Life-cycle oriented development of machine tools

B. Denkena[1], A. Harms[1], J. Jacobsen[1], H.-C. Möhring[1], D. Lange[2], H. Noske[3]

[1] University of Hannover, Institute for Production Engineering and Machine Tools, Germany

[2] Artis GmbH, Germany

[3] Ingenieurbüro Dr. Noske, Germany

Abstract

For the investment decision for new production equipment it becomes more and more common to guarantee the total amount of life-cycle-costs (LCC). In the research project "LoeWe", funded by the German Federal Ministry of Education and Research (BMBF), methods are developed to minimize life cycle costs in the development, operation and recycling phase. Exemplarily the development of an innovative vertical turning machine demonstrates various strategies to minimize LCC. Exchangeable technology modules extend the economic life and monitoring of selected machine components help to avoid unplanned service standstill. A LCC navigator optimizes the balance of purchasing and consequential costs.

Keywords

Life Cycle, Machine, Monitoring

1 INTRODUCTION

In the automotive industry a general tendency towards a life cycle cost calculation is obvious. Machine tool manufacturers are obliged to foresee and guarantee the consequential costs of their product for a previously defined lifetime. If more service and maintenance is required than forecasted, the profit of the machine tool provider is reduced. Machines with less downtime and longer service intervals become more profitable. Therefore a higher machine tool quality and a longer and predictable component lifetime become more important. Consequently, automotive industry investors do not tend to prefer the machine tool with the lowest investment costs anymore.

The modified calculation base has several consequences regarding the machine tool design. Higher quality components can be applied. Hydraulic supply, normally required to drive the clamping system of the main spindle, causes high maintenance costs. An approach to avoid these costs for a new machine tool series developed within the research project “LoeWe”, which is an acronym for life-cycle oriented machine tool, is to abandon all hydraulic components. Monitoring mechanical parts as for example ball screws, allows to replace the components when it is necessary and not at the calculated life time. This also enlarges service intervals.

An LCC navigator is being developed within the project. This software tool helps to optimize the choice of components with respect to low life-cycle-costs in the design stage. It also can be used in the development of machine tool components like clamping devices. As it offers the opportunity to clearly identify the main cost factors (including life-cycle-costs), it can be derived which components are worth to be monitored over their life-cycle.

2 CUSTOMER VS. MANUFACTURER DEMANDS

End users of machine tools have to react flexible on changing market demands to produce high-quality products at a growing variety but shrinking lot sizes.

Today’s machine tools and production systems have a lifetime of 10 to 15 years. The product series that are being manufactured on these workshop facilities have a significant lower life time in general. It might happen that new product generations that have to be manufactured on the old workshop facilities overstrain the process facilities of the old machine tools.

To overcome these limitations, companies want to invest into flexible and reconfigurable machine tools that offer a broad variety of machining operations at minimum set-up time. The operation of such multifunctional and flexible machine tools might be inefficient for financial accounting purposes, as many small and medium machine tool operating companies cannot predict their future manufacturing processes clearly. Therefore they do not know if they would ever need overqualified machine tools from their actual point of view.

In consequence the aim of the investment planning should be to evaluate the machine tools to be bought regarding their capability and their cost-effectiveness.

Next to the pure investment costs of a production facility, more and more companies also consider the total life cycle costs as there can be significant differences regarding i.e. investment costs, maintenance costs, energy costs and productivity. This leads to differences in the costs per piece of the machine tools to be compared.

The machine tool manufacturers want to produce machines at low manufacturing costs while being able to offer a high diversity of machine tool types. Furthermore they want to be more efficient in design and production and want to reduce service costs and work within the warranty period (figure 1).

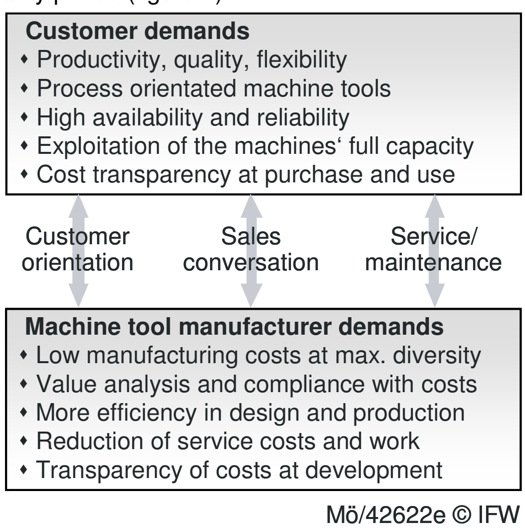

Figure 1: Customer demands vs. manufacturer demands

As more and more companies tend to buy machines only with guaranteed life-cycle-costs, the machine tool manufacturers have to undertake the task of creating appropriate offers.

A common difficulty with life-cycle-costs of technical equipment is to transform technical features and conditions into economic values.

2.1 Results of a customer survey

In order to evaluate the needs of machine tool users, a customer survey among several machine tool users with different company sizes and branches has been accomplished. The number of machine tools for metal cutting in use varied from 5 to 1500.

Two important results from the survey concerning the investment decision and the productivity are presented here.

For all customers, technology and quality have the highest priority for an investment decision. Of minor importance are life-cycle-costs and investment costs. The survey revealed that only some of the bigger companies tend to decide on their investments according to guaranteed life-cycle-costs. As an example, the developer of the TCO standard (Total Cost of Ownership), Daimler-Chrysler, only buys machine tools and production lines according to a TCO contract where the total life-cycle-costs are assured by contract for 10 years [1]. Other companies will follow in the future.

Regarding the productivity, the availability and process safety of machine tools are of highest importance for the machine tool users. Speed and acceleration are of minor importance (figure 2).

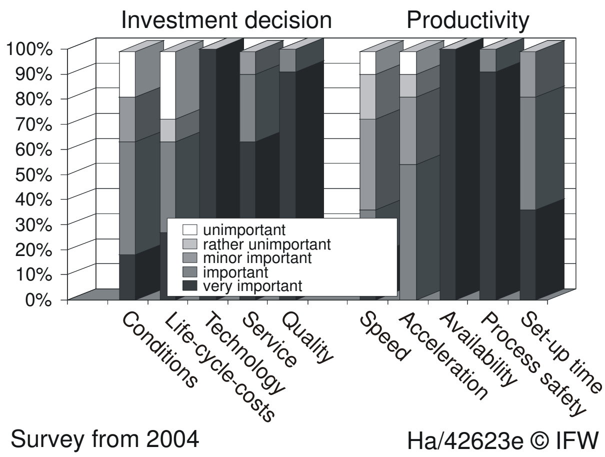

Figure 2: Results of a customer survey

2.2 Cost transparency with life cycle navigator

“Design-to-Cost” is the headline over the most developments of machine tools today. The result of such a development process is a purchase price optimised machine tool. But is this result the optimum concerning the Life-Cycle-Costs of the machine tool and therefore the moneybag of the customer? If any LCC-calculations of machine tools are done today they are realised after the development process of the machine. How will the design of a machine tool be modified if a minimum of the Life-Cycle-Costs is the benchmark of the design?

Target of the LoeWe research project where also component suppliers like Berg Spanntechnik GmbH, Franz Kessler GmbH, A. Mannesmann, Artis GmbH and Siemens are involved, is the development of a LCC-optimised machine tool. This main idea guides the whole development process of the machine tool since the first reflection of the LoeWe machine. It was accepted that the purchase costs of the LoeWe machine exceeded the purchase costs of a comparable conventional machine tool if only the LoeWe machine will show a rigorous better LCC-schedule compared to the conventional machine tool (figure 3).

In this research project, an existing software tool, the Cost Navigator which effects good results in common Design-to-Cost projects of machine tools and other capital equipments [2], is enhanced to the LCC Navigator.

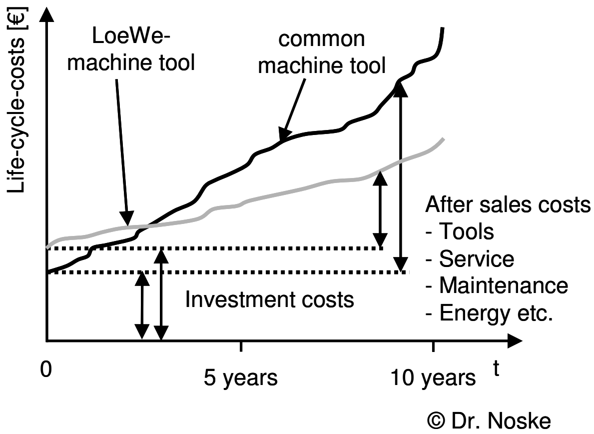

Figure 3: Cost schedule of LoeWe-machine tool vs. conventional machine tool

Using the LCC Navigator the Life-Cycle-Costs of the machine tool, including manufacturing and after sale costs, will be extrapolated during the whole development process. Each decision concerning the application or the design of a component will be made considering the calculated values of the LCC Navigator already in the earliest design phase.

The application of the LCC Navigator will be exemplarily demonstrated at the design of the workpiece clamping device of the LoeWe turning lathe.

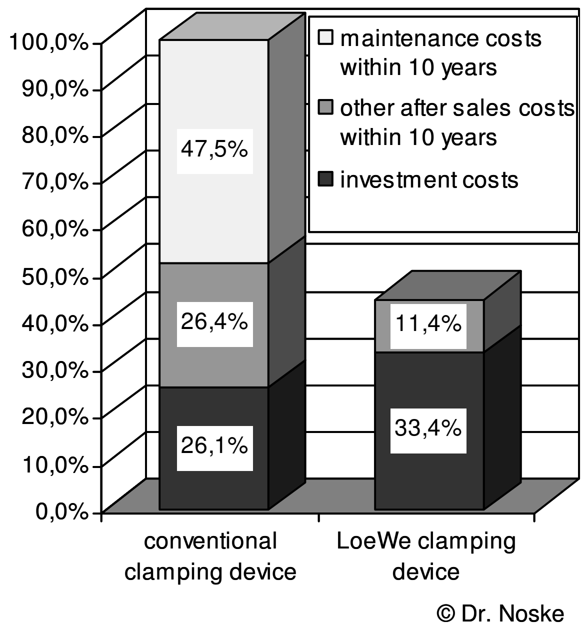

Figure 4: LCC extrapolation of the workpiece clamping system of LoeWe-machine tool vs. conventional machine

Normally a hydraulic clamping device is used for the workpiece clamping function in a turning lathe. Considering the clamping function from the point of view of LCC, a complete new solution for the clamping of the workpiece has been realized within the LoeWe project. The main cost components of a hydraulic clamping device within 10 years are maintenance costs especially for the hydraulic supply unit (figure 4). This maintenance costs rise even above the purchase costs of the whole clamping device during 10 years of operation. The new electrical clamping device of the LoeWe turning lathe is free of maintenance and generates therefore no maintenance costs during its lifetime.

Regarding only the purchase costs the conventional clamping device has an advantage compared to the LoeWe device because of lower purchase costs. The benefit for the customer becomes apparent only after the extrapolation of the entire LCC.

Other components of the LoeWe machine tool are LCC optimized e.g. the ball screws, the linear bearing units and components of the control unit based on LCC Navigator calculations.

It can be summarised that an LCC-optimized machine tool design (Design-to-LCC) creates a significantly different machine compared to a design under the aspects of only purchasing costs.

3 MODULAR MACHINE TOOL

The involved machine tool manufacturer Gildemeister focuses on a modular concept for the machine tool series that allows the usage of as many standard parts as possible. The machine tool series will be available in several stages of extension (i.e. the number of main spindles, their maximum torques and rotational speeds, different turrets and tooling systems), whereas the machine basis remains the same for all types.

A model of the vertical lathe with the integrated features for reducing the life-cycle-costs is presented in figure 5.

Even though the machine tool prototype is developed in a modular design, it is difficult to ensure a widely reconfigurable machine tool. It has to be distinguished between a reconfiguration to be performed by the machine tool manufacturer and a reconfiguration that can be realized by the machine tool operator.

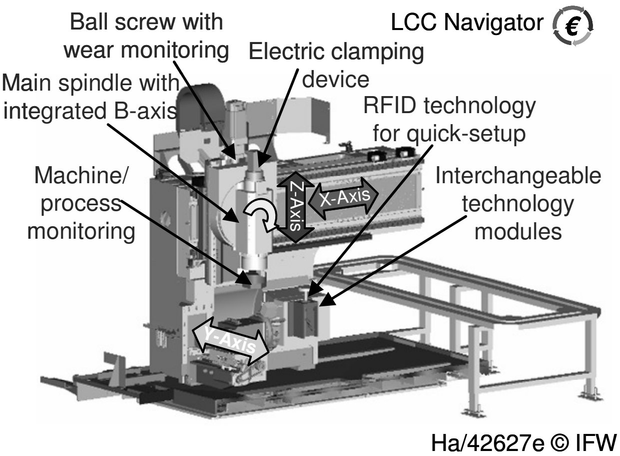

Figure 5: Model of the life-cycle oriented machine tool

3.1 Reconfiguration by machine tool manufacturer

The vertical lathe will be available in several stages of extension. The basic version is equipped with a standard spindle without B-axis. To reconfigure this machine tool to one with B-axis, extensive changes would be necessary, that can be rather practicable only for the machine tool manufacturer. Thus the cross-slide for the x- and z- axis would have to be changed. This would also imply a change of the inner enclosure of the machine tool.

Components that remain the same for all the machine types are the machine bed, the bed saucer, the outer enclosure, the electrical control unit box, the cooling unit and the operator panel.

3.2 Reconfiguration by machine tool operator

The LoeWe machine tool incorporates a platform that allows the machine tool user to use specialized technology modules in the machine (figure 5). This platform incorporates a standardized docking system that allows the referenced positioning and clamping of these modules inside the machine tool. By this the operator can use his machine tool easily for manufacturing processes that would not have been possible within the standard machine tool configuration.

The utilization of a platform to be equipped with pallet systems inside the workspace of the machine tool allows the use of a great variety of additional manufacturing processes that can be easily installed by the operator. This can be i.e. large diameter drilling, grinding etc. Pallet based technology modules, like for example grinding spindles, have to be equipped with a supply of energy and compressed air as well as with an appropriate electrical connection for monitoring sensor signals. A solution for the integration of these connections into the mechanical interface is currently investigated.

4 COMBINING INFORMATION AND COMPONENT

Relevant components of the LoeWe machine tool prototype will be equipped with data storage devices that allow the storage of specific component data for identification purposes like manufacturer, type, serial number as well as life-cycle related maintenance information.

Four selected components like the ball screw drive, the electric clamping device, the technology modules and the main spindle are equipped with RFID based transponder chips.

The electric clamping system is equipped with a RFID-chip that stores all relevant information for an automated configuration of the machine tool control. Furthermore the integrated RFID-chip will be used to store life-cycle related data. This allows to identify the component and its actual state even if it is detached from the machine tool.

To read the transponder chip, an antenna has to be placed close to the RFID-chip as data and energy are transmitted via a radio frequency field. Depending on the required data rate, different systems operating at various transmission frequencies and ranges can be used. In order to assure an acceptable transmission range that can be up to 7 mm for a RFID-chip with 2 kB memory capacity, it needs to be insulated from the metal surface ground it is mounted on.

Machine tool components that will be often exchanged as for example a palette based clamping system are equipped with a hard-wired antenna integrated into the stationary part and an RFID-chip integrated into the exchangeable part.

Other RFID-chip equipped machine tool components like a ball screw drive that have to be installed only once or twice during the machine tool life-cycle will be identified with a hand held antenna connected to the machine tool control for installation and maintenance purposes (figure 6).

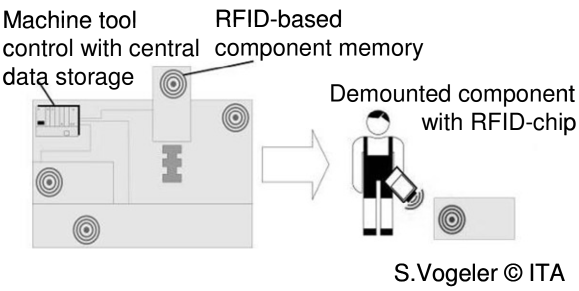

Figure 6: Combining information and component

5 COMPONENT MONITORING

5.1 Estimation of remaining lifetime of ball screws

Often the machine tool utilization time exceeds the ball screw life time. When there is no extraordinary incidence, they are exchanged after a certain cumulated traverse path regardless of their wear state. This is the state of the art to minimize the risk of unplanned failure. When a ball screw fails due to its wear, the axis becomes less precise; in particular, the clearance becomes much higher. Therefore it is not possible to choose hard long-term stable control parameter.

Dirt or chips on the ball screw can lead to a breakdown or an enlarged wear of the balls or the ball track before reaching the nominal lifetime. This also demands an unplanned exchange due to the exceeding of workpiece tolerances. Especially in automatic line operations, a downtime of several hours or even days causes substantial losses.

Therefore a reliable monitoring strategy of ball screws is important to avoid these additional costs for the machine tool user. A wear detection and prediction of the remaining life time allows to plan the exchange of the ball screw in advance to avoid unplanned downtime.

Loss of pre-load

Automatic wear measurements should be done at the most loaded location of the spindle. Because some space is required for the measurement traverse path, the test cannot be executed at the margins of the spindle. Experiences from ball screw manufacturers show that wear of ball screw trails also reproduces wear on the balls. Therefore, an alternative wear measurement at another position of the machine tool axis represents the mean wear of the screw. In the following, two possible methods of wear measurement are presented. Both are based on pre-load loss detection, due to a reduced ball diameter by pitting effects. They base on investigations of horizontally arranged ball screws within a project funded by DFG (German Research Foundation) [3]. An aim of the investigations is to use as less sensors as possible. The best would be to use only control integrated signals such as linear and rotary encoder and nominal torque.

Natural frequency

The natural frequency of an axis is influenced by the slide mass, the stiffness of the part of the ball screw participating in the force flux and the stiffness of the nut. Therefore the natural frequency depends on the slide position and on the wear of the balls respectively their decrease of diameter. Figure 7 shows the pre-load dependant frequency responses. A loss of pre-load leads to a lower eigenfrequency of the spring-mass-like ball screw system as shown by the smoothed line in the grey plane in the diagram.

The analysis of vertical axes within machines is more complicated because several modal frequencies superpose the ball screw frequency. A reliable extraction of the wear dependent frequency might be difficult.

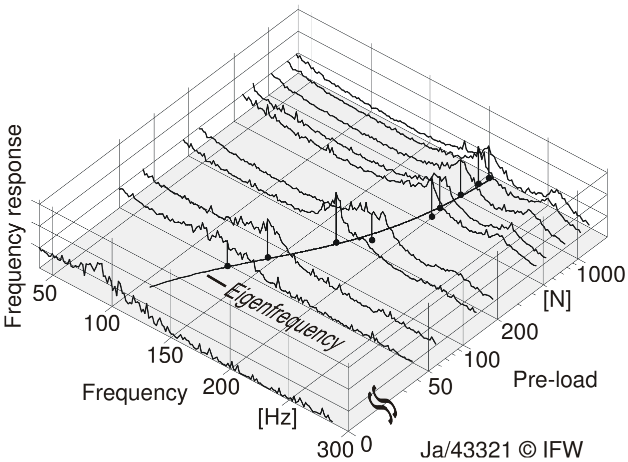

Figure 7: Eigenfrequency vs. pre-load

Nonlinear spring characteristic of ball screws

An unworn ball screw has a nearly linear spring characteristic. The deflection can be measured comparing the linear and the rotatory encoder, compensating the position depending ball screw stiffness. When the balls are worn, the screw gets a clearance as transmission characteristic. This is indicated by less stiffness in the range of low forces. The former linear spring characteristic becomes shaped like an 'S'. The first diagram of figure 8 presents the dependence of measured spring curves vs. pre-load of a horizontally mounted ball screw.

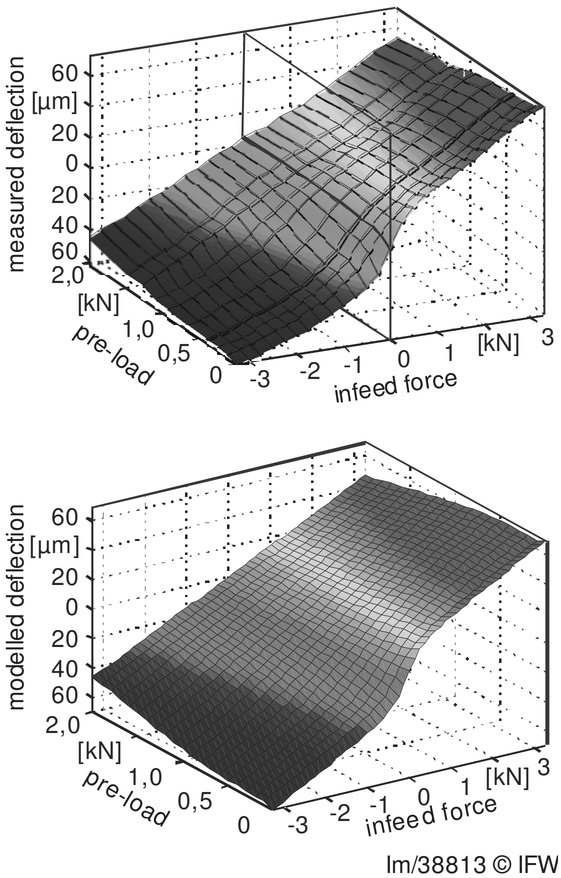

Figure 8: Measured and modelled spring characteristic

The Morgan-Mercer-Flodin growth model formula possesses a similar shape like a nonlinear differential compliance spring characteristic. The model parameter can be adjusted to fit the measurement curve to get a smoothed model of the ball screw loss of pre-load, as shown in the second diagram. Using this MMF-model, test cycles can be executed to determine the pre-load reserve. The general trend of the wear loss should be found by experiment or can be modelled according to the German norm DIN 31051 to estimate the remaining ball screw lifetime [3,4].

Dynamic velocity profile

The previously shown results base on measurements using a horizontally mounted ball screw within a solid test bench. Testing vertically mounted ball screws is more complicated. The experimental rig is shown in figure 9. It is equipped with a Siemens control, a linear and rotary encoder, a strain gage at the spindle nut for measuring the pre-load, infeed force and vibration sensors. A comparison of the two encoder signals results in the ball screw deviation, when the bearing and the position dependant ball screw stiffness are compensated.

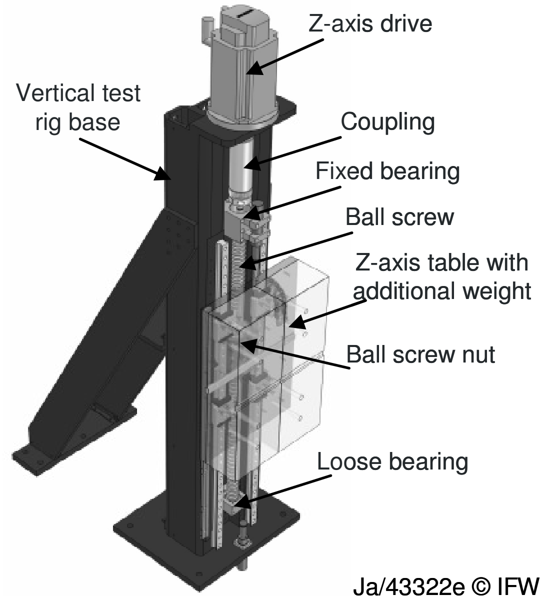

Figure 9: Experimental rig

Position dependent oscillations of the machine body with various frequencies influence the measurement signals and the infeed force is overlaid by the gravitational force, dependent on the axis slide mass. The major effect of clearance occurs at small infeed forces. These low forces can be achieved by driving against a stopper from above to compensate gravitation. A disadvantage is that additional components are necessary and the test can only be executed at one certain axis position. Another possibility is a dynamic short time test. The ball screw infeed force is nearly zero in the case of a free fall. Due to the inertia of the ball screw and the drive, the motor torque is not nearly zero at this test and therefore the axis has to be accelerated. The friction torque of the bearings and the screw nut must be applied and the guideway friction has to be compensated. Varying the acceleration about -1 g, the desired infeed forces can be applied. An exemplary velocity profile with a slide mass of 500 kg and an infeed force of 1 kN is shown in figure 10. Because friction compensation with a change of movement direction is quite difficult, the measurement starts at the highest point of the movement and ends when the maximum velocity is achieved. This range is marked by the vertical lines. The jerk of the movement before the measurement start is minimized to avoid disturbances by machine oscillations. In the near future, wear measurements will be done using this kind of velocity profile.

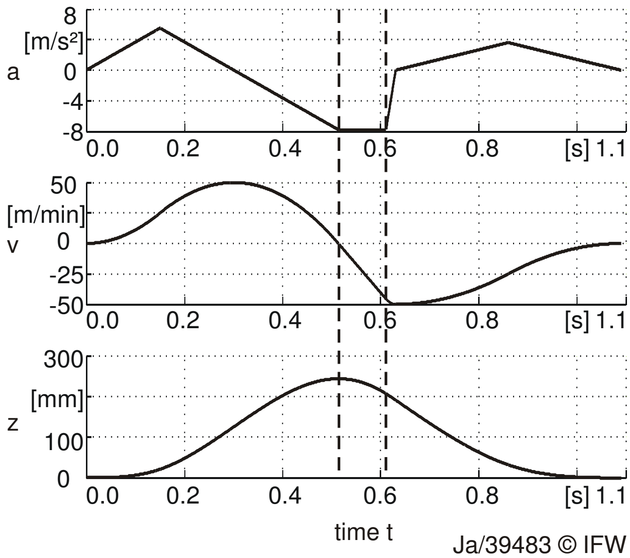

Figure 10: Velocity profile

5.2 Artis component monitoring system

Using a life-cycle oriented machine tool, it is necessary to know the condition of the machine and its components. One objective of the project is to calculate the remaining life time of the components from the actual condition, from the behaviour in the past and from any additional signals; see also 5.1. Accordingly, it should therefore be possible to plan service and maintenance tasks in advance. For that purpose, a condition monitoring system must be integrated in the machine tool.

A concept is shown in figure 11. The central module is a hardware board, which can be integrated in the open control system of the machine. This monitoring module is the communication and interface platform to the components, control system, sensors, various bus systems and drive units. The monitoring system is a PCI board equipped with Profibus and Ethernet interfaces.

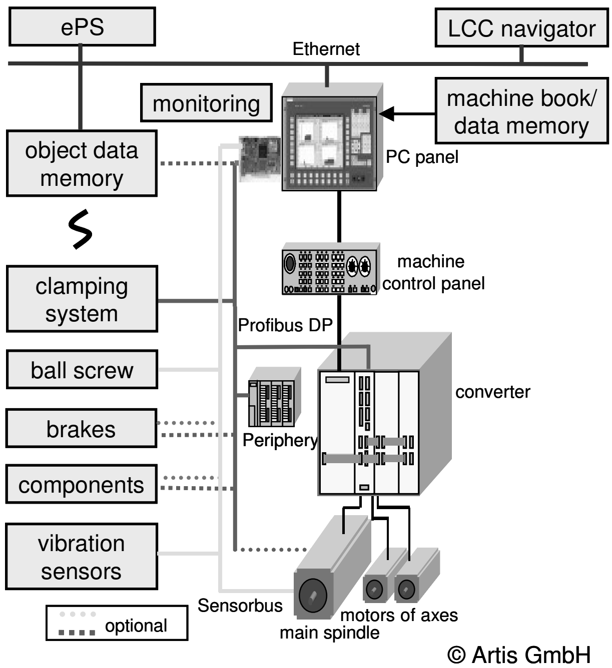

Figure 11: Concept for the life-cycle monitoring system

Depending on the machine tool being used in each case, different components need to be monitored. The clamping system is adapted to the Profibus interface, and condition data of this new device can be transmitted via the field bus to the control system and to the monitoring system. For that purpose, the number of clamps, in connection with the clamping force, can also be counted. For the measurement of the initial stress of the ball screws, a sensor system based on the use of strain gages was developed. This system is connected to the sensor bus of the monitoring system.

The system also uses the internal drive data of the control system. The torque data of the spindles and axes is transmitted from the NC system to the monitoring system via the Profibus interface. With that data, the spindles and drives can be measured to determine whether they are tight or damaged. The condition of other mechanical parts, such as ball screws, the housing of the machine table, guideways, can also be checked. Vibration sensors measure the acceleration next to critical parts, such as spindles and tool holders. To install the vibration sensors in the housing of the spindle, special small housings were developed. The vibration measurement can be used for the detection of bearing damage and unbalanced tools.

The control system can be connected to an external server, for example, to an ePS server. Additional data can be stored on the server, and the machine tool builder as well as the monitoring system provider is able to access this data. The machine tool builder can use the data to obtain information about the condition of his machine and can then plan active service tasks. If the component supplier needs to deliver the correct spare part, he is often faced with the problem that he doesn't know exactly which part has been installed in the machine. With RFID (object data memory) technology in combination with the ePS server, the component supplier can determine precisely which part has been installed in the machine tool.

The LCC navigator must have a link to the monitoring system of the machine tool in order to be able to verify the pre-calculated costs and compare them with the actual machine tool condition and the actual costs.

Parallel to the condition monitoring process, the monitoring system checks whether tool breakage, a missing tool or tool overload has occurred during the cutting processes [5]. For the tool monitoring process, the same signals from the control system and the sensors can be used.

6 CONCLUSION

Currently a rethinking regarding cheap machine tools and production lines takes place in industry. The consumption, repair and maintenance costs have not been considered in the past in general. The lowest purchase price of machine tools was crucial for the investment decision. In the near future the total life-cycle costs will come to the fore and high quality machinery equipment will be seen from a different point of view. In the LoeWe research project several approaches are investigated to minimize life cycle costs i.e. a complete renunciation of hydraulic components in the machine. Furthermore component monitoring is a appropriate method to estimate the technical state of machine tool components. Also a modular machine tool design is essential to adapt the machine to changing manufacturing demands. An LCC navigator helps the machine manufacturer to optimize the machine design and the customer is supported in investing into the right production equipment. Further information about the research project can be found at [6].

REFERENCES

[1] Nau, D.: Total Cost of Ownership (TCO) bei Daimler Chrysler. Conference “Life-Cycle_Performance in der Produktionstechnik”, Karlsruhe, 09/2004, Vol 11.

[2] Noske, H.: Design-to-Cost auf Knopfdruck, Auf sicherem Entwicklungskurs mit dem Cost-Navigator, in: Konstruktion & Engineering; 25 (2002) 5, S. 34

[3] Imiela, J.: Verfügbarkeitssicherung von Werkzeugmaschinenachsen mit Kugelgewindetrieb durch modellbasierte Verschleißüberwachung, Dissertation, PZH-Verlag. ISBN 3-939026-04-2, Hannover, Germany, 2006

[4] DIN 31051: Fundamentals of maintenance, 2003

[5] Lange, D.: Alles unter Kontrolle - Prozessüberwachungssystem sichert Teilequalität bei der Fertigung auf Bearbeitungszentren. MM Maschinenmarkt 15 (2005), Würzburg

[6] http://www.projekt-loewe.de