we assumed the quality of the PM work to be constant. In other words, it need not be necessary to control for the maintenance technician performing the work. This assumption could be criticized as there is bound to be some variation in the skills of the field technicians. However, as the case company had detailed process descriptions for the maintenance work, along with a process for monitoring technician performance, we felt this assumption (and simplification) did not threaten the validity of the study.



Implementation effort	None, a part of the equipment design process	Low, intervention restricted to IT backend (operative systems)	Low (new equipment) – High (retrofit), requires sensors, communication infrastructure and analytics
Required data typically owned by	OEM	Service provider	Customer or OEM
Service timing determined for	Equipment design	Pools of similar equipment operating in a similar environment	Individual equipment
Service timing principle	Avoid under-maintenance	Eliminate both over- and under-maintenance	Eliminate both over- and under-maintenance
Learning mechanism	None	Adjust and observe	Real-time observation and adaptation

Figure 7. APM in relation to other PM approaches.

The developed SPC-based measure and the process for controlling service timing are intended for optimizing the relationship between output and outcome. The developed SPC based measure and control process together form the basis for APM, which essentially complements the current available options of DPM and CBM (figure 7). While CBM will provide the basis for the most optimal PM timing, APM provides better results than DPM over time, due to the control process which serves as a learning mechanism that reduces both over- and under-maintenance. However, in contrast to APM, CBM cannot be implemented for all maintainable technologies, and while CBM and APM share the need for an IT backend implementation, CBM also requires sensors to be installed at the equipment and data communication infrastructure for connectivity. While this is hardly a problem for new equipment, it may become a daunting effort when retrofitting larger, aging service bases.

Based on the benefits of APM relative to DPM (which is less optimal) and CBM (which requires more effort), we argue that APM may serve as a prerequisite and catalyst when moving towards more outcome-based contracts (OBCs). APM facilitates the transition through offering a cost-effective way of improving outcome attributability and quantifying/reducing outcome uncertainty (Eisenhardt, 1989a; Hypko et al., 2010b). While OBC-related research tends to focus on where OBCs work, where they do not and why (cf. Selviaridis and Wynstra, 2014), there is less research on the transition to OBCs, especially from the supplier's perspective (Sols and Johannesen, 2013). Considering OBC-related research, this study contributes by creating a design for performance measurement in the transition phase. In effect we highlight that outcome attributability and outcome uncertainty (which are antecedents to OBCs' success and attractiveness) can be affected by operations management designs.

From the service suppliers' perspective, moving towards OBCs implies a redefinition of service productivity and while service productivity remains a driver for profitability after the transition, productivity itself is redefined to "inputs per outcome" instead of "inputs per output". In other words, efficiency can no longer be measured separately from effectiveness; changing the focus moves it from productivity to effectiveness (Djellal and Gallouj, 2013). This issue emerged during the demonstration of the design, as the developed measure was contrasted against the established way of measuring service performance (resource utilization and efficacy). Here there is a partial trade-off between the two in the case of over-maintenance and mutual reinforcement in the case of under-maintenance, in other words, reducing over-maintenance leads to reduced resource utilization, while reducing under-maintenance leads to improved resource utilization. Considering this, we emphasize that despite the established methods of measuring service efficiency, effectiveness has to come first. A failure to appreciate this may lead to excess service in order to maintain high resource utilization, a similar but reversed phenomenon to the one described by Oliva and Sterman (2001).

7 Conclusions

In this paper we develop and describe a measure for managing PM service outcomes. The measure is founded on reliability theory and based on identifying special-cause failures (early and wear-out failures) amongst common-cause failures (random failures). The theoretical foundation implies that SPC is well suited for measuring PM service outcomes as SPC was originally developed to separate common- and special-cause failures. However, in contrast to many of the earlier applications of SPC, this measurement approach explicitly seeks to find the borderline where special-cause failures start to emerge. Thus, this approach not only seeks to eliminate under-service but also over-service, making it a suitable tool for the optimization of the total costs of quality.

The developed measure was tested in an empirical setting of three embedded cases where we found no indication of wear-out failures, and consequently we were able to conclude that the service provider could prolong their maintenance intervals by at least 5–10% on average. Further, we found evidence of maintenance induced failures, which means that in these situations prolonging the maintenance intervals would not only lead to sustained but also improved levels of service quality.

Considering the measure's impact on service operations, we have argued that being able to quantify outcome uncertainty and to attribute service outcomes to service actions through the presented measure is a precondition for moving into deeper relationship-based services with OBCs. This transition, involving at least a partial transfer of risk from customer to service supplier, also requires a change in the service operations management approach as a fleet perspective on service quality is introduced. The fleet perspective provides the basis for distributing risk among customers and, as presented in this paper, also serves as a basis for optimization of service provision. Further, the use of established service operations management KPIs, such as resource utilization, were discussed in the sense that measuring inputs, outputs and outcomes separately may, in the studied context, lead to providing services in excess.

The measure was founded on reliability theory, which provides a good basis for generalizing it, but we noted that information availability may limit applicability. Further, we noted that while remote-monitoring-enabled CBM essentially accomplishes the same objective as the measure (through eliminating over-maintenance), remote monitoring is more costly to implement (especially with old equipment) and is typically only applied for the most critical parts in equipment. Thus these two approaches for eliminating over-maintenance are essentially complementary.

Further research should be conducted in order to test the measure in different contexts within the limits of its generalizability. This research could be expected to reveal further context dependent mechanisms which may limit the applicability of the measure. Additionally, other service contexts where the outcomes are not clearly attributable to the service actions would probably be interesting contexts in which to apply the relative measurement approach presented here. Also other contexts where the services may be of a preventive and reoccurring nature (such as in health care and social services) are naturally interesting considering the application of the results of this study.

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