Evaluating the effectiveness of machine acquisitions and design by the impact on maintenance cost – a case study

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Preparation of Papers for IFAC Conferences & Symposia: Maintenance and Circular Economy 4.0 -

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Abstract: Industry 4.0 and circular economy are paradigm shifts for the industry. More and more machines will be used and the capability to maintain the machines becomes vital. The maintainability of a machine is to a large extent set already in the design phase; the goal of this article is to use a case study to investigate the quality of the machine design from a maintenance perspective. The results show that maintenance cost is gradually increasing in the initial part of the machine life cycle, that the new machines have higher maintenance costs than the machines approaching end of life, and that design weakness is a significant contributor to the maintenance cost. To understand more clearly why, further research in knowledge management, complementary qualitative interviews and smart maintenance is suggested.

Keywords: circular economy, maintenance management, smart maintenance, industrial acquisitions, industrial investments

1. INTRODUCTION

The society is changing faster and faster and companies need to adapt to be able to stay competitive. Society is demanding shorter development cycles and increased resource efficiency (Lasi, Fettke, Kemper, Feld, & Hoffman, 2014). To meet these expectations, Industry 4.0 has risen from industry and academia to address the next paradigm shift in industry; towards enabling the usage of internet of things and collaborative and proactive solutions (Bokrantz et al, 2017). When in place, the Industry 4.0 factory should have developed into an intelligent environment where the system of production equipment is exchanging information, triggering actions and controlling each other autonomously (Weyer et al, 2015). Industry 4.0 is also implicating that more and more, machines will be used to replace work previously performed by humans, meaning that there will be an increased number of machines in the industrial system. Another paradigm shift is the transfer to circular economy. Circular economy is an economic system with a main focus of reducing and eventually eliminating waste (Sheposh, 2017), and considered as an innovative approach used to increase the resource efficiency in companies by keeping equipment functioning for as long as possible (Wakiru et al, 2018). These paradigm shifts mean that the need to be able to maintain machines will increase exponentially. This shift will put even higher demands on designing the production system, on acquiring the machines and enable the ability to maintain them. Studies have shown that industry today has a low level of maturity regarding maintenance, with an industrial average still on 60% corrective activities (Ylipää et al, 2017). Of course, companies aiming for higher levels of automation must increase the amount of preventive maintenance work orders to avoid unexpected and costly disturbances. Simply investing in new technology for predictive maintenance could facilitate such shift. Other studies have shown that the design phase of industrial equipment is of particular importance for performance of the industrial system (Pistikopoulosa et al, 2000). Hence, it is important to track the industrial performance of the machines to evaluate the quality of the design process; the maintenance cost per equipment is one indicator of equipment performance (Salonen et al, 2011). Modernised maintenance operations, often referred to as smart maintenance (Bokrantz et al, 2019) could be a useful concept to take the next steps for the industry to reduce maintenance cost per equipment. This paper is evaluating the quality of the design process, in this case the acquisitions of machines, by focusing on the evolution of maintenance cost per equipment from a life cycle perspective. The outline of the paper is to start to describe the research approach including a description of the case company and the selected data, then a review of the theoretical framework of sustainability, circular economy, importance of design for maintainability and the importance of maintenance. The results of the case study is then presented, together with analysis and recommended further research.

2. RESEARCH APPROACH

The research design is a case study setup (Bryman et al, 2003) and is set-up as a empirical quantitative data analysis (Creswell, 2014). The studied case company is a global actor in the transport solution business with about 100.000 employees world-wide. Several brands are represented in the portfolio and also a variety of vehicles, from excavators to buses and trucks. This paper focus on data from one plant in the production system and the machining shop in that plant. The shop is producing a significant volume for the company; hence the conclusions are considered to have high relevance for future applications. The plant is mature in data collection, having captured waste and loss data on a significant level of detail for more than ten years. The data collection technique used is to use the already existing quantitative waste and loss data that the site has captured, focusing on a five-year period. The specific data criteria is selected to understand the difference in maintenance costs during two specific phases in the life time of a machine; in the young stage and in the end of life stage. The data is automatically captured real-time and one quarter represents close to 100.000 data points and quantifies the financial impact of the loss. The loss categories are applied by several companies in the automotive world (Chiarini et al, 2015), but other companies may have slightly other definitions and ways to capture the data. For confidentiality reasons, the data has been adjusted with a factor to only visualise the relative evolution, not the actual costs. No currency is displayed for the same reason.

This case study concerns the machining shop in one plant in the production system. This plant has around 1000 machines with large size, complexity and purchase value. The operations that are performed are subtractive manufacturing or machining with the advanced operations of turning, drilling and milling. The data is collected real time or the same day, and is aggregated each quarter for analysis and prioritisation of improvement projects. The data is collected to a large extent automatically but also manually in the operational processes. The data is then categorised in one of 110 categories to select from. For maintenance, there are six categories of breakdown root causes:

1. Autonomous maintenance – Wrong autonomous maintenance procedure performed by the production operator
2. Human error craftsman – Wrong contractor maintenance due to lack of knowledge
3. Human error maintenance – Wrong procedure performed by maintenance professional due to lack of knowledge
4. Human error operator – Wrong operation performed by the operator due to lack of knowledge
5. Professional maintenance – Wrong procedure or procedure not executed by the maintenance professional
6. Design weakness – Wrong design of the machine

The last category, design weakness, is the most relevant root cause to investigate for this article. This category is used as the booking code for breakdowns that occur in production which are related to the design of the machine. There could be other problems that could be traced to design, but breakdowns booked in this category are directly linked to design weakness. All breakdown data is collected by the maintenance technician in a specific standardised format for each breakdown. All six categories described in are defined together with the metadata such as the machine number, component number, problem description and other useful information. A photo of the component is also added to the documentation. The technicians are trained in how to fill this in. Each of the breakdowns is reviewed in a fora with a team of technicians to secure the competence growth, but also to have second opinions on the selected root cause. In the training, the team is advised to thoroughly investigate the possibility of the root cause to be in the number one to five categories before selecting the "design weakness", as design weakness is the most difficult category to improve. For that reason, the bookings made on design weakness is probably a conservative number. On a high level, there are two different types of design weaknesses. The first type is the lack of inherent strength, resulting in a component that is not able to fulfil its task. The second type is related to an improper design that creates failures somewhere else, i.e. the component is sufficient, but it creates failure in another function. The maintenance costs is calculated as the cost if missed time in production, plus the cost of the time for the maintenance technicians plus the cost of the spare part, if any component needs to be replaced.

The approach for this case study is to compare breakdown data as maintenance cost which is collected for 21 <u>new</u> machines during a five-year period, 2014 to 2018, and compare to the maintenance cost for <u>existing</u> machines which is about 1000 machines. The 21 machines have been continuously purchased since 2014 and their cost of maintenance have been evaluated during the coming five years. These machines' maintenance cost is then compared to the maintenance cost of another 120 machines closing to their end of life, with the assumption that the average life cycle is 25 years. The maintenance cost is tracked for all machines in the plant. The maintenance cost consists of both corrective and preventive maintenance and the total maintenance cost is the sum of the two.

3. FRAME OF REFERENCE

The urge from society and industry to provide and ensure a sustainable way of living is increasing more and more. We are using the earth's resources at a pace that cannot be maintained (Farley et al, 2013). Continuing on the current development path would require approximately 2.3 planets earth to support existing levels of resource and energy use, and waste production, projected out for a global population which will reach 9 billion by 2050 (Bell, 2016). The word "sustainable" is now used across many sectors of society and can be difficult to define exactly what is meant (Carr, 2018). The Cambridge dictionary defines it as "the quality of being able to continue over a period of time" and with environmental sustainability the definition is slightly more detailed; "the quality of causing little or no damage to the environment and therefore able to continue for a long time". Bell (2016) has described sustainability as being about "designing and organizing human activity in such a way that the complexity and interconnectedness of all systems are taken into account and the survival of any one system is dependent on the health of the others". Bell continues, "Sustainability is generally concerned with both the health of the planet as a provider of life systems for humanity and the establishment of knowledgeable and empowered societies."

Connected to sustainability, and with a more business-oriented focus, is the term circular economy. Circular economy is an economic system with a main focus of reducing and eventually eliminating waste (Sheposh, 2017). Sheposh states that "a circular economy follows a founding principle of reduce, reuse, and recycle. It advocates reducing the use of raw materials, reusing materials to make new products, and recycling existing products. A circular economy (…) attempts to eliminate waste by designing business models, materials, and products to maintain their maximum value". As more and more activities will be automised via machines, which are supposed to be connected to each other in Industry 4.0, more machines and above all more advanced machines will likely be the result. The sustainability and circular economy ambitions, including ensuring that the maintenance activities in themselves are environmentally friendly and eco-responsible, so called green maintenance (Stuchly et al, 2014), will then mean that the ability to maintain these machines will be of significant importance. As with any product, the engineering design of a machine follows the same product development steps. Also for machines, engineering design is nowadays more environmentally conscious, which leads designers to investigate the environmental impact of the products (Kamrani et al, 2013). Sustainable design is nowadays looking at the full cycle of the product, from "cradle to grave"(McDonough et al, 2002). When designing an industrial machine for the automotive business, the uptime of the machine and the maintainability becomes very important functional requirements to support the "reduce, reuse and recycle" principles of circular economy. The maintainability is decided already in the design phase of the machine, sometimes referred to as the early management process (Diaz-Reza, et al, 2019). Early management is defined as the process of applying "techniques to design a low life cycle cost by creating reliable, safe equipment, and processes that are easy to operate and maintain". There are various reasons why a company would like to invest in new machines; it could be to increase capacity, replacement or introduction of new products that the current equipment is not capable to produce. Equipment acquisition in this definition concerns machines that are not bought off the shelf but are instead design to order, leading to longer lead times and higher procurement cost (Yeo et al, 2006). To meet this challenge in product development, a well-developed collaboration between supplier and buyer is advocated (Hoegl et al, 2005). Equipment investments are usually conducted in projects, which entails project metrics as time and cost (Jha et al, 2007). Internal documents states that the purchase of the machine should not only be about the investment but rather to procure the best possible equipment by using existing knowledge and experience. To make sure the adequate knowledge is available for ongoing projects, several activities need to take place outside of the project environment (Stenholm, 2018). Knowledge should be collected from several parts of the organisation and be fed into the procurement process to ensure the best equipment is purchased from several angles of operations.

To improve, or keep the performance of any manufacturing system, or to make it reliable, maintenance is considered as an important aspect. Maintenance is a process for maintaining equipment to keep its good operational state; either by preventing it to reach to a failed state or by restoring it to an operational state (Misra, 2008). To execute the process, various types of maintenance activities are performed, such as preventive, predictive or corrective. Effective maintenance is critical to many operations like extending equipment life and retaining it in acceptable condition so that the equipment´s availability improves (Swanson, 2001). In general, old and deteriorating equipment is not able to produce the correct quality output, which leads to low overall equipment effectiveness (OEE) and high prices (Al-Najjar, 1996). To achieve high equipment availability and high performance, the execution of efficient equipment management programmes like maintenance processes are necessary (Raouf et al, 1995). If maintenance process is not run efficiently, it shows effects on disturbances in production processes which further leads to reduced productivity, increased product cost and thereby reduces profitability (Alsyouf, 2007) (Cholasuke et al, 2004). The aims of enhancing a company´s profitability and continuous cost reducing plans can be achieved through good maintenance process and efficient early equipment management. The maintenance work performed to uphold the equipment in acceptable state is categorised as preventive maintenance (PM), corrective maintenance (CM) or predictive maintenance. The maintenance activities performed after the failure occurred are under corrective maintenance, whereas preventive maintenance activities intervene in the equipment process before failure occurs. With the change in requirements from industry, these activities are shifting from preventive maintenance (PM) to design-out maintenance (DOM) and total productive maintenance (TPM). Another terminology is predictive maintenance which is seen more in literature and is aspired by the industry. Deighton (2016) states that equipment reliability over time can be described in several curves as Figure 1 is showing below. Until recently it was thought that curve A was the predominant representation of the lifetime of a machine or component. Recent research shows that this is actually only true on 4% of the cases. Figure 1 shows also that only in 5% of the cases (curve C) the failure rate is progressively increasing over time.

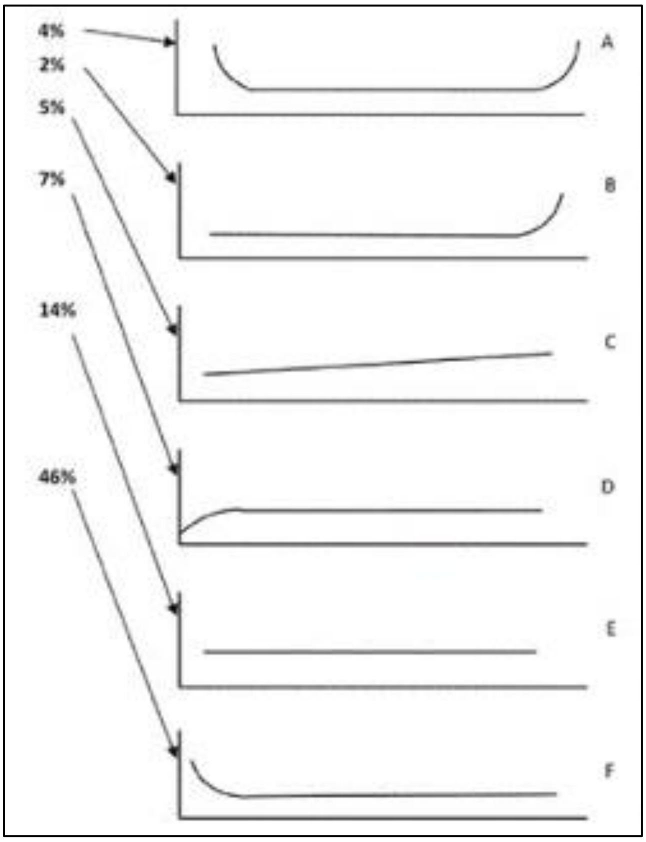

Figure 1: Visual representation of failure rate in components or machines from cradle to grave (Adapted from Deighton, 2016)

To summarise; from theory it is known that soon there will be more machines than ever in the industry. The paradigm shift towards circular economy is also shifting the view of maintenance as a cost source to a value adding activity. The equipment performance is established in the design phase which means that there is a need to secure the role of maintenance holistically and to leverage the potential of maintenance already in the design phase.

4. RESULTS

Figure 2 shows the maintenance cost evolution, both in absolute terms and in percentage increase every year in the initial phase of the machines' life. The expected lifetime is assumed to be 25 years. Year 0 is the year when the machines started to be purchased and as described below, the maintenance cost is increasing each year. For confidentiality reasons the costs are masked to only show the relative increase. Figure 2 shows that the maintenance cost is increasing with 59% from year 1 to year 2, with 12% between year 2 and year 3, and with again 18% between year 3 and year 4.

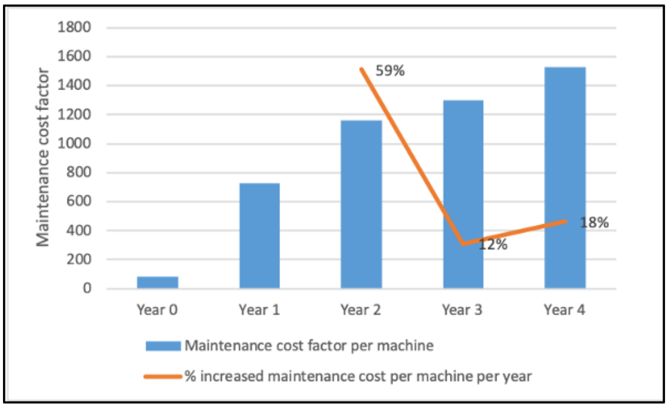

Figure 2: Maintenance cost evolution for the initial life of the purchased machines; absolute numbers and the relative increase per year (a cost factor is used for confidentiality purposes)

In Figure 3, the maintenance cost per machine in the initial phase of the lifetime is plotted together with the maintenance cost for machines that are being phased out and compared to the bathtub curve from Figure 1. This shows that the data is not following the expected evolution in terms of component reliability. The bath-tub curve is chosen only to show the profile of the curve, the amplitude of where it should be placed on the y axis is difficult to state. The graph indicates that the old machines, close to end of life, is performing better in terms of maintenance cost per equipment than the recently purchased machines.

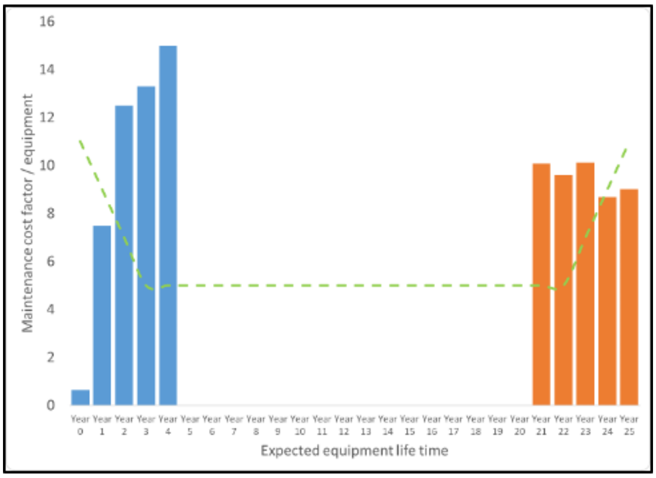

Figure 3: Maintenance cost data for the initial and end phase of the life cycle, plotted against the theoretical bath-tub curve regarding reliability of components and machines

To understand more the impact from design in the maintenance cost evolution, Figure 4 shows the evolution of design weakness as the root cause of maintenance cost. The breakdowns due to design weakness is increasing the first three years and is after that on a more stable level. Also, the share of maintenance breakdowns due to design errors continues to be between one quarter and one third of all breakdowns. Design errors should normally be detected in the early stages of operations and then eliminated by adjustment. The data below is following that theory initially but is then staying on a plateau without further reduction and still contributing with a significant share of the total number of breakdowns.

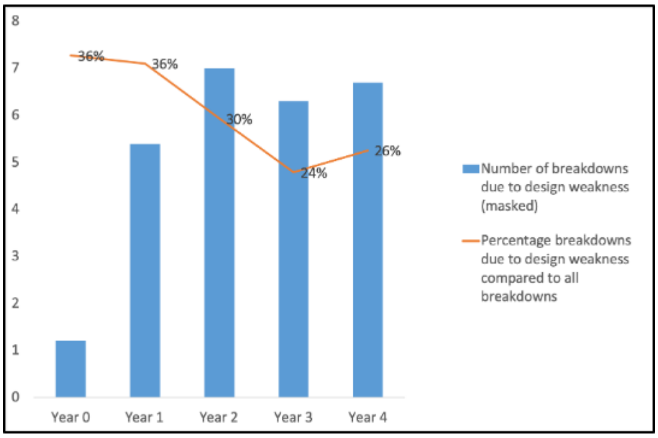

Figure 4. Comparative occurrence of breakdowns due to design weakness over years in production

5. ANALYSIS AND CONCLUSIONS

Exploring the contribution from maintenance into circular economy, the data from the study shows three major findings:

1 From Figure 2; in contrast with theory, the maintenance cost per machine seems to increase instead of decrease during the initial phase of the life cycle.

2 From Figure 3; in contrast to the ambitions with the design process, the new machines have higher level of maintenance cost than the end of life machines

3 From Figure 4; in contrast with theory, the design weakness part of the maintenance issues stays on a plateau rather than decreasing in the initial phase of the life cycle

The data is showing that maintenance of new machines continues to be an issue for the case company and could possibly also be an increasing issue. This is supported by the data in Figure 2 where the maintenance cost is increasing with between 12 to 18% each year in the initial life of the machine. To evaluate the effectiveness of the acquisition process, the data from Figure 3 shows that the machines that are purchased recently have higher maintenance cost factor; year 4 the factor is 15, than the old machines that are nearing their end of life that has a maintenance cost factor of in around 9. Figure 4 is also investigating the effectiveness of the acquisition process; that this in year 4 in the life of the machine, maintenance problems that are related to design issues is still 26% of the total number of breakdowns. The findings support the theories that the design process is becoming less effective; but could also mean that the machines that are purchased recently are more complex to operate and maintain. The data is showing that design weakness, meaning a problem with the machine that is due to the design of the machine, is on a high level and continues to be. There could be numerous reasons for this, for example increased workload of the engineers, complexity increase in the machines or increased complexity and globalisation of the supplier base; but it indicated that there is an opportunity for increased awareness and knowledge of maintenance aspects in the design phase. Earlier studies in the case company (Blomberg et al, 2019) have shown that the success of the design projects in terms of expected properties fulfilment is only monitored, in the best case, for one year. There is a potential to follow the performance of the equipment for a longer period to detect the true issues and feedback to the design process as learnings from production. The metrics shown in this article could be used as performance metrics for the engineering community. Earlier studies in the case company have also shown that the design guidelines are more of procedural guidelines on a macro level and could benefit to move to a more analytical micro level of guidelines to support the knowledge creation and reuse further (Blomberg et al, 2019). For machines, maintainability described as a property indirectly influenced by the developer, could be treated as a product characteristic as it is one of the main characteristics that the company wants when buying this kind of product. Design for maintainability could therefore be more emphasised in the design guidelines. Smart maintenance could be an interesting concept to modernise the maintenance operations. The main factors in this concept are data-driven decision making, human capital resource, internal integration and external integration; and it is mentioned that all four components are important to be able to be “smart”. By using this model to analyse the findings from this case study, this paper shows how data could be used in decision-making in the design phase by deeper integration, not only between production and the acquisition organisation but also the potential to involve the suppliers further. To be able to do this the human capital and knowledge re-use need to be further developed. Some limitations of this paper; the scope was on these 21 machines which are in a specific part of the workshop, it would be valuable to perform this analysis on the entire machine park. Another limitation is that the data is purely quantitative, the understanding of this data could be enriched were it complimented with interviews.

6. FURTHER RESEARCH

To understand further the three major findings, it would be relevant to learn more about the management regarding individual, global and organisational maintenance knowledge. Firstly; how deep is the knowledge regarding maintenance in production, and secondly; how is that knowledge from operations transferred and reused in design of the equipment? It would also be interesting to have more qualitative data regarding the quantitative data that is presented in this paper; how does the organisation interpret the data and are there other parameters that were not considered by just looking at the quantitative data? Lastly, comparing this data from the case company to other industries would be highly relevant to understand the validity of the conclusions outside of the studied case. Broadening the focus; and considering the research agenda for industrial maintenance management as defined by Bokrantz et al (2019), the suggestion is to not only look into what smart maintenance could support with, but also to investigate the enablers of smart maintenance. Three categories of enablers are identified; the institutional fit, the contingency fit and the contextual factors. These enablers could support the community to understand further why maintenance organisations need to undergo structural adjustments and why this adjustment is difficult.

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