Journal of Machine Engineering, Vol. 11, No. 4, 2011

reliability, life cycle costing,
predictive maintenance

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LIFE CYCLE COSTING USED FOR JUSTIFYING TRANSITION TO PREDICTIVE MAINTENANCE STRATEGIES

As the market imposes constantly increasing levels of reliability and availability of production equipment, it is necessary to shift the focus of maintenance toward predictive strategies. However, as any other investment, implementation of the required condition monitoring systems has to be cost justified. This paper presents a case study showing use of LCC calculations to assess changes of maintenance strategy for a CNC machining centre. It was proven that replacing reactive maintenance tasks with simple condition monitoring and preventive activities results in lower whole life cycle cost of the analysed machining centre.

1. INTRODUCTION

Maintenance is today recognized as critical factor for effective production. This is due to two reasons. Firstly, ability to provide a wide range of customised products is today a qualifying competitive priority. The need to ensure short lead times at low inventory levels forces flexibility and reliability of production lines as well as good coordination within logistics channels. Secondly, the maintenance function consumes substantial funds, and efforts should be made to turn it to be cost effective. Depending on the industry, maintenance costs account for between 4 to 15% of operational costs. Typically, this corresponds to approximately 20% of the value of fixed assets in the company [6].

Jon Moubray [4] recognises three generations of maintenance - the first one, until the World War II, characterised by focusing on repair tasks, the second , lasting till beginning of seventies, focusing on preventive maintenance and improvement of planning and scheduling, and the third, present-day generation focusing on predicting, preventing and avoiding the consequences of equipment failures (“the reliability centered maintenance culture” RCM). During last twenty years we have also seen extensive research efforts taking up topics like maintenance prevention, failure elimination, early equipment management (focus on equipment selection), as well as design for maintainability and reliability. It could be called for the fourth generation of maintenance [1].

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The first and second generations of maintenance were based on the assumption that the life cycle of any component behaves according to the profile ‘A’ in Fig. 1. This profile, called ‘bath tub’ illustrates increased frequency of defects immediately after installation,

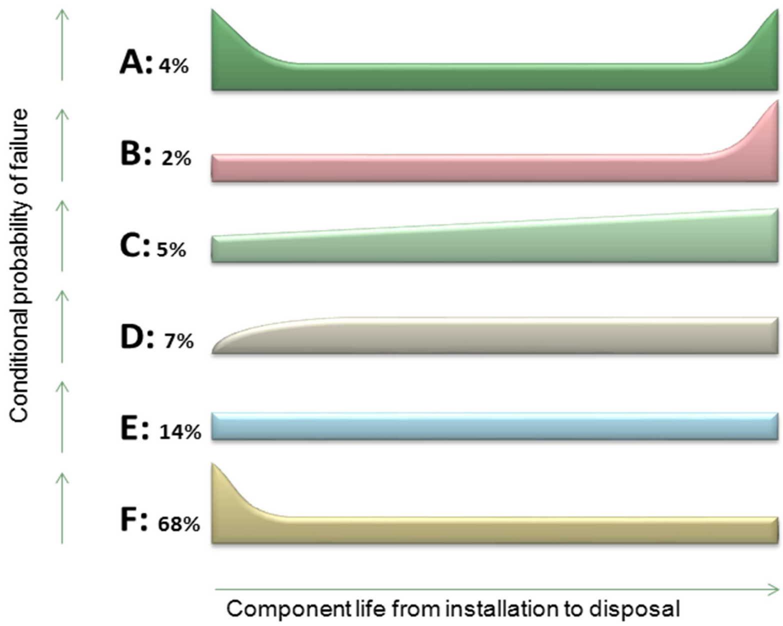


Fig. 1. Conditional probability of failures with regards to life span

then a relativelly stable period of operation, and then, to the end-of-life, re-growth defects caused by wear out. It was presumed, that knowing the time when the failure frequency start to grow one may determine when the component should be replaced. There are however some weak points in this reasoning, in the first place, even if the increase in frequency of failures could be found, the spread of the data was large, and the ‘optimal live period’ quite unsure.

The most important achievement of the third generation of maintenance (RCM) was model describing six basic types of failure modes for common equipment components (A:F in Fig. 1) developed by Heap and Nowlan. Conducting a comprehensive study, they showed that not more than about 4% of the components behave according to the ‘bath tub’ pattern (‘A’), and warned against excessive faith in the effectiveness of periodic prevention methods.

An important observation from Fig. 1 is, that 72% of the components (patterns ‘A’ and ‘F’) show an increased incidence of defects immediately after installation (‘infant mortality’). This means that a lot of problems are initiated by the maintenance work it selfs.

Besides that, as much as 89% of components (patterns ‘D’, ‘E’, and ‘F’) do not show any sign on wear out. Observe that from this point of view, the frequently used periodic component replacement strategy turns out to be a hazardous venture. Paradigm shift to focus on predictive maintenance techniques (condition based maintenance, CBM) is necessary. However, many experienced maintenance people are today skeptical to the CBM approach.

The reason lays probably in the mistakes of the past. Complicated and expensive measurement tools required employment of specialists in the field of signal analysis and vibration theory. Unfortunately, they often had no experience in maintenance and were primarily focusing on development of signal analysis, while research on the development applications to prediction of faults have been neglected. Much to often the purchased systems do not lead to increased plant availability and only caused increased maintenance costs. The main reason for unsuccessful deployments was mainly overlooked real cost of these solutions, and lack of sufficient understanding and properly addressing of maintenance issues. Restoration of a positive trend in the development of predictive maintenance requires establishment of a credible economic model showing the total real costs of considered maintenance strategies. In this article I demonstrate a practical example of use of machine life cycle costs model (LCC) for this purpose.

2. LIFE CYCLE COST

LCC is a net present value of the total direct and indirect costs and consequences incurred in all phases of the entire life cycle of the asset. It includes cost of the initial investments in development, production, and installation, along with the further costs of operation, maintenance, and disposal, together with all the risks associated with the asset.

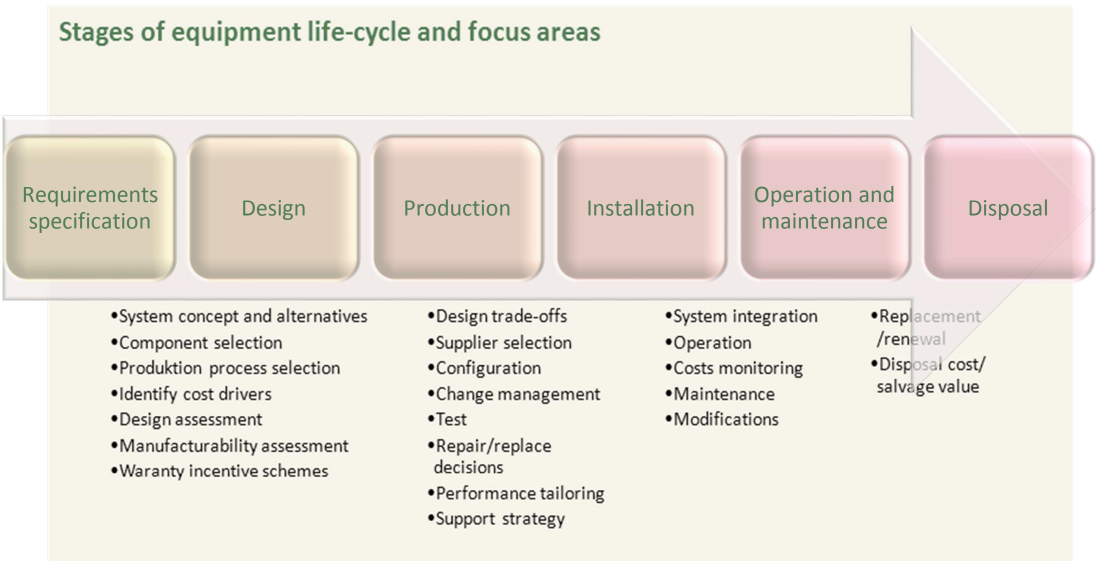


Fig. 2. Stages of a product life-cycle

LCC is not widely used – only ca 14% of all companies use it today. Most companies prefere to use “Minimum Adequate Design” (MAD) approach, where the purchase costs are kept to a minimum, and the cheapest system meeting the requirement specification is purchased. A larger budget is than assigned to the operation phase. Experiences show however, that such investments suffer from poor initial decisions, and result in high whole life cycle costs [3]. From this point of view, LCC is a much better tool.

Structure of LCC model and the cost drivers used depend on the objectives. In an early investment stage, the objective may be, for instance, to assess some proposed solutions with regards to system level performance parameters such as total acquisition cost, business interruption cost, or final total operational cost. In the exploitation phase, one would like to assess some different projects aimed at, for instance, increasing availability, reducing maintenance costs, or prolonging equipment life.

In both cases the LCC model is build by defining objectives and criteria for the outcome solution, and then identification of relevant cost drivers allowing comparison of (at least two) competing alternatives. Final sensitivity and risk analysis is necessary in order to evaluate the uncertainty related to each of the cost drivers.

3. COSTS OF DEFECTS AND FAILURES

A Failure is defined as inability of an asset to deliver the required function within the required performance. The initial capability of an asset have to be somewhat higher than required, so the machine may operate within a maintainable envelop, and allow (by trending) to find onset of failures.

Costs associated with machine breakdown may be identified by breaking down the related processes into basic activities, and find out costs associated with them in the breakdown situation. One should take into account not only the costs incurred from maintenance work and spare parts but also the production losses, costs of idle assets and unoccupied personnel during the repair, cost of redundant assets put in place to cover the insufficient availability, cost of facilities, cost of re-planning and moving the production, as well as the lost opportunities for profiting. There are also incurred costs associated with management activities, data processing (documentation personnel), other departments involved or effected in any way, including any utilities used during the breakdown. Consequential costs such as returns, legal costs and penalties, environmental effects, medical costs, etc. also have to be considered [2],[5].

Based on the total costs associated with the possible failures, as well as predictions of failures frequency it is possible to calculate the costs that might be incurred throughout the whole life-cycle of the asset.

4. THE CASE STUDY

This case study covers selection and economic justification of some changes in maintenance approach made with the purpose to improve the operation of a horizontal CNC machining centre SW EMAG B600-2. This centre is used for milling of internal bearing sections of connecting rods, and is installed in one of the Swedish automotive companies. Machining process is carried out by two identical spindles located in a distance of 600 mm from each other. The machine is operated on a 3-shift basis.

An operator connected to this machine is measuring sample connecting rods, once in every two minutes. He is doing the same job for two machining centres, thus he spends half of the shift on measurements. The purpose of the measurements is to track any deviation from the required tolerances, and than stop the production.

The main problem with the system is the relatively high number of unexpected interruptions in the production process having a considerable impact on the exploitation costs. Therefore, it was worth to check if change in maintenance routines would improve the situation. In this purpose two alternatives are compared:

1. The current system being in operation (called further ‘alternative A’)
2. A system with changed maintenance routines using more condition based monitoring techniques (‘alternative B’)

Alternative A - the current way of working – In the current situation, maintenance of the machining centre is based mostly on reactive and only partly on planned preventive maintenance. Typical corrective work includes fixing or replacing some defective components and calibration. If an encountered failure cannot be localized /diagnosed, a specialist performing a comprehensive machine test is called in.

The machine test includes ball bar test, vibration analysis (trend), thermography and standard geometry measurement. The whole test takes between one to two hours, and requires that the work centre is closed down. The frequency analyzer is able to diagnose several mechanical disturbances, related to bearings, rolling elements, holders, surfaces exposed to friction, fittings and even some lubrication problems inside the machining centre.

Although the machine test could be used for condition based maintenance, it is used in the present setting as diagnostic tool after a failure occurs (reactive maintenance).

Alternative B – change of maintenance routines. Selection of appropriate changes was performed by identifying critical components together with related failures and failure modes. Each failure mode was than associated with a proactive task, and corresponding monitoring technology. The critical components and related failures were identified in FMEA table build by using failure history records from company’s CMMS system. The software stores reported start time of the failure, failure type, priority, action taken (including report on used people and resources) and completion time Table 1.

Table 1. A fragment of failure history records from CMMS system

Failure No	Type of Failure	Definition of Maintenance Task	Priority	Start Date/Time	Finish Date/Time
1	Mechanical Failure	Turret aligned	1	2003-09-07 22:40	2003-09-08 02:30
2	Electrical Failure	Position scale adjusted	1	2003-09-10 00:21	2003-09-10 02:00
3	Mechanical Failure	-	1	2003-09-30 20:39	2003-10-01 10:00
4	Electrical Failure	Fault fixed, turret aligned	2	2003-12-15 06:44	2003-12-15 07:30
5	……..				
….	……..				

The priority code system of the failures is based on 6 different levels, of which two are associated with serious consequences: 1 – break down with safety problems, where immediate work is required, 2 – break down with production stop. The other failure priorities do not require immediate intervention; the machine run to failure and then become level 1 or level 2 failure. Therefore level 3 failures are disregarded in the model. Level 4, 5 and 6 type failures and actions belong to scheduled maintenance work section.

The historical maintenance data was available from September-2003, when the centre was installed, until the day of analysis (2011). During this 8-year period, 200 individual level 1 and level 2 failures have occurred - 116 mechanical and 84 electrical.

The failure history records allow calculation of the cost until 2011. To compute the total life cycle costs, the costs of the rest of the equipment life (15 years) were estimated.

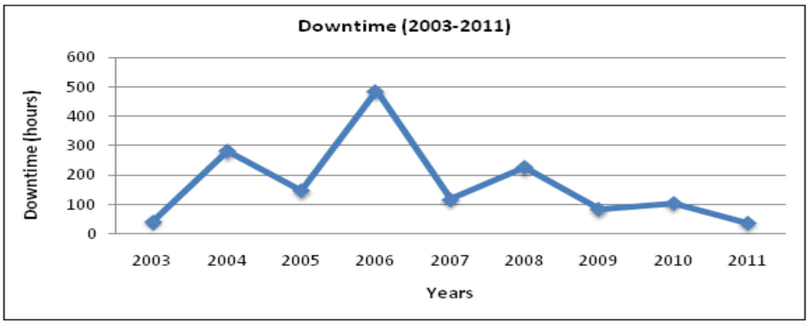


Fig. 3. Annual downtime caused by unexpected failures.

In addition to the downtime due to unexpected failures the production is also stopped for planned preventive maintenance. The data is available from CMMS as well, and, as above, interpolated for years 2012-2018. In average, the frequency of preventive maintenance is 5 times per year, and the average time spend is 452 minutes.

FMEA Table 2 shows that the most frequent failures have been observed on three componens – turret, spindles, and supports. 64 out of the total 200 unexpected failures have occurred due to the malfunction of them. The frequently recurring failures on these components were positional misalignment and excesive vibrations.

After analysis I found, that the two failure types may be prevented by two simple means:

1. Human senses – operators will perform weekly inspections of positions and condition of turret, spindles and supports – any possible onset of problem will be reported and proper action planned by maintenance technicians. This inspection is estimated to take 30 minutes.
2. Machine test – the machine test used today for diagnosis will be instead scheduled as monthly routine to trend the vibrations and positioning problems in aim to prevent the unexpected failures on turret, spindles and supports. Duration of one test session is set to 1.5 hours, and will include all the other preventive tasks, and there will be no other stops for planned preventive maintenance activities.

These two methods do not require any additional initial investments as they are already accessible in the actual production environment.

Table 2. FMEA for selected components

Sub System: Turret

No.	FUNCTION	FUNCTIONAL FAILURE		FAILURE MODE		FAILURE EFFECT	FREQUENCY
1	Holding multiple cutting tools and indexing them for auto tool changes and operations also many auxiliary functions including providing a solid base and coordinates movement etc.	A	Tool change not possible	1	Calibration out	Excessive vibrations. Stop. Average downtime 5.5 hours	35
		B	Stop due to electrical malfunction	1	Sensor false alarm	Tool change operation effected, quick maintenance check needed, average downtime is 0.56 hours	2
				2	Control card malfunction	Tool change operation effected, control card &/or LT module changed and average downtime is 5.82 hours	2
		C	Normal tool function not possible	1	Turret driver needs lubrication	Excessive vibrations. Driver has to be lubricated. Average downtime 0.42 hours	1
				2	Worn out bearing	Excessive vibrations. Bearing has to be replaced. Average downtime 30.3 hours	1
		D	Coupling failure / disconnection from main shaft	1	Coupling malfunction	Tool change not possible . Coupling has to be repaired. Average downtime 1.6 Hours	1

Sub-System: Spindle

No.	FUNCTION	FUNCTIONAL FAILURE		FAILURE MODE		FAILURE EFFECT	FREQUENCY
2	Tool holding and rotation	A	Product out of tolerances	1	Spindle misaligned	Cutting operation fails to meet tolerances and average downtime is 7.65 hours	4
				2	Spindle unstable	Cutting operation fails to meet tolerances and average downtime is 5.18 hours	5
				3	Base plate damaged	Machine stops, average downtime is 4.75 Hours	1

Sub System: Support

No.	FUNCTION	FUNCTIONAL FAILURE		FAILURE MODE		FAILURE EFFECT	FREQUENCY
3	Support for longer work pieces. Damps vibrations.	A	Geometrical displacement	1	Support gets misaligned	Machining tolerances are effected due to the misalignment. Average downtime 5.95 hours	4
				2	Support damaged	Machine stopped. Average downtime 15.1 hours	1
		B	A bearing failure	1	Residue buildup	The bearings and the support become clogged with residues and effect operation. Average cleaning downtime 3.66 hours	2
				2	Bearings worn-out	Work piece dimensions out of tolerances. Average downtime 15.71 Hours	2
				3	Bearing screws loose	Work piece dimensions out of tolerances. Average downtime 0.46 Hours	2

The cost drivers related to purchase, installation, operation, maintenance, consequences of downtime and disposal with their detailed sub-elements were quite easily obtained from economy department. As the cost of downtime was recently examined by the department, the involved peeople had the details freshly in memory. There are in total thirty three cost elements used in the model. They are put togheter in an excel table organized as below Table 3.

Table 3. Fragment of the LCC model for alternative A

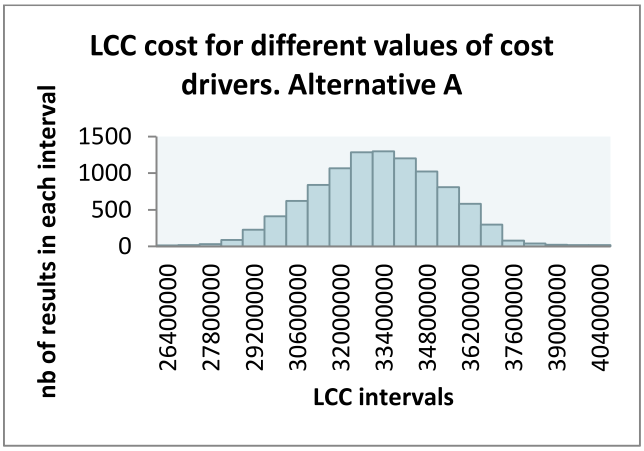
ALTERNATIVE A								
COSTS			2003	2004	….	2015	TOTAL	NPV
Purchase			8587422	…				8587422
Installation			451973	…				451973
Operation	utilities	electricity	119500	…				3768023
		lubricant	289	…				9120
		coolant	8305	…				261877
	workforce		306000	…				14368409
	material		15000	…				623834
Maintenance	corrective	labour	10500	…				809446
		material	2165	…				111262
	planned	labour	4000	…				152239
		material	825	…				20684
	CBM		0	…				0
Consequences	idle operator		7250	…				442365
	lost production		62350	…				2468934
	safety/ environment		0	…				0
Disposal	uninstallation			…				0
	transport			…				0
	Legal			…				0
TOTAL COSTS								32371687
SAVINGS								
maintenance			3500	…				167378
disposal	salvage			…				666317
	reusable parts			…				0
TOTAL SAVINGS				…				833696
WHOLE LIFE CYCLE COST				…				31537991

5. RESULTS OF THE LCC ANALYSIS:

Comparison of LCC for the two alternative strategies for maintenance of the studied machining centre is showed in Table 4. As we can see, implementation of predictive maintenance (Alternative B) results in lower whole life-cycle cost and should be considered for implementation. However, before we can make this decision it is necessary to investigate uncertainty of the model. Analysis of model sensitivity is done using Monte Carlo method. The cost drivers are described with their probability distributions (when known) or presumed vary within ±10%. We change all the cost drivers with smal increments and calculate the total LCC cost. The simulation results are shown below as histograms Fig. 4.

Table 4. Net present values for each alternative (discount interest rate 4%)

NPV of Costs & Savings (SEK)	Alternative A	Alternative B
Total Costs	32.371.687	31.713.997
Total Savings	833.696	839.240
Whole Life-Cycle Cost	31.537.991	30.874.757



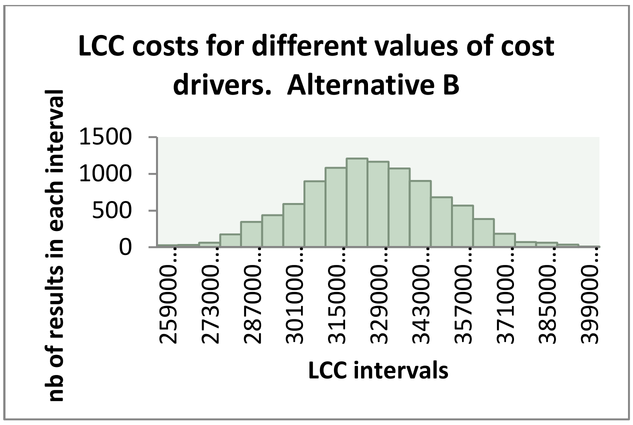


Fig. 4. Distribution of Monte Carlo simulation results. Histograms for alternatives A and B

6. CONCLUSIONS

This paper presents development of life cycle cost model aimed to support decision making when selecting maintenance strategies. The model was used in a case study for assessment of maintenance actions for a machining centre. It is demonstrated that this model may add high credibility to the maintenance planning process.

The model was built in three steps. The first step was to define correct cost drivers for the whole life cycle cost of the analysed machining centre. Some of the cost drivers overlapped each other, so relations between them were identified to achieve correct cumulative results. The model structure was analysed from different points of view and discussed with many stakeholders. As the company recently accomplished investigation of downtime costs for the actual department, the economy people had the details fresh in their minds and the work proceeded quickly and efficiently. The next step was to develop calculation sheets, put all the data together, and calculate net present value of the two alternatives. This step was quite laborious. Finally, Monte Carlo Simulation was used to investigate if the possible parameters uncertainty may affect the results - i.e. if the life cycle cost was lowest for, in this case alternative B, within the entire parameters space.

For the given case study, we could prove that applying periodical visual checks, 4 times a month, in addition to regular machine test once a month is considerably decreasing number of production stops, and results in lower live cycle cost of operations than in a case when the company continues the present way of maintenance.

This research is very promising and will be continued. The next step is development of dynamic LCC structures and procedures for automatic extraction of data from CMMS and ERP systems.

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