THESIS ON MECHANICAL AND INSTRUMENTAL ENGINEERING E28

Models for Monitoring of Technological Processes and Production Systems

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Dissertation was accepted for the commencement of the degree of Doctor of Philosophy in Engineering Sciences on June 21, 2006

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Commencement: August 31, 2006

Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any degree or examination.

ISSN 1406-4758
ISBN 9985-59-641-2

MASINA- JA APARAADIEHITUS E28

Tehnoloogiliste protsesside ja tootmissüsteemide monitooringu mudelid

TAUNO OTTO

Abstract

A general concept and mathematical models for monitoring technological processes and production systems in engineering industry suitable for SME have been investigated in the thesis. For that data flows in machining units were analysed and modelled regarding both technological process and characteristics of the machining tools. The elaborated measurement methodology made it possible to monitor tool wear development with a CCD camera. A dynamic model of manufacturing with two degrees of freedom was proposed for process monitoring by indirect measurements. An exemplary system has been developed at machining unit level for testing new cutting tools and materials. Providing an operator with provably safe instructions is essential but possible only with adequate process and operator behavioural models. As a new solution a formal model checking technique has been proposed as an extension to Reliability and Operations Monitoring System tools.

Online resource databases allow production enterprises to cooperate effectively. Usability of such databases can be significantly increased by adding search engines that are able to propose a full production chain implementing user needs and restrictions. A model checking technique has been elaborated for enabling automated building and verification of machining unit models. The elaborated system concept supports the strategic planning of technology transfer, it also could be used as a basis for the industrial enterprises in elaborating co-operation networks and developing towards extended enterprises. Description and evaluation of innovation capacity through human resources development is a novel solution taken into consideration in the building of the model. It enables to improve factor conditions of regional productivity, enhancing Porter's Competitive Diamond Model. Results at this phase are used to develop the technological and human resources database test version. The current solution is focused on the sector of metalworking, machinery and apparatus engineering and has been realised in Estonia and six other European countries.

Keywords*:* tool wear, CCD measurement, network monitoring, lathe, vibration, e-community, formal methods, resource allocation, databases

PREFACE

The mankind of the 21st century is in constant need of new products, rarely thinking about how these are manufactured. The production of the 21st century is still man-dependent and the dreams of the 90s of unmanned enterprises have been buried as unprofitable by financial calculations.

The current study has been targeted onto development of models for monitoring technological processes and production systems starting from a single machine tool and ending with an extended enterprise. The subject has been initiated by research towards development of a machining unit capable of testing new cutting tools and tool materials. Scepticism is a basis of science, therefore both composition and verification of models have been included in this work. During the research the role of a human being became evident – in similar manufacturing situations and with similar equipment results can be different depending on competence of workforce. Considering the presence of manpower and making the corresponding competences measurable has been an additional task to be solved. The proposed solution encompassing the sectors of metal industry, machinery and apparatus engineering in Estonia today has been financed by the European Union.

AKCNOWLEDGEMENTS

The thesis has been strongly influenced by the late Professor Jyri Papstel who supervised this work from 2001 up to September 2004.

Special thanks belong to Professor Rein Kyttner who took over supervising, offering encouragement and valuable advice in finalising the work.

Many thanks to Jyri Vain, Tatyana Karaulova, Gennady Aryassov, Alar Kuusik, Svetlana Gromova, Lembit Kurik – the co-authors of several articles – and all the other colleagues from Tallinn University of Technology. During the research I have felt the constant support of the Estonian Federation of Engineering Industry (EML) and its chairman Dr Jyri Riives. I would also like to thank Leo Teder for his assistance in experiments. It has been a pleasure to realise the ideas with partners from INNOMET project. In realisation of IT solutions Markus Keerman and Alertix Ltd. have been of great help.

The Estonian Science Foundation (Grant No 6795) is acknowledged for supporting the research. Likewise, TUT Department of Research, Archimedes Foundation and IVA are thankfully acknowledged for their assistance in covering several travelling and subsistence costs connected with the research and presentations at conferences. The EU Leonardo Centre, Foundation Innove and Enterprise Estonia are acknowledged for financing the testing of the research results in practice.

This thesis would not have been possible without the support of my wife Kairi and son Tanel. I am also grateful to my relatives and friends for patience and understanding.

CONTENTS

LIST OF PUBLICATIONS

The main results of the research have been published as follows: in a book as a separate chapter (I), in peer-reviewed magasines (II–IV) and in leading worldwide proceedings as a preprint (V) – the latter is accepted for publication in November 2006 by Elsevier. The editors of publications I–V have given their written permission for publishing copies in the current thesis.

The dissertation is based on the following papers

I. Otto, T., Kurik, L., Papstel, J. (2003). A digital measuring module for tool wear estimation, DAAAM International Scientific Book 2003, Ch 38, pp. 435–444, Ed. B. Katalinic, DAAAM International Vienna, Vienna.
II. Aryassov, G., Otto, T., Gromova, S. (2004). Advanced dynamic models for evaluation of accuracy of machining on lathes. Proc. Estonian Acad. Sci. Eng., 10, 270–280.
III. Otto, T., Papstel, J. (2003). Network monitoring of technological equipment and processes, Machine Engineering, Vol. 3, No. 1–2, 161–167.
IV. Otto, T., Papstel, J., Riives, J. (2004). Knowledge management in the framework of technological resources network, Machine Engineering, Vol. 4, No. 1–2, 21–28.
V. Otto, T., Vain, J. (2006). Model checking in planning resource-sharing based manufacturing. 12th IFAC Symposium on Information Control Problems in Manufacturing. Preprints. Vol II: Industrial Engineering. Ed. A. Dolgui, G. Morel, C.E. Pereira, 535–540.

Other publications (not included in the thesis)

VI. Otto, T., Kurik, L., (2000). Digital tool wear measuring video system, Proceedings of 2nd International Conference of DAAAM National Estonia, Tallinn, pp 144–146.
VII. Riives, J., Otto, T., Olt, M. (2002). Business-aid networking in production, Proc. 3rd Int. Conf. DAAAM National Estonia, Tallinn, 249–252.
VIII. Karaulova, T., Papstel, J., Otto, T. (2002). Machine cell modeling and monitoring, Proc. 3rd Int. Conf. DAAAM National Estonia, Tallinn, 92–95.
IX. Riives, J., Papstel, J., Otto, T., Olt, M. (2002). Integrated real time advisory system for educational and industrial needs, Annals of DAAAM for 2002 & Proc. 13th Int. DAAAM Symposium, Ed. B.Katalinic, Published by DAAAM International Vienna, Vienna, Austria 2002, 469–470
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XI. Kuusik, A., Otto, T., Vain, J. (2003) Handling industrial hazards by pre-emptive model checking, 4th International Conference Industrial Automation: Actes. Proceedings, June 9–11 2003, Montreal, Canada.

XII. Riives, J., Papstel, J., Otto, T. (2003). Network monitoring of educational and industrial needs for the mechanical engineering sector, DAAAM International Scientific Book 2003, Ed. B.Katalinic, Published by DAAAM International Vienna, Vienna, 507–518.

XIII. Aryassov, D., Otto, T., Gromova, S. (2004). Analysis of lathe vibration influence on blank roughness, Proc. 4th Int. Conf. DAAAM Estonia, Tallinn, 120–123.

XIV. Riives, J., Otto, T., Papstel, J. (2004). Monitoring of technological resources for extended usage, Proc. 4th Int. Conf. DAAAM Estonia, Tallinn, 272–275.

XV. Riives, J., Papstel, J., Otto, T. (2004). Possibilities of the Innomet system for human resources development in enterprises, Proc. 4th Int. Conf. DAAAM Estonia, Tallinn, 276–278.

XVI. Vain, J., Otto, T., Kuusik, A. (2004). Model checking for planning resource-sharing production, Proc. 20th Int. Conf. CAD/CAM, Robotics and Factories of the Future, Ed. Miguel A. Marquez R. San Cristobal – Venezuela , 151–158.

XVII. Karaulova, T., Otto, T. (2005). Development of database of business processes for SME on the base of quality system. Annals of DAAAM for 2005 & Proc. 16th Int. DAAAM Symposium, Ed. B. Katalinic, DAAAM International Vienna, Vienna, Austria, 179–180.

XVIII. Riives, J., Otto, T. (2006). Integrated human resources development and monitoring system. Proc. 5th Int. Conf. DAAAM Baltic, Tallinn, 219–224.

ABBREVIATIONS

A/D – Analog-to-Digital converter
AC – Alternating Current
B2B – Business to Business
BMP – standard Bit-Mapped graphics format used in the Windows environment
CAD – Computer-Aided Design
CAE – Computer-Aided Engineering
CAM – Computer-Aided Machining
CCD – Charge Coupled Device
CNC – Computer Numerical Control
DC – Direct Current
DV – Digital Video
DVC – Digital Video Camera
EDM – Electrical Discharge Machining
FMS – Flexible Manufacturing System
GIF – Graphics Interchange Format
IMM – Intelligent Machining Module
IMP – Intelligent Manufacturing Plant
IT – Information Technology
JPEG – Joint Photographic Experts Group
MC – Model Checking
MU – Machining Unit
R/OMS – Reliability and Operations Monitoring System
RFID – Radio Frequency Identification
SME – Small and Medium-Sized Enterprises
SOM – Self-Oriented Maps
TA – Timed Automata
TCTL – Timed Computational Tree Logic

1. INTRODUCTION

1.1. Background

Manufacturers face many challenges including increased competition in worldwide markets, shortened delivery times, lower production cost, higher quality, increased pressure from consumers, etc. In order to meet these and others challenges, one has to look at all aspects of doing business. A manufacturer must:

- Understand the business trends driving the global economy; find a niche to be competitive in.
- Increase the productivity in manufacturing.
- Use comprehensive, well-supported software to design products, drive machine tools and support management and planning operations.
- Employ human resource development practices that are more effective.

New technologies prompt new ways of thinking about processes, systems, and manufacturing goals. Advancements in technologies, machines and tools have resulted in faster production of higher-quality products and also components of the process enabling advanced manufacturing practices to become economically viable. Smarter machines combined in a smarter, more efficient manner into a manufacturing system help companies reduce labour requirements, while improving the productivity and production quality.

Manufactures are evolving to a digital enterprise in which the physical world is designed, implemented and monitored in a digital world. At the core of a digital enterprise solution is a knowledge management capability to provide interactivity and the management of multiple applications.

The term 'knowledge' is often used to refer to a body of facts and principles accumulated by mankind in the course of time. Knowledge can be explained as a set of information, selected on the basis of context and experiences. Information itself consists of symbols arranged by certain syntax into data, having understandable meaning for the user (Fig. 1.1).

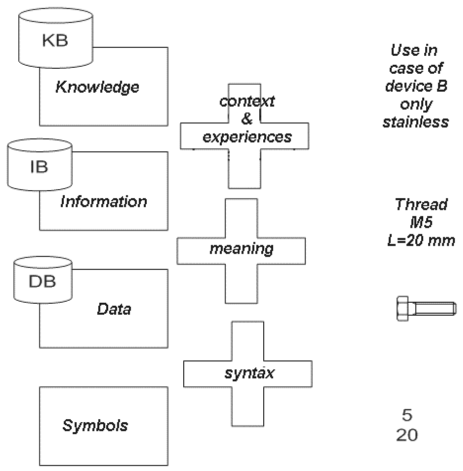


Figure 1.1 Ontology of knowledge

Knowledge management is the process through which organizations generate value from their intellectual and knowledge-based assets. The world of industry has been changed by the developing information infrastructure. Over the past few years, the Internet has been a market maker, a market destroyer, an industry change-agent, and even an inverter of traditional ways of conducting business. The Internet and Web technologies have presented established firms with both opportunities as well as threats. Several buzzwords such as E-hubs, Internet exchanges, E-markets, E-procurement, and E-exchanges have been coined by industry to refer to different models of B2B E-commerce (Ranganathan, 2003).

However, only few of the started projects have been sustainable. A survey of organizations, in which enterprise systems management solutions were deployed, found that only 24% of the implementations were considered successful, 64% of management had mixed feelings about the success of the projects, and the remainder felt their projects were failures (Gallagher, 1998). That is because modern e-systems set high requirements to their reliability and safety. Reliability benchmarking indicates that 70% of reliability issues are operations induced versus the mechanical integrity concerns (Birchfield, 2000). The impact and knowledge of a single person is a critical factor in success of the process unit operation (Schustereit, 2002). Especially it applies to rare conditions that require prompt actions and are hard to predict or occur sporadically. Decision support systems that can predict process behaviour in critical situations will significantly reduce the risk of hazard conditions and allow optimising of process parameters. The conventional manufacturing planning is based on the priority of relations between the part and the manufacturing plan. Available machine tools are defined from the set of existing in the companies' machine tools. The set can be expanded when the concept of virtual enterprise or extended enterprise is used. Scheduling process should be in good accord with process planners using different task variants ("down-up" process planning) (Papstel, 2003). The specific machining database stores related data on the available machines, the kinds of operation that can be performed by each machine, quality parameters including obtainable surface finish for individual machines, and operating cost for each machine (Shehab, 2002). An enterprise should expand the business market to the customer and supplier, which causes the enterprises to be expanded and globalized. Advanced manufacturing models, in which the member enterprises located in different regions, or even distributed throughout the world, have closer relationships and collaborative benefits by cooperating in the development of products, which need Internet/Extranet/Intranet-based information systems to support mutually beneficial collaboration in quality management activities among its members (Tang, 2002).

At a cluster level, knowing the real-time functionality expectations and evaluating the experience on speed performance and limits of data interaction amount of commercial solutions drive the cluster to build up a new system (Viharos, 2003).

A survey of e-Work applications (Nof, 2005) has shown, that e-X is not the same as X. e-Work and e-Production/e-Business are not the same as work, production, and business. A traditional operation cannot be copied as-is to an e-Activity, some changes must be made. For example, comparing a search for information by three generations of specialists (a. Search through manual records; b. Search of a database by a query; c. Search of the Web by a browser) one can realise that they all are different.

1.2. Problem setting

The recent trend in machining is to add intelligence to the machine tools and CNC system (Altintas, 2000). International technology research centres forecast that for the year 2010 about 90–95% of information on the Web will be tied with intercommunication of intelligent machines for solving predetermined tasks, and only the remaining relatively small part is connected to direct human communications. The term Intelligent Machining Module (IMM) has been brought into use to describe CNC systems that allow limited manipulation of machining conditions by the end users, but where additional sensors, which can measure the forces, vibrations, temperature, and sound during machining, are installed on machine tools. Various intelligent machining tasks, such as adaptive control, tool condition monitoring and process control, can simultaneously run on the system (Håkansson, 1999). To reach this goal the system has to be equipped with measurement hardware and data transfer and -processing software and analysis methods. Integration of different sensors and measuring instruments into a uniform system is a problem of the modern technological machinery (Russo, 1999). Mathematical models, which correlate the relationship between measured sensor signals and state of machining, are formed. The mathematical models are coded into real-time algorithms, which monitor the machining process and send commands to CNC for corrective actions. It appears that the existing knowledge based decision support systems, e.g. Nexus Oz from Nexus Engineering or neural network systems have certain disadvantages: a system could fail in previously unknown conditions and require tens of years of experience to fulfil database of real needs. Therefore, some additional techniques should be developed for a more effective support of control of engineering systems.

1.3. Main objectives

The primary aim of this work is the development of a general concept and mathematical models for monitoring technological processes and production systems in engineering industry suitable for SME.

To obtain the goal the following tasks have to be solved.

- Firstly, data flows in machining units should be analysed and modelled regarding both technological process and characteristics of the machining units (MU).
- Secondly, the models should be generated by using certain patterns which could be verified.

- And last but not least, the most erroneous part of technological systems – human resource – should be made measurable, improving factor conditions of Porter's Competitive Diamond Model (Fig. 1).

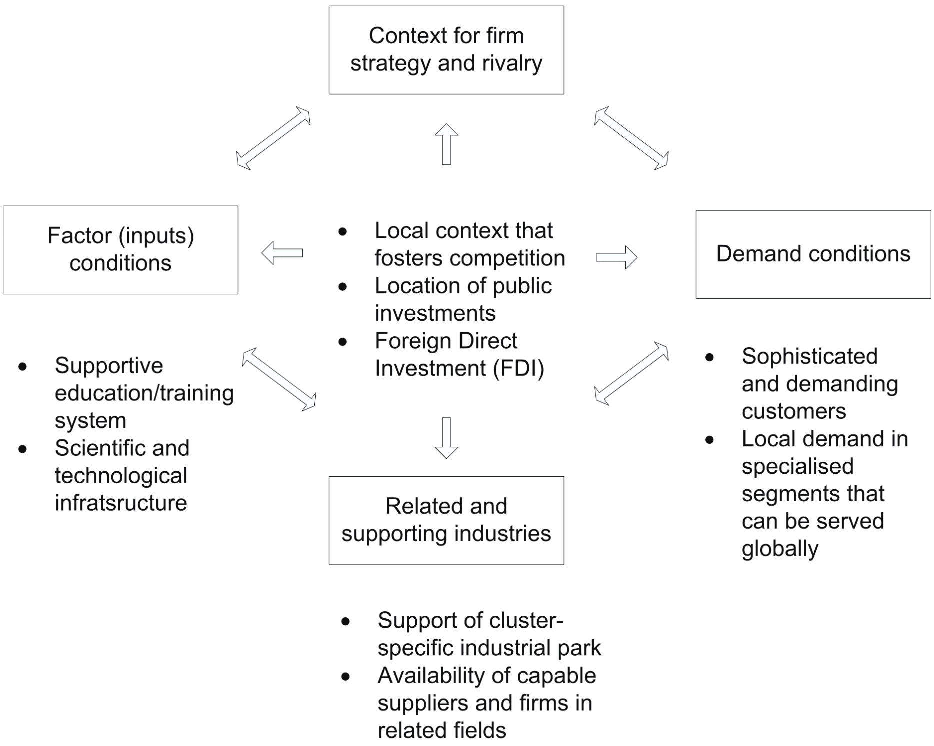


Figure 1.2 Porter's Competitive Diamond Model: determinants of regional productivity (Porter 1990)

The four attributes (1. Factor conditions, 2. Demand conditions, 3. Context for firm strategy and rivalry, 4. Related and supporting industries) are self-reinforcing and catalyse the process of continuous innovations. The model focuses upon the conditions that support firm competitiveness at the national scale. In a study of Estonia in transition Porter shows that the quality and efficiency of Estonian workers was regarded by many as ahead of Finland, known for its hard-working culture. However, Estonia was experiencing a shortage of highly qualified labor (Porter, 2006).

To solve the tasks data flows are modelled for MU by using direct and indirect measuring techniques. Verification of models is investigated using UppAal model checking tool. Possibilities of model checking can be used for searching in web-based inter-organizational resource and knowledge databases to find cost-effective manufacturing solutions for new products developing. In addition to locating technical production and logistic capabilities such system can also include knowledge requirement parameters based on database information. To solve the

Porter’s Diamond Model task an online system of technological and human resources is proposed. The most erroneous part of technological systems – human resource – is analysed on the basis of competence, thus making it possible to elaborate a methodology for evaluation and development of the database model for adding innovation capacity of labour force and entrepreneurs of the metal engineering, machinery and apparatus sector.

1.4. Limitations

Though the current solution is focused on the sector of metalworking, machinery and apparatus engineering the proposed methodology can be transferred also to other industrial sectors (wood processing, chemical industry, construction materials industry, etc).

On the process level machining processes, especially metal turning and grinding, as examples, are discussed in more detail. Cutting process changes constantly due to tool wear, and therefore cannot be considered time-invariable. Typical wear criteria are the average wear land width and the maximum wear land width. Using these criteria it is possible to evaluate the average and maximum intensity of wear and implement these data in mathematical models predicting tool life. When it comes to the analysis of tool wear, it is recognised that the flank wear is of prime concern, so that all tool life testing has primarily considered this wear (Astakhov, 1999). Knowledge of tool wear is used for modelling the process, validating the model, and implementing it into the technological resources network.

As to the human resource evaluation only most widely known engineering professions of the machinery sector have been studied. A demo system module was developed in order to map different aspects of qualifications (general skills and knowledge, specific skills and knowledge, personal qualities, etc) and also tested in selected companies.

The realisation of the Porter’s Competitive Diamond Model enhancement is limited to one branch – factor conditions.

In building the application only freeware was used (Apache server, MySQL database, UppAal toolbox). However, this realisation does not limit the applicability of the proposed model and can also be implemented with another piece of freeware or commercially available software (e.g. Oracle).

2. MODELS FOR MONITORING TECHNOLOGICAL PROCESSES

2.1. Process Modelling in Machining Unit

Technologically, machining as a process has made a significant progress. However, lack of suitable cutting models is a main bottleneck in developing of machine tools using adaptive control. It is rather difficult to predict vibration, tool wear and breakage, thermal deformation of the machine tools, and similar processes based on events using off-line theoretical models (Altintas, 1999). Drawbacks of the prior art models are unsuitability for complex cutting path with changing diameter (e.g. stepping shafts) and complex cutting contour.

In turning operations, tool vibrations influence both product quality and productivity and may also have a negative influence on the working environment (Hakansson, 1999). The effect of lathe vibration on the roughness of machined surface is considered in this work. Dynamical phenomena concerned with the vibration are caused from external factors on the strained system of the lathe. During the machining of material all disturbances finally lead to relative displacements of the cutter and the blank. It allows to link parameters of the surface roughness with the relative vibrodisplacements of the cutter and the blank (Gaponkin, 1995).

Integration of different sensors and measuring instruments into a uniform system is a problem of the modern technological machinery (Russo, 1999). Data collected by contact and non-contact measuring means should be managed in one system. Solutions capable of data mining can be achieved, in theory, by SOM (Self-Oriented Maps) programme, for example in MatLab software environment (Vesanto, 2002). By stimulating cooperation between different manufacturers and research laboratories, synergies can be achieved to realise the abovementioned main criteria successfully. However, achievement of this goal could become very expensive; therefore networking and cooperation are remarkable resources of a company on the way to become more efficient (Riives, 2002). To solve this problem the idea about real time web based advisory system was initiated. The user interacts with the control module, the role of which is to work out the search strategy on the basis of initial data given by user, via user's interface (Papstel, 1999). As a result, a knowledge supply chain is created.

Tool wear as one of the important factors in machining has been investigated by using different methods. Indirect methods involve noise recognition with a microphone, cutting temperature monitoring with thermocouples, vibrations measurement (speed or acceleration) with a modal analyser, surface roughness measurement with a profilograph, work piece dimension changes measurement with gauges. Direct methods include tool wear monitoring with CCD cameras. Every method suffers from some drawback; however, combined monitoring could be a solution. In Fig. 2.1 a monitoring system covering all the aforementioned devices for tool condition monitoring is proposed.

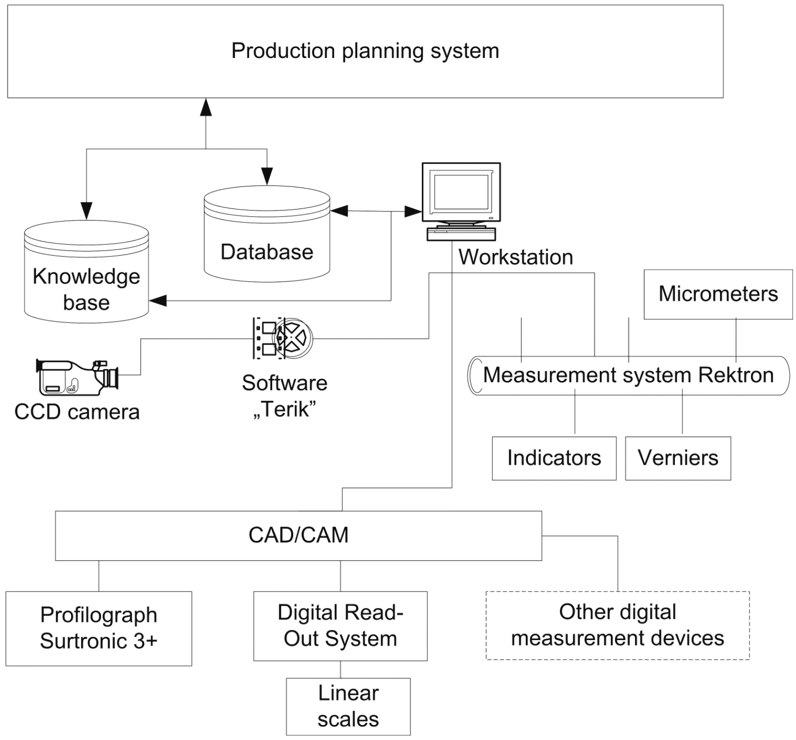


Figure 2.1 Use of modelling in production planning system

Machine-tool vibrations were evaluated using a modal analyser. Vibrations level classification by ISO 2372 was used for evaluation the current system. In Fig. 2.2, a snapshot of turning is shown. At 50 Hz the vibrations are caused by an electrical set, the highest result 2.2 mm/s^2 can be evaluated as unsatisfactory and the system has to be alarmed. Human intervention in this case is required at the decision level (perception of further details of operation and emergency actions).

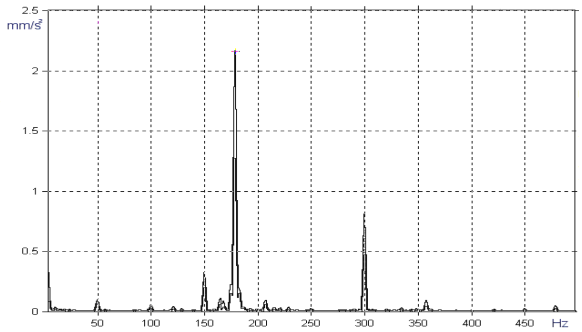


Figure 2.2 Vibrations on CNC lathe

That a worn tool causes different noise is known by all CNC machine tool operators. In Fig. 2.3 the difference between machining with an unworn (lower line) and a worn cutting tool is shown.

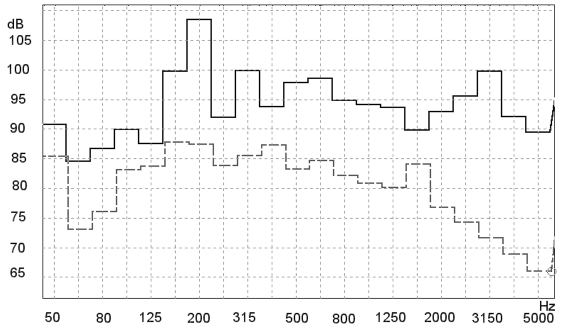


Figure 2.3 Noise recognition in machining

As the cutting process is in a continual state of change due to tool wear, it cannot be considered time-invariable. Typical wear criteria are average wear land width and maximum wear land width. Using these criteria it is possible to evaluate the average and maximum intensity of wear and implement these data in mathematical equations or models predicting tool life. When it comes to the analysis of tool wear, it is recognised that the flank wear is of prime concern, so that all tool life testing techniques have primarily considered this type of wear (Astakhov, 1999). It occurs on the flank of the tool below the cutting edge and cannot be avoided. The size of the flank wear can be measured as the distance between the top of the cutting edge and the bottom of the flank wear land. Modern cutting inserts have often chamfered cutting edges, enabling to extend the tool life (Fig. 2.4a). Therefore flank wear can be recognised both on the cutting edge and on the flank face.

At small cutting speeds flank wear is dominating. In Fig. 2.4b the flank wear is indicated by $h_{\alpha w}$, the width of chamfer by b_{γ}, and the flank angle by a_0. At the same time chamfer width b_{γ} decreases, and the corresponding decrease is indicated by $b_{\gamma w\alpha}$.

At average cutting speeds, over built-up edge formation limits, a notch is formed at the rake face. The depth of notch is small and the rake angles γ_{o1} and γ_{o2} remain the same. The first phase is shortening both from rake and flank faces. The chamfer width decreases during machining at the flank and rake faces. Usually cemented carbide tools should be replaced when the average width of the flank wear land reaches 0.3 mm (by ISO 3685-1977) when wear land is uniform, or 0.6 mm when cutting edge is chipped.

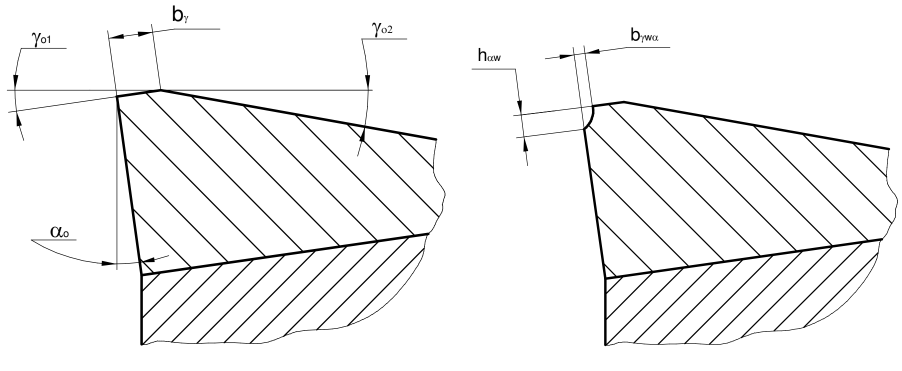


Figure 2.4 An unworn cutter with chamfer honing (a), and a worn cutter at small cutting speeds (b)

However, it should be noticed that at high speeds the significance of rake wear rises, causing crater formation on the face of tool (see Paper I). By normal machining the crater will gradually enlarge, causing the rake angle to increase, until it breaks through a part of the cutting edge, as wedge angle has been decreased. Intensities of flank and rake wear can be used for tool life estimation. Such measurement can be realised with a video system, as a conventional microscope is unable to take into account eroded edge parts. Thus a more precise tool life prediction is also made feasible.

Realization of monitoring can be achieved by building up a set of local networks. It involves integration of elaborated technical solutions, monitoring of technological parameters in the network, and generalization of gathered data for complementing the Reliability and Operations Monitoring System (R/OMS) (see Fig. 2.5).

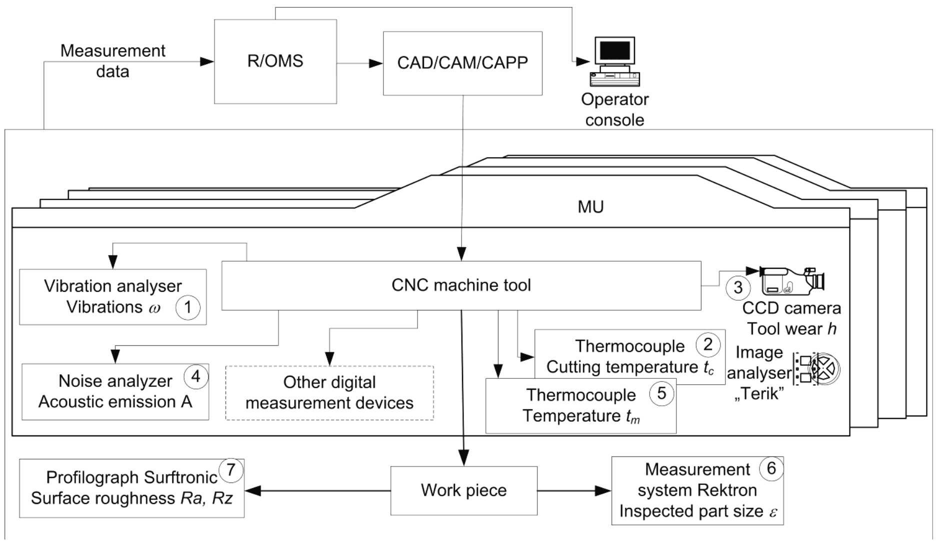


Figure 2.5 Planned data flows in the Intelligent Machining Unit

2.2. Experimental setup for process analysis by electronic image processing

Electronic image processing systems are used in different branches of industry. They deliver objective test results that can be reproduced at any time. Camcorders are being replaced by digital video cameras (DVCs). Thanks to progress in semiconductor technology, DVC performance has improved dramatically. Moving images can be input to computers with DVCs. Analog video camera will soon be replaced with DVCs because of various advantages of the digital equipment.

Industrial CCD cameras used for cutting process investigations have several drawbacks. First, they need permanent electric supply through an AC adapter. Further, there has to be permanent connection to a video recorder or a computer. When the distance between the camera and the computer is bigger than 100 meters, the signal is to be amplified (Zebala, 1999).

The whole camera system consists of a computer, a connection kit and a camera body equipped with changeable standard lenses and an adapter. The camera (Panasonic NV-DS5EG) operates in colour mode including stereo sound recording capabilities. Data specifications of the current DVC are described in Table 2.1. Sound recording is important when during extensive tests relevant data can be recorded just by voice. Digital still pictures can be decoded as graphical bitmap files, permitting later analysing and display, both for science and industry. Furthermore, the system offers the possibility of image calibration.

Table 2.1. Data specifications of the DVC camera

Image sensor	1/3-inch
Standard illumination	1400 lx
Minimum illumination	1 lx
Tape used	6.35 digital video tape
Recording time	60 min
Shutter speed	1/50–1/8000 s
Iris value	F1.4–F16.0
Zoom	10:1 power zoom
Supply voltage	DC 7.9 V
Weight	750 g (without lens)
Dimensions	78 (W) x 95 (H) x132 (D) mm

The current system records data in mini DV format to digital video tape. Afterwards any digital still picture from this tape can be transferred at a rate of 115 kbps into computer using serial port connection. In the computer pictures received from video tape are decoded, saved in bitmap format and automatically analysed. Digital still pictures also contain some data e.g. recording date and time.

A digital video camera with 1/3” and 680 000 pixels image sensor was used. A part of sensor area is reserved for digital image stabilising, so the resulting picture resolution is 696×532 pixels. Size of the image sensor elements and magnification of the optical system sets certain limitations to picture quality. Two object points are separated only if their images are located on different sensor elements. Depending on the object we need minimum depth of field. In macro range (magnification about one) the depth of field becomes very low. It is about 0.1 mm for an f-number (n_f = (focal length) / (diameter of lens aperture)) of 8 and magnification is about one. In Fig. 2.6 a range of usable magnifications and the depth of fields calculated for the current image sensor are presented. From this it can be seen that best pictures of 3D objects are taken using a blue light source and minimum lens aperture.

In standard optical systems the stop is placed at the principal point, but telecentric imaging with the stop at the second focal point is preferable (Jähne, 1997). In the current case: with object position varying the magnification stays the same. In imaging flat objects good results are attained with a standard lens but for correct calibration the camera should always be placed at the same distance from the object.

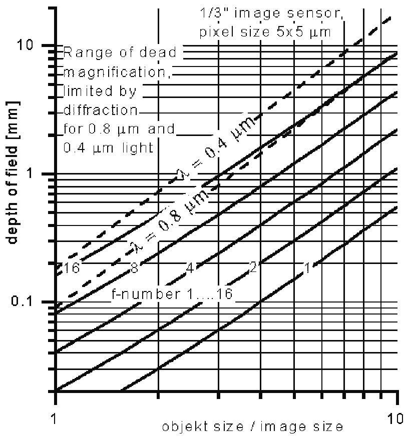


Figure 2.6 Depth of field/magnification curves for the current system

A special computer program *Terik* was written for tool wear investigations**.** It was designed for image based measurements and works in the Microsoft Windows environment. The program *Terik* loads from computer memory drive or directly from other application bitmap picture in BMP (.bmp), JPEG (.jpg) or GIF (.gif) formats and measures geometrical dimensions of different objects on a loaded image (area, perimeter, distances).

With a conventional microscope only the length and maximal width of wear lands can be measured. Also, an accurate estimation of the average wear is time-consuming, depending on researcher's experience. The system proposed offers the possibility of image calibration. After thresholding and removing noise by digital filtering a black image on the white background is obtained for automatic measuring area, minimum and maximum dimensions in horizontal and vertical directions and a source for perimeter detecting. The length of wear land perimeter is one possible additional parameter of wear uniformity. The angle measuring function was added to the program to estimate chip flow direction. In rake face measuring with a CCD camera the chamfer width b_γ, the contact area and the angle between chip flow direction and the cutting edge can be registered.

The wear land of a cutting tool is not on a plane. The capability of measuring 3D objects has been added to help image based measurements. Traditionally, to achieve these kinds of measurements the object measured must be observed at least from two directions. As the real dimensions of the cutting tool are known, it will be possible to make measurements from one direction only. Orientation of the observation camera (towards the cutting tool) in two rotation axes in reasonable scales is optional. Rotation of the camera around the optical axis of an objective has to be prevented or restricted by other means. A rotation tool has been added to the proposed software solution *Terik* to correct the turning angle.

The calibration of the camera/lens/program combination is important for determining relationships between object and image co-ordinates. System elements are not ideal and transformation parameters must be calibrated experimentally. Axes units in horizontal and vertical directions can be also regulated separately for correcting image distortions in optical, electrical and digital parts of the measuring system.

In bitmap images each pixel is treated individually. For image recognition and measurement, it is important to know relations between different pixels. The first step in this direction is an analysis of the small neighbourhood of each pixel. Program *Terik* uses two neighbourhood operators: non-linear median filter for removing noise, and a variation of Roberts filter for edge detecting. For faster image computing and deselecting non-interesting areas only a part of picture can be selected for image manipulation. All results can be saved into formatted text files for future analyzing in other programs (MS Excel, etc). Experimentally the measurement time was reduced from 90 min (by conventional microscope) to 3 min (by using video measurement system). In Fig. 2.7 a screenshot is shown of the program *Terik* working window, written in Visual Basic.

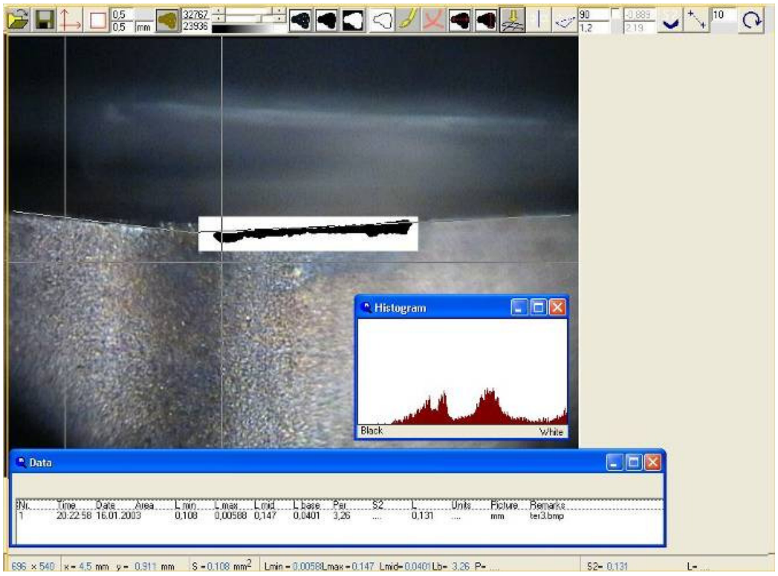


Figure 2.7 Working windows of the image processing program *Terik*

A smooth, uniform illumination system is the most important factor influencing machine vision (Tervola, 2001), therefore a cold light source with preferably gooseneck fibre optics is essential. Variations in radiation affect the image formation system, thus causing difficulties in boundary detection. As the authors' experience shows, the unstable illumination direction can influence the measurement results about 10 %. The problem arises in IMS due to chip flow influences.

The *Terik* solution has been successfully used in several industrial researches, e.g. to reduce burring in milling PLC plates for electronic industry, and to estimate the influence of counter-clockwise and clockwise milling on burr formation.

2.3. Prediction of machining accuracy

Dynamical phenomena of vibrations are caused by external factors on the strained system of the lathe. In the turning operations, tool vibrations influence both product quality and productivity and may also have a negative influence on the working environment. The relative dynamic motion between cutting tool and workpiece will affect machining results, the surface finish in particular (Hakansson 1999). During the machining of a material, all disturbances finally lead to relative displacements of the cutter and the blank. It allows us to link the parameters of surface roughness to the relative vibrodisplacements of the cutter and the blank (Sharma, 2004). In the calculation of dynamics characteristics, the real elastic system of the lathe was replaced by a system with finite degrees of freedom. In the case of insufficient accuracy of the underlying data, complicated calculation schemes can lead to significant errors in the calculation (Bayard, 2003). Therefore we used simplified schemes, composed on the basis of experimental investigations.

The internal friction is due to imperfect elasticity of vibrating bodies – the main factor of damping in the lathes. Internal friction can be determined by non-elastic damping factor of frequency of cyclical strains. In many cases structural damping depends on the type of machine tool construction. It was assumed, therefore, that non-elastic damping coefficient includes also the losses caused by structural damping. Experimental measurements were performed on the lathes of type 1K62 at different cutting speeds, feeds and depths of cut. After every cutting, surface roughness was measured with a profilograph Surtronic 3+.

In order to simplify the dynamic model, the factors of a minor effect on the results were eliminated. In this study only dynamic models with one and two degrees of freedom were investigated (Fig. 2.8).

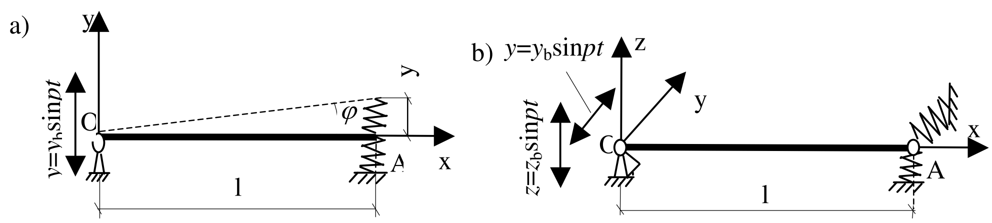


Figure 2.8 Dynamic models with one (a) and two (b) degrees of freedom

In machining of a detail on the lathe, the cutting force F (Fig. 2.9) is not constant. It is determined by several factors, as the change in the thickness of the cut-off chips, the change in the mechanical properties of the blank material and tool wear. The input of the lathe system is the cutting force F as the function of time and the output is the displacement of the cutter or the blank.

The differential equation of forced vibrations caused by the cutting force F (Fig. 2.9) according to the theorem of kinetic moment is

$$J_0 \ddot{\varphi} + k_y \varphi l^2 = M_y \sin p\, t + \left(F_r + F_a \cos \omega^* t\right) l_1 \tag{2.1}$$

where J_0 is the moment of inertia of the blank around the headstock (spindle), φ is the declination angle of the blank, k_y is the horizontal spring constant of elastic support of the blank, l is the length of the blank, $M_y = mp^2 y_b l / 2$, m is the mass of the blank, $p = 2\pi f$, f is the frequency of foundation vibrations (Hz) and y_b is the amplitude of the foundation vibrations.

The cutting force F is reproduced as a sum of the following items: the constant component F_r determined in practice by the simplified empirical formula (Arshanski, 1998) and the variable component $F_a \cos \omega^* t$, whereas l_1 is the coordinate of the cutting force. The amplitude of the variable component of the cutting force is related to the roughness value and changes in a rather wide range.

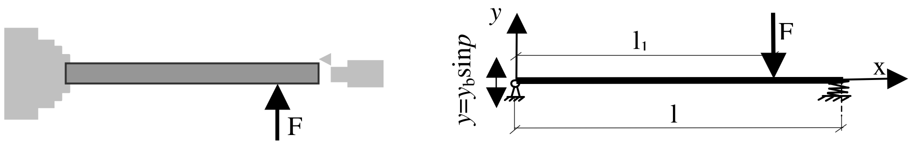


Figure 2.9 Calculation scheme in cutting

The solution of Eq. (2.1) can be expressed in the form of displacement of the blank end in relation to initial conditions y_0 and v_0:

$$y = \varphi l = \left(y_0 - F_0 l_1 - E l_1 l\right)\cos\omega t + \left(\frac{v_0 - D l p}{\omega}\right)\sin\omega t + D l \sin pt + F_0 l_1 + E l l_1 \cos\omega^* t, \tag{2.2}$$

$$D = \frac{M_0}{J_0(\omega^2 - p^2)}, \qquad F_0 = \frac{F_r}{kl}, \qquad E = \frac{F_a}{J_0(\omega^2 - \omega^{*2})} \tag{2.3}$$

where ω is the natural frequency of the lathe system.

In the previous section the solution was obtained in the case of the simplified model of cutting force with regard to the blank. Now we are dealing with a changing cutting force (Fig. 2.10). The differential equation of forced vibrations caused by the motion cutting force F

$$J_o \ddot{\varphi} + k_y l^2 \varphi = M_y \sin pt + F_r(l - ut) + F_a \sin\omega^* t \cdot l - F_a \cdot ut \sin\omega^* t, \tag{2.4}$$

where $u = s n_b 10^{-3} / 60$ is the velocity of the cutter, s is the feed of the cutting tool, n_b is the rotational frequency of the blank.

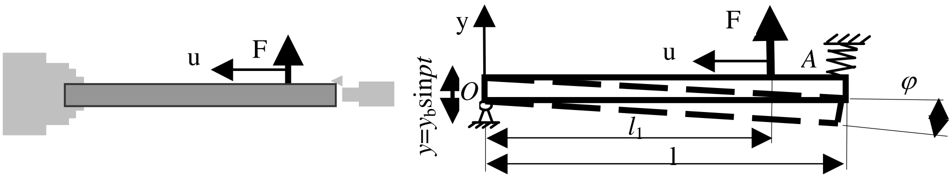


Figure 2.10 Calculation scheme in the case of changing cutting conditions

The general solution of the differential equation (2.4) for the declination angle of the blank taking into account the initial conditions

$$\varphi = \varphi_1 + \varphi_2 = C_1 \cos \omega t + C_2 \sin \omega t + \frac{M}{J\left(\omega^2 - p^2\right)} \sin pt + \frac{F_r}{kl} - \frac{F_r u}{kl^2} t +$$
$$+ \frac{F_a l}{J\left(\omega^2 - \omega^{*2}\right)} \sin \omega^* t + \frac{2F_a u \omega^*}{J\left(\omega^2 - \omega^{*2}\right)^2} \cos \omega^* t - \frac{F_a u}{J\left(\omega^2 - \omega^{*2}\right)} t \sin \omega^* t \tag{2.5}$$

where

$$C_1 = \varphi_0 - \frac{F_r}{kl} - \frac{2F_a u \omega^*}{J\left(\omega^2 - \omega^{*2}\right)^2},\; C_2 = \frac{\dot{\varphi}_0}{\omega} - \frac{Mp}{\omega J\left(\omega^2 - p^2\right)} + \frac{F_r u}{\omega k l^2} - \frac{F_a l \omega^*}{\omega J\left(\omega^2 - \omega^{*2}\right)} \tag{2.6}$$

From Eq. (2.5) it is easy to find the displacement $y = \varphi l$ and the rotation speed v of the blank end in relation to initial conditions y_0 and v_0.

2.4. Dynamical model with one degree of freedom with damping

It has been so far assumed that no frictional resisting forces act on the systems in free vibrations, but actually, in practice, such forces are always present and will in time damp out the vibrations. Usually, in the study of steady-state vibration, the values of the components, which determine free damping vibrations, are reduced. However, it is impossible to achieve it in this instance, because the operating conditions in the cutting are changed due to surface roughness. Dynamical models without damping are more precisely described in Paper II.

The differential equations of forced vibrations with damping varying with the velocity in much the same way as in Eq. (2.4):

$$J_o \ddot{\varphi} + \beta \dot{\varphi} l^2 + k_y l^2 \varphi = M_y \sin pt + F_r (l - ut) + F_a \sin \omega^* t \cdot l - F_a \cdot ut \sin \omega^* t, \tag{2.7}$$

where β is the damping factor.

The general solution of Eq. (2.7) represents free vibrations:

$$\varphi_1 = \exp(-nt)\left(C_1 \cos \omega_1 t + C_2 \sin \omega_1 t\right), \tag{2.8}$$

where $2n = \beta l^2 / J_o$ is the natural frequency of free damping vibrations.

The values of the damping factor for the lathe are assumed $n = (0.06\ldots0.08)\ \omega$ (Hakansson, 1999). In practical problems it can be assumed with sufficient accuracy that small resisting forces do not affect the frequencies, thus $\omega_1 \approx \omega$. A particular solution of Eq. (2.7), depending on the foundation vibrations and disturbing force (moving cutting force), represents the forced vibrations of the system φ_2^{*} and φ_2^{**} accordingly, which is represented as follows:

$$\varphi_2 = \varphi_2^{*} + \phi_2^{**} \tag{2.9}$$

where $\varphi_2^{*} = \dfrac{M_y}{J_o\left(4n^2 p^2 + \left(\omega^2 - p^2\right)\right)}\left[\left(\omega^2 - p^2\right)\sin pt - 2np\cos pt\right]$, (2.10)

$$\varphi_2^{**} = A + Bt + C\sin\omega^{*}t + D\cos\omega^{*}t + Et\sin\omega^{*}t + Kt\cos\omega^{*}t, \tag{2.11}$$

where $N = 4n^2\omega^{*2} + \left(\omega^2 - \omega^{*2}\right)^2$, $B = -\dfrac{F_r u}{J_o \omega^2}$,

$$C = \frac{F_a l\left(\omega^2 - \omega^{*2}\right)}{J_o N} + \frac{2n\left(\omega^2 - \omega^{*2}\right)F_a u}{J_o N^2} + \frac{4n\omega^{*2}\left(\omega^2 - \omega^{*2}\right)F_a u}{J_o N^2} - \frac{8n^3\omega^{*2}F_a u}{J_o N^2} + \frac{4n\omega^{*2}F_a u}{J_o N^2},$$

$$D = -\frac{F_a l 2n\omega^{*}}{J_o N} - \frac{4n^2\omega^{*}F_a u}{J_o N^2} - \frac{8n^2\omega^{*3}F_a u}{J_o N^2} - \frac{4n^2\omega^{*}\left(\omega^2 - \omega^{*2}\right)F_a u}{J_o N^2} + \frac{2\omega^{*}\left(\omega^2 - \omega^{*2}\right)F_a u}{J_o N^2},$$

$$E = -\frac{F_a u}{J_o N},\ K = \frac{F_a u 2n\omega^{*}}{J_o N} \tag{2.12}$$

Adding the general solution (Eq. (2.8)) and partial solution (Eq. (2.9)–(2.12)), a general solution of the differential equations for the declination angle of the blank

$$\begin{aligned}\varphi &= \exp(-nt)\left(C_1\cos\omega_1 t + C_2\sin\omega_1 t\right) + \\ &+ \frac{M_y}{J_o\left(4n^2 p^2 + \left(\omega^2 - p^2\right)\right)}\left[\left(\omega^2 - p^2\right)\sin pt - 2np\cos pt\right] + \\ &+ A + Bt + +C\sin\omega^{*}t + D\cos\omega^{*}t + Et\sin\omega^{*}t + Kt\cos\omega^{*}t,\end{aligned} \tag{2.13}$$

Taking into account the initial conditions $\varphi(0) = \varphi_0$ $\dot{\varphi}(0) = \dot{\varphi}_0$, the constants of integration

$$\begin{aligned}C_1 = \varphi_0 &+ \frac{nmp^3 y_0}{J_o\left(4n^2 p^2 + \left(\omega^2 - p^2\right)\right)} - \frac{F_r l}{J_o\omega^2} - \frac{2nF_r u}{\omega^4 J_o} + \frac{F_a l 2n\omega^{*}}{J_o N} + \frac{4n^2\omega^{*}F_a u}{J_o N^2} + \\ &+ \frac{8n^2\omega^{*3}F_a u}{J_o N^2} + \frac{4n^2\omega^{*}\left(\omega^2 - \omega^{*2}\right)F_a u}{J_o N^2} - \frac{2\omega^{*}\left(\omega^2 - \omega^{*2}\right)F_a u}{J_o N^2},\end{aligned}$$

$$\begin{aligned}C_2 = \frac{\dot{\varphi}_0}{\omega_1} + \frac{nC_1}{\omega_1} &- \frac{mp^3 y_0\left(\omega^2 - p^2\right)}{2J_o\omega_1\left(4n^2 p^2 + \left(\omega^2 - p^2\right)\right)} + \frac{F_r u}{J_o\omega^2\omega_1} - \frac{\omega^{*}F_a l\left(\omega^2 - \omega^{*2}\right)}{J_o N\omega_1} - \frac{2n\omega^{*}F_a u}{\omega_1 J_o N} \\ &- \frac{\omega^{*}2n\left(\omega^2 - \omega^{*2}\right)F_a u}{\omega_1 J_o N^2} - \frac{4n\omega^{*3}\left(\omega^2 - \omega^{*2}\right)F_a u}{\omega_1 J_o N^2} + \frac{8n^3\omega^{*3}F_a u}{\omega_1 J_o N^2} - \frac{4n\omega^{*3}F_a u}{\omega_1 J_o N^2}\end{aligned} \tag{2.14}$$

Finally the displacement $y = \varphi l$ and the rotation speed v of the blank end in relation to initial conditions y_0 and v_0 should be found from Eq. (2.13).

2.5. Dynamical model with two degrees of freedom

2.5.1. Dynamical model with two degrees of freedom without damping

The differential equations of forced vibrations, caused by the cutting force F, according to the theorem on kinetic moment, are presented in the following form:

$$J_0\ddot{z} - A\omega_b\dot{y} + k_z z l^2 = M_z l \sin pt,$$

$$J_0\ddot{y} + A\omega_b\dot{z} + k_y y l^2 = M_y l \cos pt + F_r l_1 l + F_a l_1 l \cos\omega^* t, \qquad (2.15)$$

where ω^* is the angular velocity of blank rotation, $M_y = mp^2 y_b l/2$ and $M_z = mp^2 z_b l/2$, y_b and z_b are the amplitudes of the foundation vibrations, k_z and k_y are spring constants, and A is the moment of inertia of the blank in relation to the axes of rotation.

The general solution of Eqs (2.15) represents free vibrations

$$\begin{aligned} y_1 &= a_1 \sin(p_1 t + \alpha_1) + a_2 \sin(p_2 t + \alpha_2), \\ z_1 &= \mu_1 a_1 \sin(p_1 t + \alpha_1) + \mu_2 a_2 \sin(p_2 t + \alpha_2) \end{aligned} \qquad (2.16)$$

where a_1, a_2, α_1 and α_2 are constants of integration to be determined from the initial conditions, μ_1 and μ_2 are ratios of the amplitudes of the two principal modes of vibrations, p_1 and p_2 are the natural frequencies of vibrations with gyroscopic forces:

$$p_{1,2} = \sqrt{\left(\left(J_0 l^2(k_y + k_z) + A^2\omega_b^2\right)^2 \pm \sqrt{\left(J_0 l^2(k_y + k_z) + A^2\omega_b^2\right)^2 - 4J_0^2 l^4 k_y k_z}\right) 0.5 J_0} \qquad (2.17)$$

Our analysis shows that with an increase in the value of ω_b the difference between the higher and the lower frequencies, p_1 and p_2, is increased.

It was found that for the first mode with the higher frequency p_1, the ratio μ_1 was positive, i.e. their vibrations y_1 and z_1 were in phase or in the so-called direct precession. For the lower frequency p_2, their vibrations y_2 and z_2 were in the opposite phase or in the so-called reverse precession. In the first mode of vibration, a point of the blank axis moves along the circle in the direction of its own rotation, while in the second mode it moves in the direction opposite to rotation.

A particular solution of Eqs (2.8), depending on the disturbing force, represents the forced vibrations of the system, which are represented as follows:

$$y_2 = B\cos pt + b\cos\omega^* t + F_r l_1 / k_y l, \qquad (2.18)$$

where

$$B = \frac{M_z l pA\omega_b - M_y l\left(k_z l^2 - J_o p^2\right)}{p^2 A^2 \omega_b^2 - \left(k_y l^2 - J_0 p^2\right)\left(k_z l^2 - J_0 p^2\right)},$$

$$D = \frac{M_z l\left(k_y l^2 - J_o p^2\right) - M_y l p\omega_b}{\left(k_z l^2 - J_0 p^2\right)\left(k_y l^2 - J_0 p^2\right) - p^2 A^2 \omega_b^2},$$

$$b = \frac{-F_a l_1 l\left(k_z l^2 - J_0 \omega^{*2}\right)}{A^2 \omega_b^2 \omega^{*2} - \left(k_y l^2 - J_0 \omega^{*2}\right)\left(k_z l^2 - J_0 \omega^{*2}\right)},$$

$$d = \frac{-F_a l_1 l A \omega_b \omega^*}{\left(k_z l^2 - J_0 \omega^{*2}\right)\left(k_y l^2 - J_0 \omega^{*2}\right) - A^2 \omega_b^2 \omega^{*2}} \tag{2.19}$$

Adding the general solution (Eq. (2.16)) and partial solution (Eq. (2.18)), a general solution of the differential equations (2.15) for displacements y and z of the blank end was obtained, which allow an easy determination of velocities v_y and v_z.

2.5.2. Dynamical model with two degrees of freedom with damping

Usually, in a study of steady-state vibration the values of the components determining free damping vibrations are reduced. However, it is impossible to achieve it in this case, because the operating conditions in the cutting are changed due to surface roughness. The differential equations of forced vibrations with damping, caused by the cutting force F according to the theorem on kinetic moment, are presented in the following form:

$$J_0 \ddot{z} - A\omega_b \dot{y} + \beta l^2 \dot{z} + k_z z l^2 = M_z l \sin pt\,,$$

$$J_0 \ddot{y} + A\omega_b \dot{z} + \beta l^2 \dot{y} + k_y y l^2 = M_y l \cos pt + F_r l_1 l + F_a l_1 l \cos \omega^* t\,, \tag{2.20}$$

where β is the damping factor.

To determine the general solution of Eqs (2.20) representing free vibrations, a complex variable was used:

$$\lambda = z_1 + i y_1 \tag{2.21}$$

The second equation of Eqs (2.20) is multiplied by i and added up with the first equation (we have to do with the homogeneous system of equations)

$$J_0 \ddot{\lambda} - A\omega_b \dot{y} + (\beta l^2 + i\dot{z} A\omega_b)\dot{\lambda} + k l^2 \lambda = 0\,. \tag{2.22}$$

The characteristic equation of Eq. (2.22)

$$J_o s^2 + \left(\beta l^2 + i A \omega_b\right) s + k l^2 = 0\,, \tag{2.23}$$

the roots of which

$$s_{1,2} = \frac{-\left(\beta l^2 + iA\omega_b\right) \pm \sqrt{\left(\beta l^2 + iA\omega_b\right)^2 - 4 J_o k l^2}}{2 J_o} \tag{2.24}$$

Considering that

$$\left(\beta l^2 + iA\omega_b\right)^2 - 4 J_o k l^2 = \beta^2 l^4 + i 2\beta l A\omega_b - \omega_b^2 A^2 - 4 J_o k l^2\,,$$

define

$$a_1^* = \beta^2 l^4 - \omega_b^2 A^2 - 4 J_o k l^2\,, \tag{2.25}$$

thus

$$s_{1,2} = \frac{-\left(\beta l^2 + iA\omega_b\right) \pm \sqrt{a_1^* + i b_1^*}}{2 J_o} \tag{2.26}$$

According to de Moivre's formula

$$\sqrt{a_1^* + ib_1^*} = \sqrt{\rho}\left(\cos\varphi/2 + i\sin\varphi/2\right), \tag{2.27}$$

where

$$\rho = \sqrt{\left(a_1^*\right)^2 + \left(b_1^*\right)^2}\,, \quad \tan\phi = b_1^* \big/ a_1^* \tag{2.28}$$

so it is possible to represent as follows

$$\sqrt{a_1^* + ib_1^*} = a_2^* + ib_2^* \;, \tag{2.29}$$

where

$$a_2^* = \sqrt{\rho}\cos\varphi/2 = \frac{1}{\sqrt{2}}\sqrt{\sqrt{(a_1^*)^2 + \left(b_1^*\right)^2} + a_1^*}\,,$$

$$b_2^* = \sqrt{\rho}\sin\varphi/2 = \frac{1}{\sqrt{2}}\sqrt{\sqrt{(a_1^*)^2 + \left(b_1^*\right)^2} - a_1^*} \tag{2.30}$$

Then the roots of the characteristic equation (2.23)

$$s_1 = -n_1 + i\omega_1 \,(31),$$

$$s_2 = -n_2 - i\omega, \tag{2.31}$$

where

$$\omega_1 = \left(b_2^* - A\omega_b\right)/\,2J_o \;, \omega_2 = \left(b_2^* + A\omega_b\right)/\,2J_o\,, \tag{2.32}$$

$$n_1 = \left(\beta l^2 - a_2^*\right)/\,2J_o\,, n_2 = \left(\beta l^2 + a_2^*\right)/\,2J_o\,, \tag{2.33}$$

while it is always $\beta l^2 > a_2^*$.

The general solution of the system of differential equations (2.20)

$$\lambda = C_1\exp\left(s_1 t\right) + C_2\exp\left(s_2 t\right), \tag{2.34}$$

Finally it was obtained

$$\begin{aligned}\lambda = {} & \left(D_1 + iD_3\right)\exp\left(-n_1 t\right)\left(\cos\omega_1 t + i\sin\omega_1 t\right) + \\ & + \left(D_2 + iD_4\right)\exp\left(-n_2 t\right)\left(\cos\omega_2 t + i\sin\omega_2 t\right)\end{aligned} \tag{2.35}$$

After separating the imaginary part from the real in Eq. (2.35) according to the introduced complex variable λ (Eq. (2.21)), the displacement of the blank end

$$\begin{aligned} z_1 = {} & \exp\left(-n_1 t\right)\left(D_1\cos\omega_1 t - D_3\sin\omega_1 t\right) + \\ & + \exp\left(-n_2 t\right)\left(D_2\cos\omega_2 t + D_4\sin\omega_2 t\right) \\ y_1 = {} & \exp\left(-n_1 t\right)\left(D_1\sin\omega_1 t + D_3\cos\omega_1 t\right) + \\ & + \exp\left(-n_2 t\right)\left(-D_2\sin\omega_2 t + D_4\cos\omega_2 t\right)\end{aligned} \tag{2.36}$$

A particular solution of Eqs (2.20) represents the forced vibrations of the system:

$$y_2 = a_1\cos pt + b_1\sin pt + F_r l_1/k_y l + c_1\cos\omega^* t + d_1\sin\omega^* t$$

$$z_2 = a_2\cos pt + b_2\sin pt + c_2\cos\omega^* t \tag{2.37}$$

where

$$a_1 = b_2 = \frac{\left(kl^2 - J_o p^2 + A\omega_b p\right) M l}{(kl^2 - J_o p^2 + A\omega_b p - \beta l^2 \omega_b)},$$

$$b_1 = -a_2 = \frac{M l^3 \beta p}{(kl^2 - J_o p^2 + A\omega_b p - \beta l^2 \omega_b)} \tag{2.38}$$

$$k = \left(k_y + k_z\right)/2, \; M = \left(M_y + M_z\right)/2 \tag{2.39}$$

$$c_1 = \frac{(k_y l^2 - J_o \omega^{*2}) F_a l l_1}{(k_y l^2 - J_o \omega^{*2})^2 + (\beta l^2 \omega^*)^2 + (A\omega_b \omega^*)^2},$$

$$c_2 = \frac{A\omega_b (k_y l^2 - J_o \omega^{*2}) F_a l l_1}{\beta l^2 [(k_y l^2 - J_o \omega^{*2})^2 + (\beta l^2 \omega^*)^2 + (A\omega_b \omega^*)^2]},$$

$$d_1 = \frac{\omega^* [(\beta l^2)^2 + (A\omega_b \omega^*)^2] F_a l l_1}{\beta l^2 [(k_y l^2 - J_o \omega^{*2})^2 + (\beta l^2 \omega^*)^2 + (A\omega_b \omega^*)^2]} \tag{2.40}$$

The general solution of Eqs (2.22) is the sum of Eqs (2.36)–(2.37):

$$\begin{aligned} z = z_1 + z_2 &= \exp\left(-n_1 t\right)\left(D_1 \cos\omega_1 t - D_3 \sin\omega_1 t\right) + \\ &+ \exp\left(-n_2 t\right)\left(D_2 \cos\omega_2 t + D_4 \sin\omega_2 t\right) \\ &+ a_2 \cos pt + b_2 \sin pt + c_2 \cos\omega^* t, \end{aligned}$$

$$\begin{aligned} y = y_1 + y_2 &= \exp\left(-n_1 t\right)\left(D_1 \sin\omega_1 t + D_3 \cos\omega_1 t\right) + \\ &+ \exp\left(-n_2 t\right)\left(-D_2 \sin\omega_2 t + D_4 \cos\omega_2 t\right) + \\ &+ a_1 \cos pt + b_1 \sin pt + F_r l_1 / k_y l + c_1 \cos\omega^* t + d_1 \sin\omega^* t, \end{aligned} \tag{2.41}$$

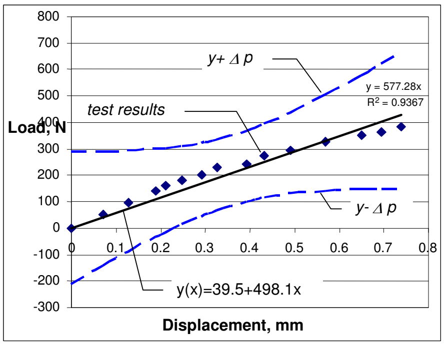
where D_1, D_2, D_3 and D_4 are constants of integration to be determined from the initial conditions, ω_1 and ω_2 are the natural frequencies of vibrations with gyroscopic forces and damping.

2.6. Experimental Analysis

2.6.1. Preliminary experimental test

2.6.1.1. Experimental test of the spring constant of the lathe

The accuracy of the accepted models was tested on the lathe 1K62. During the theoretical analysis, calculation accuracy depends both on the degree of fitness of the accepted models of the real system and on how accurately mechanical characteristics of the lathe are determined. One of these characteristics is the spring constant of the lathe. Figure 2.11 shows the results of statistical analysis of the experiment data in the form of correlation functions, where the coefficient of direct regression estimates the unknown rigidity. The coefficient of correlation was obtained close to a parameter that indicates the linear correlative function between the load and the displacement.



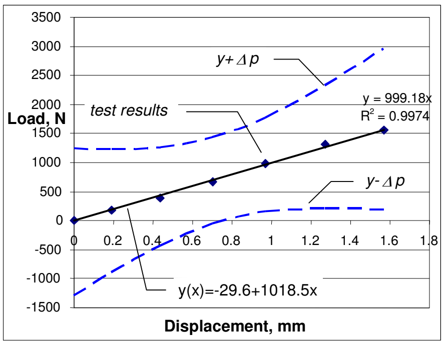


Figure 2.11 Correlation functions between the load and static displacement for horizontal (a) and vertical (b) loads

2.6.1.2. Experimental analysis of vibration on idling of the lathe

Figure 2.12 shows the results of vibration measurements without rotation of the blank in the horizontal and vertical planes, theoretical reference results of vibration velocity are also given (Aryassov, 2004). A similar experiment was conducted in the case of the rotating blank. Tests were carried out at different frequencies of the rotation of the spindle. In contrast to the previous test, one of the piezoindicators was installed on the tailstock. That slightly distorted measurement results, but the overall picture remained unaltered. It was confirmed by measurements with the vibrometer PICOLOG, which was in contact with the surface of the rotating blank. Test results in horizontal and vertical planes and the corresponding theoretical results of the vibration velocity according to (Astakhov, 1999) and Eqs (2.18–2.19) with gyroscopic forces are shown in Fig. 2.12.

The rotation frequency of the spindle was 1600 rpm. As can be seen in Fig. 2.12, the theoretical results obtained considering gyroscopic forces agree with the experimental results.

The experimental results satisfactorily coincide with the theoretical ones in the certain frequency range. However, an increase in the frequency leads to a gradual increase in discrepancies between the theoretical and experimental results. That is explained by a certain inadequacy of the accepted dynamic model with one degree of freedom. On the other hand, there were too few accelerometers installed onto the blank. The transducer did not record the vibrations if located in a node of normal modes, e.g. at horizontal vibrations of frequencies 188.75 and 405.00 Hz, and vertical vibrations with frequencies 123.75 and 306.00 Hz, where the largest differences between experimental and theoretical results occurred.

a) b)

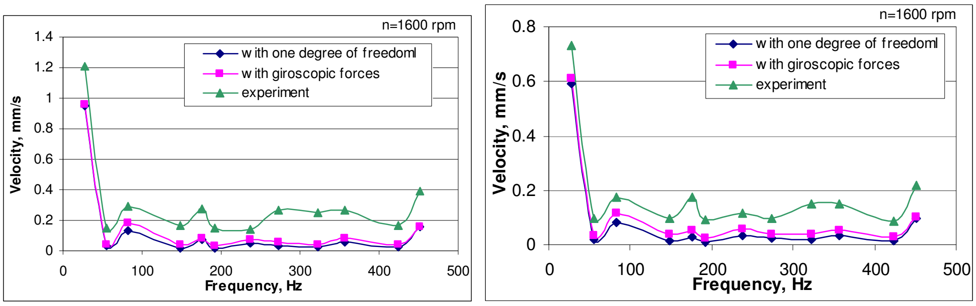


Figure 2.12 Experimental and theoretical results on horizontal (a) and vertical (b) vibrations for blank rotation with gyroscopic forces

On the basis of static experiment tests and experimental analysis of vibration on idling of the lathe, it was concluded, that the blank can be considered an ideal solid body hinged in the head-stock and elastically hinged in the back-stock. Therefore, the system with one degree of freedom for vibration analysis in the horizontal plane (Fig. 2.12a) and that with two degrees of freedom (Fig. 2.12b) were admissible.

2.6.2. Measuring of vibration while cutting

Experimental measuring was performed at different cutting speeds, feeds and depths of cut. After every cutting, surface roughness was measured with the profilograph Surtronic 3+. The amplitude value F_a of the variable component of the cutting force in Eq. (2.1) was taken according to the experimental value of roughness. The analysis of roughness measurement data confirmed the accuracy of the calculation model. Surface roughness parameters of the blank quite satisfactorily agree with the data of the theoretical investigation. The results of calculation with gyroscopic forces according to Eqs (2.11)–(2.13) agree with the experimental results. Test results and results of the calculation using Eqs (2.5)–(2.7), and (2.12)–(2.14), taking into account the dynamical model with one degree of freedom are presented in Fig. 2.13.

a) b)

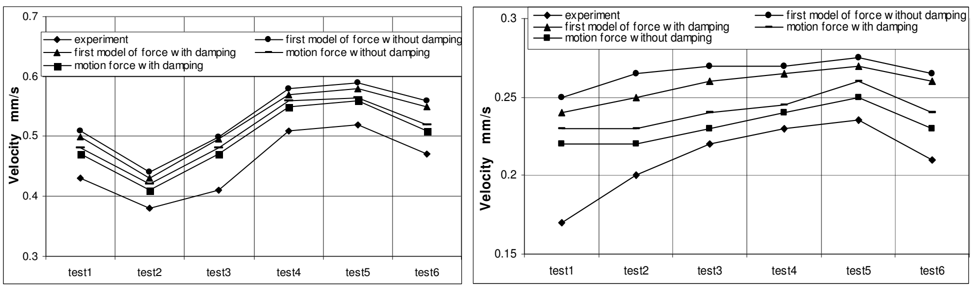


Figure 2.13 Comparative analysis of experimental and theoretical results (dynamical model with one degree of freedom) about horizontal (a) and vertical (b) vibrations by cutting

Analogically, test results and results of the calculation using Eqs (2.18)–(2.19) and (2.37)–(2.41), considering gyroscopic forces, are presented in Fig. 2.14.

a) b)

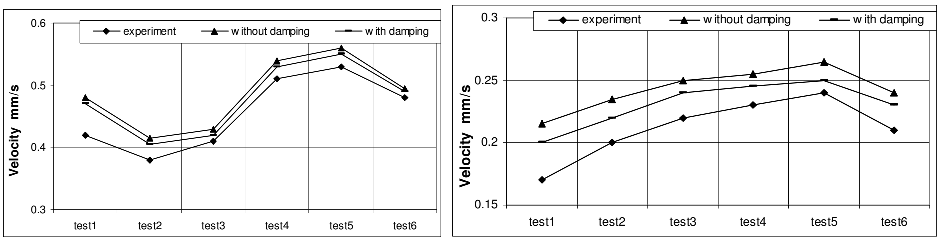


Figure 2.14. Comparative analysis of experimental and theoretical results (dynamical model with two degrees of freedom) for horizontal (a) and vertical (b) vibrations by cutting

2.7. Conclusions of Chapter 2

Data flows at MU have first been investigated by direct measurement with a video measuring system.

1. The main advantages of the digital video measuring system described above rely on a relatively low cost, portability and extended possibilities of digital image analyses, e.g. exact measuring of surface areas, average wear land lenghts and perimeters. Automated measuring also excludes human mistakes and due to saved images permits to analyse all data later off-line, which is important when carrying out long-lasting non-repeatable machining tests.
2. However, video measurement does not provide suitable results in industrial conditions due to excessive chip flows, use of a coolant, and changing lighting conditions. Measurements with a profilograph are time-consuming and difficult to automate. Therefore the received data can be used for development of indirect monitoring models for estimating the influence of tool wear dynamics by cutting forces, vibrations and noise measurement.
3. Analysis of roughness measurements data confirmed the accuracy of the dynamical calculation model. Surface roughness parameters of the blank quite satisfactorily agreed with the corresponding data of the theoretical investigation.
4. The calculation model with two degrees of freedom was used to analyse the influence of gyroscopic forces on surface roughness. The results of calculation when taking into account the damping forces correspond to the experimental results.
5. Analogically the calculation results for the dynamical model with one degree of freedom and motion cutting force are in a good agreement with the experimental results in comparison with the cutting force first model. The results of experimental and theoretical investigations show that the dynamical model is adequate and can be used for control of a lathe making it possible to attain the surface quality requested with a single run.

3. MODELS OF RELIABILITY AND OPERATIONS MONITORING SYSTEM

3.1. Use of pre-emptive model checking

Model checking (MC) is an algorithmic technique for verifying that a model of the system satisfies a given specification. The procedure normally uses an exhaustive search of the state space of the system to determine if some property of the system is true or not. Although restricted with finite state systems, MC can be combined with various abstraction, compositionality and induction principles to handle certain classes of infinite state systems (Clarke, 1999).

Model checking has several advantages over other system validation methods making it suitable for analyses: it conducts an exhaustive exploration of all possible behaviors and can even be used by investigation of certain infinite systems. MC is fully automatic and allows counter example (diagnostic trace) generation. In the current case MC can be used to evaluate all database units listed to determine if the defined requirements of production speed, cost and confidence level (previous experiences) of a product can be met. Using timed computational tree logic TCTL the conditional existence properties can be specified by formula templates (see Paper V). As a result, a solution for production chain will be provided by the model checker in the form of diagnostic trace.

In general, the properties expressible in temporal logics are combinations of *safety* and *liveness* properties. Safety properties express the fact that "*something bad does not happen*", i.e., if the property is falsified by an infinite execution of the model, then this is already observable on a finite prefix of that execution. Liveness can be paraphrased "*something good will happen*". Liveness cannot be falsified by a finite prefix. The bounded liveness properties can be expressed as safety properties and checked efficiently using the technique of test automata.

The proposed role of MC in Reliabiality and Operations Monitoring System (R/OMS) is to prove that the emergency behaviour suggested by an expert system satisfies all necessary safety and (bounded) liveness requirements before presented to an operator. Formally, given a system model M_s, the planned behaviour model M_o and a correctness requirement φ, we prove that the parallel composition $M_s \parallel M_o$ satisfies φ, denoted $M_s \parallel M_o \models \varphi$.

The loop of R/OMS that is extended with MC is depicted in Fig. 3.1. The expert system receives sensor data from the measurement system. When the potential emergency is detected, the expert system starts inference process using its accumulated hazard avoidance and handling rules.

The result of the inference is an action sequence or control strategy that has been successful in similar emergency situations and has been stored in the knowledge base. Since the rules of the expert system are heuristic in their nature, their applicability always includes some uncertainty.

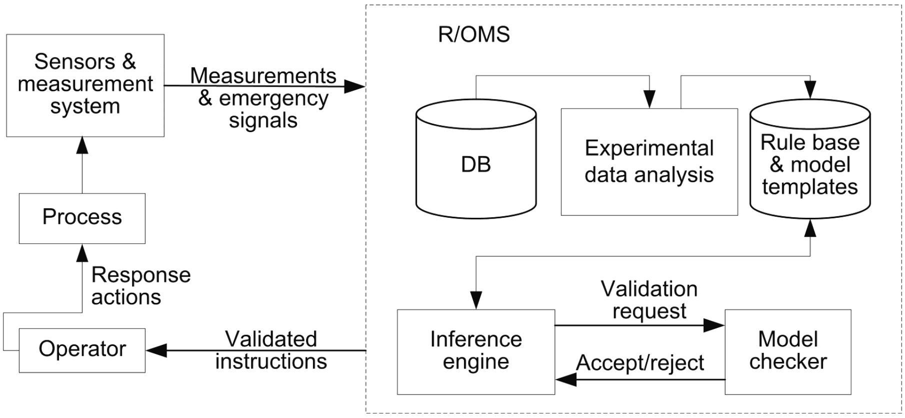


Figure 3.1 Model checking in an operator advisory system

To follow the principle "better no advice than questionable advice" the R/OMS has to verify its emergency action sequences before instructing the operator. Therefore, the R/OMS is extended with a model checking tool Uppaal (Larsen, 1997). Before starting the model checker's search engine the following steps have to be made:

- system model M_s has to be updated with the parameter values received from sensors and the measurement system at time instance t, when the potential hazard was detected (updated model M_s^t);
- the emergency operation strategy inferred by the expert system is encoded in the operator model M_o^t;
- safety criteria and other constraints to be met during emergency handling are stated in formula φ (here the specification patterns kept in the knowledge base are exploited).

Ideally the verification is completely automatic. However, in practice it involves external assistance that in our case is a part of the expert system responsibility, i.e., the expert system incorporates also rules for composing verification tasks and selecting verification strategy. In case the MC detects requirements violation, the expert system is provided with a diagnostic trace. The diagnostic trace is used as a counter example for the checked property and is stored for later improvement of the expert system's consistency.

3.2. An example: CNC lathe

System model M_s is defined in terms of parallel composition of timed automata (Fig. 3.2). Here each work unit of the system is modeled as a single automaton. The behaviour of automata is synchronized through local clock conditions. The parameters observable by sensors are defined in the model as global variables that can be reinitialized when a new model checking task is started. In our model those parameters are R_z – surface roughness of the work piece; Tc – cutting temperature; h – tool wear, wear land height; ω – cutter vibration acceleration; A – acoustic emission.

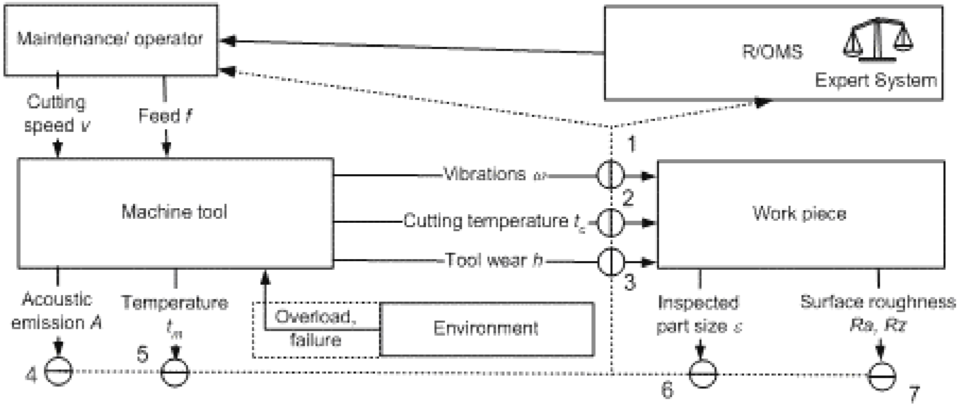


Fig. 3.2 Functional dependencies of IMM modules, where ⦶ – monitored resettable variables of the model

The correctness conditions to be checked are constructed from atomic conditions on observable parameters using logical connectives and temporal modalities: **A** – *always*; **E** – *sometimes*; $\Box$ – *globally*; $\Diamond$ – *eventually*. The atomic conditions are divided into two categories: those characterizing the quality of the work pieces (e.g. R_z) and those characterizing the state and working conditions of processing tools (T, h, ω, A). Atomic conditions for a parameter x are defined either in positive form $\varphi \equiv X^- \leq x \wedge x \leq X^+$, where X^- and X^+ are respectively lower and upper bounds of the interval where x is expected to be, or in negative form $\neg\varphi \equiv X^- > x \vee x > X^+$. The simplest composite correctness condition that requires system steadiness for certain period of time τ without operator's interference can be expressed as invariance property $\varphi \equiv \mathbf{A}\,\Box\,(clock \leq \tau \Rightarrow (\wedge_i\ \varphi_i))$ where *clock* models global time of the model and formulas φ_i are positive atomic conditions for parameters T, h, ω, A, R_z. Here, the verification task $M_s \parallel M_o \models? \varphi$ is reduced to the task $M_s \models? \varphi$. As an operator's activities are involved in the similar task, we run the task $M_s \parallel M_o \models? \varphi$. The result says whether the chosen operator's activities (encoded in M_o) keep the process safe during the time interval τ. Proving invariance properties requires generally traversal of the full search space and it may be too time consuming in the presence of emergency conditions. Therefore, properties of well defined emergency operation scenarios are more feasible to check by formulating them as bounded reachability problems. It means that when starting the operator's action somewhere out of safety region we ask whether it is possible to restore the safe mode during given reaction time. To check this task, the model M_s has to be reset, at first, with emergency values of process parameters, i.e. $\neg(\wedge_i\ \varphi_i)$ holds and the so-called inevitability property $\varphi \equiv \mathbf{A}\Diamond(\text{clock} \leq \tau \wedge (\wedge_i\ \varphi_i))$ has to be verified for updated model composition $M_s^t \parallel M_o^t$. A simulated MU, Detail and Operator are shown in Fig. 3.3.

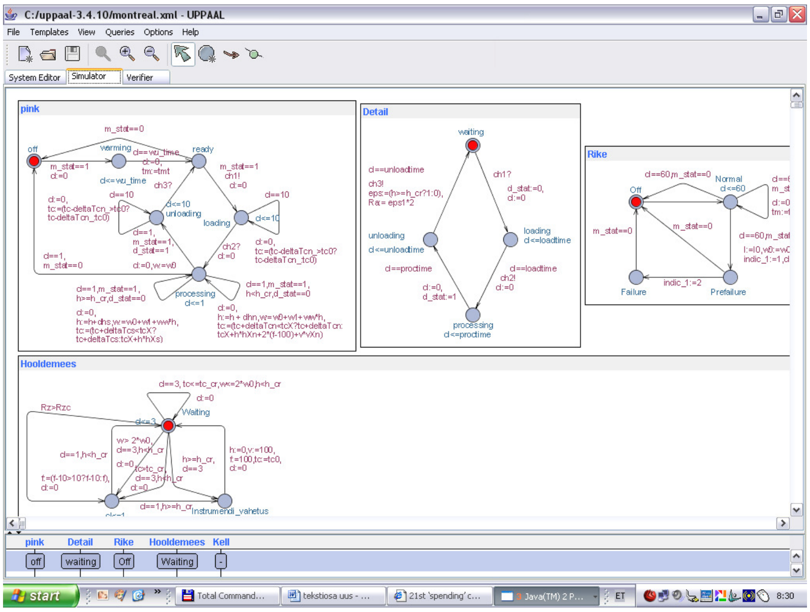


Figure 3.3 A snapshot of Uppaal model checker

3.3. Modeling production systems with patterns of timed automata

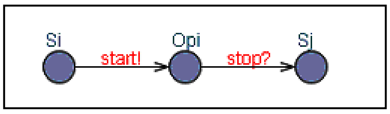
For modeling a production system the timed automata (TA) based formalism is used. It is appropriate for systems that can be modeled as a collection of non-deterministic processes with finite control structure and real-valued clocks (i.e. timed automata), communicating through channels and (or) shared data structures. Typical application areas include real-time controllers, communication protocols, and other components in which timing aspects are critical. Suitable computing engine for TA based MC is UppAal (www.uppaal.com).

To solve a production system model the pattern-based modeling and parametric model checking method can be used. For different tasks various specialized views of a root model M_0 are constructed and analyzed. The model M_0 consists of a parallel composition (denoted by ||) of UppAal automata that are constructed using basic model patterns $\boldsymbol{T^r}$ and $\boldsymbol{T^m}$, i.e., $M_0 \equiv (\|_i\, T^r{}_i) \,\|\, (\|_j\, T^m{}_j)$.

- Pattern $\boldsymbol{T^r}$ **–** “recipe”– is an automaton that models a technological process, i.e., the precedence relation of technological operations that are necessary to manufacture a certain type of product (Fig 3.4a).
- Pattern $\boldsymbol{T^{\,m}}$ is an automaton for modeling machining units performing technological operations (Fig 3.4b).

Here we distinguish between the concepts *pattern* and *template* that seemingly have a similar meaning. Since *template* has fixed semantics in UppAal denoting a class of automata that can be instantiated by giving explicit values to its parameters, we use a more general notion – *pattern* – denoting typical fragments of automata that occur repeatedly in the model. Both patterns are sequential and the operations of pattern $\boldsymbol{T^r}$ and their performing by MU represented in $\boldsymbol{T^m}$ are synchronized via channels. Let S_i denote a state (in the pattern instant T^r_k) where a work piece being just processed by some operation Op_l according to a recipe j is waiting for processing by Op_i. The interoperation states S_i are used for modeling transport delays between different locations where processing takes place.

(a)



(b)

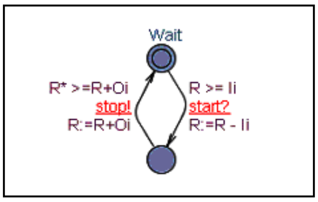


Figure 3.4 Model patterns: (a) a fragment of technological process "recipe";
(b) a fragment of a machining unit performing an operation

The root model M_0 can be simplified considerably by abstraction if general resource and performance estimation problems must be solved (analysis of phase P2). If the global performance or resource usage are of interest it is possible to abstract from recipe automata and introduce instead the so-called *buffer* (or *storage*) *variables* to $\boldsymbol{T^m}$ models – a pair for each (observable in the model) machining operation. Since machining operations share their input and output buffers the variables modeling buffers are joint for several operations. Thus, the machining view can be constructed from initial $\boldsymbol{T^m}$ patterns using the following rule: if two recipe automata T^r_1 and T^r_2 include the same operation Op_i, then there are buffer variables R_i and R_{i+1} in the modified $\boldsymbol{T^m}$ model such that for all operations preceding immediately Op_i in $\boldsymbol{T^m}$ their common output buffer is modeled by the variable R_i, and for all operations of T^r_1 and T^r_2 following immediately Op_i their input buffer is modeled by variable R_{i+1}. Denoting the number of work-pieces needed for Op_i by I_i and the number of products or resources released after completing the operation by O_i, the guards and assignments of transitions to and from the state Op_i in $\boldsymbol{T^{m*}}$ (i.e., $t(.,i)$ and $t(i,.)$), are defined in the following way: $G(t_{xi}) \equiv R_i \geq I_i$, $Asg(t_{xi}) \equiv R_i - I_i$; $G(t_{ix}) \equiv RR \geq R_{i+1} + O_i$, $Asg(t_{ix}) \equiv R_{i+1} + O_i$ (see Fig. 3.4). The machining view completely preserves the parallelism of machining units and can be used for planning machine load and throughput.

UppAal toolbox is one candidate for performing the model checking task (Rennik, 2005). However, it uses XML files which are not comparable with corresponding database formats. Therefore in practice the XML output from database is transformed using Python software based model converter Finke, analysed by UppAal, and thereafter tranferred back by expert system Prolog. The suitable Java interface application has been elaborated at TUT (Mäe, 2006).

In FMS situated at a laboratory of TUT (Fig. 3.5), several technological devices are involved, including a Milling CNC machine (M8), Robot «Mentor» (M2), Robot «Serpent» (M7), Load module (M4), Height measurement device (M3), Diameter measurement device (M5), Conveyer 1 (M1), Conveyer 2 (M6), Indexed table (M9), Operator.

In Fig. 3.6 a scheme of FMS is presented, a data model (IDEF0) shown in Fig. 3.7 (Karaulova, 2002, 2004) can be received after decomposition stages.

Figure 3.5 FMS at TUT

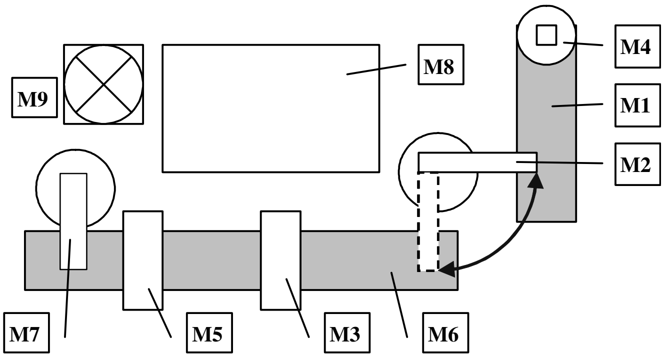


Figure 3.6 Scheme of FMS and modules decomposition

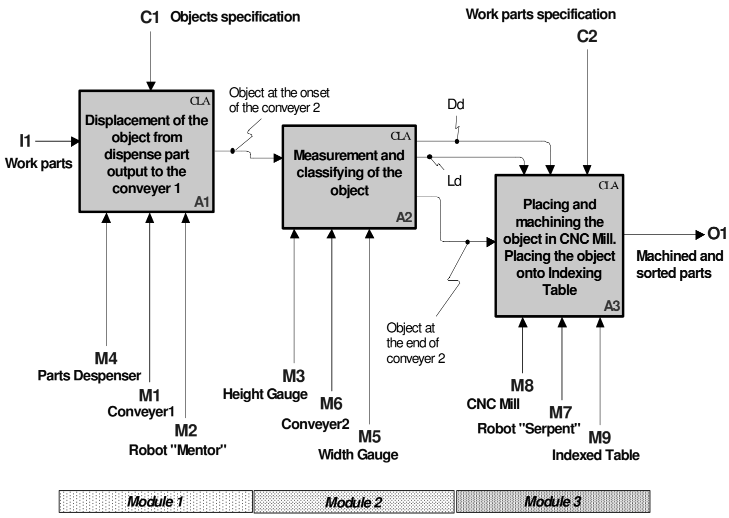


Figure 3.7 First level decomposition of the diagram

As a timed automaton, the milling machine can be represented as a graph of initial position Wait and the position Op4 with clock cl1<=6. The milling machine reaches Op4 after synchronisation with a command start4, whereas clock cl1 is set to 0. The operation is performed after the clock reaches the value of 6 and activates the synchronisation stop4 (Fig. 3.8).

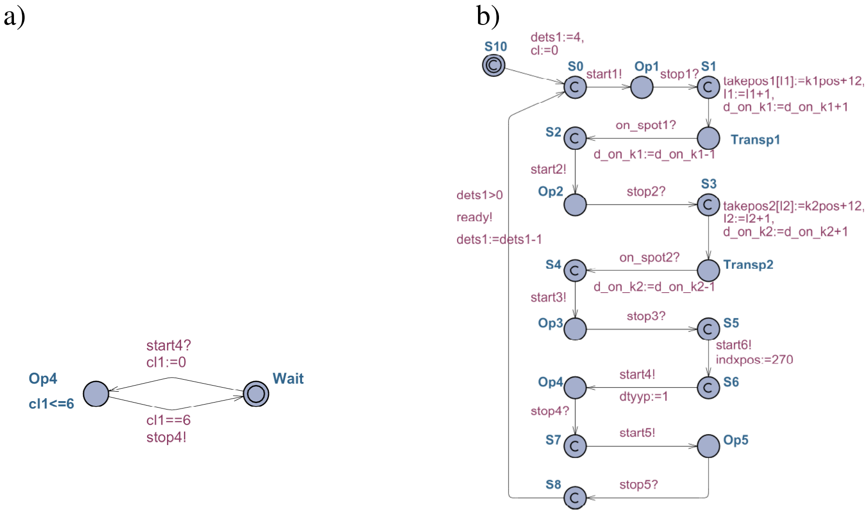


Figure 3.8 Milling machine (a) and detail fragments of FMS as the timed automata models

3.4. A case study: technology of worm shaft machining

The case study is based on an example of technological traces for machining worm shafts. As a first step feature surfaces are analyzed by an expert system and possible technological chains are offered (Fig. 3.9). However, the real possibilities of an enterprise could differ from ideal situation, where all technological possibilities are available.

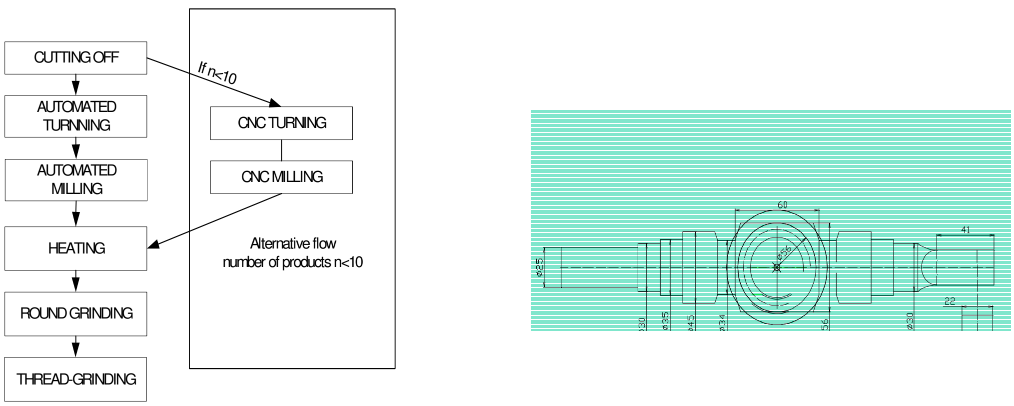


Figure 3.9 An example of trace for manufacturing worm shafts

Turning and milling operations can be performed either by using conventional, CNC or automated machine tools. In case of need the available resources can be ordered from networked resource-sharing enterprises.

For solving planning tasks of the wormshafts manufacturing the workflow diagram is represented by the automaton “Manufacturing process” and the technological resources needed for that by automata “Milling_m_1” … “Milling_m_n”, …, “Lathe$_1$”, …, “Lathe$_n$” grouped by their locations (Fig. 3.10).

When running the Uppaal model checker with constraint specification “E<>Manufacturing_process.Sf” with the option “diagnostic trace – fastest”, it means that a path from the global initial state to the global final state that includes Manufacturing_process.Sf is searched and that the path has the shortest duration. The diagnostic trace generated by optimal solution provides us also with the locations where performing the machining operations gives the shortest cycle time.

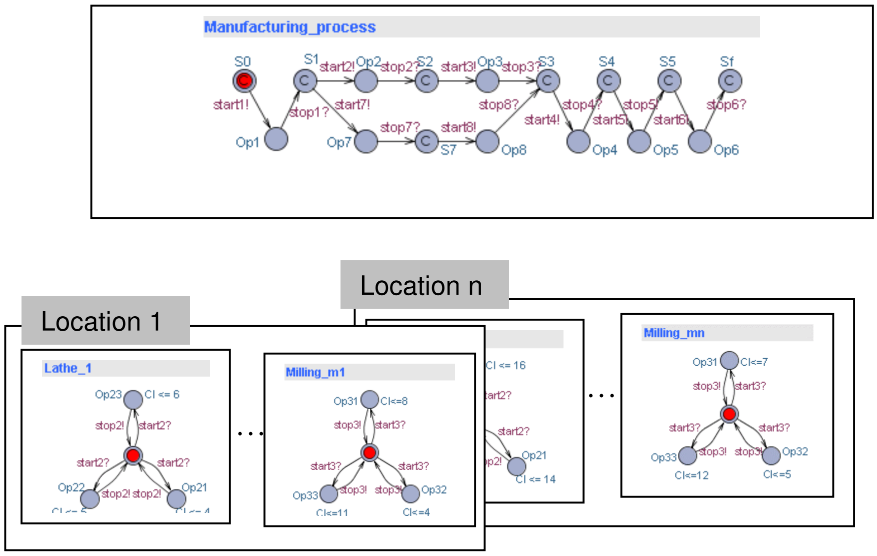


Figure 3.10 The M_0 model for solving wormshafts production planning tasks

3.5. Conclusions of Chapter 3

1. Generally, the efficiency of MC depends heavily on the used model and correctness condition to be checked. The MC strategies such as over/under approximations, breadth first/depth first search, state space reuse and reduction provide substantial speedup if properly chosen. Current experience shows that the definition of model checking task templates for given application has to be accompanied with strategy selecting rules that constitute a part of the expert rule base in R/OMS.
2. A formal model checking technique was proposed as an extension to R/OMS tools. Providing provably safe instructions for an operator is possible only when having adequate process and operator behavioural models. Real time model updating in this approach is performed by measurement system and expert

system in cooperation during process run. The final instruction decision is made only after model checker's acceptance.

3. The approach is illustrated by examples developed at Tallinn University of Technology. The elaborated model-checking module can be implemented with minor changes in other automated systems and is able to reduce hazardous situations caused by insufficient human competencies.

4. MODELS FOR MONITORING THE RESOURCES OF ENTERPRISES

4.1. Modelling the shared use of technological resources

The conventional manufacturing planning is based on the priority of relations between the manufacturable part and the manufacturing plan. An enterprise should expand the business market to the customer and supplier, which causes the enterprises to be expanded and globalized. Advanced manufacturing models, in which the member enterprises located in different regions, or even distributed throughout the world, have closer relationships and collaborative benefits by cooperating in the development of products, which need Internet/Extranet/Intranet-based information systems to support mutually beneficial collaboration in management activities among its members (Tang, 2002). A central design consideration of effective e-Work is "KISS" (Keep It Simple, System!), meaning that the computer and communication support system can be designed as complex as necessary, as long as it can work autonomously, in parallel to and supportive of humans, subject to their inputs and instructions (Nof, 2006).

Fields of machine building, metal and apparatus engineering can be characterised as a rising trend in Estonia. At the same time the following overall tendencies have to be taken into account in manufacturing industry:

- general globalisation;
- shrinkage of markets and formation of integrated manufacturing capacities;
- increasing quality requirements and growing clients' expectations to contractors;
- urgent demand for well trained personnel;
- continuous appreciation of resources.

These trends have a direct impact on the competitive position of an enterprise forcing to look for new ways targeted at raising the marketing feasibility. From aforementioned an idea of current research has been derived, proposing clusters and co-operation networks as means for raising productivity and efficiency of an enterprise and thereby also for upgrading competitive ability. Only in co-operation can large development projects, unprofitable for single enterprises, be realised. Likewise, it has to be taken into consideration that we are living and working in conditions of restricted resources (machinery, software, IT solutions, etc.) the cost of which is progressively increasing. Therefore concentrated attention has to be paid to rational or even shared use of resources.

Requirements for shortening of cycle times, increase in quality and rational use of resources create main preconditions of need for special forms of co-operation.

The Federation of Estonian Engineering Industry unites over 100 enterprises as an umbrella organisation. Estonian enterprises are mainly small or medium size and regionally concentrated in bigger cities. In competition with other countries, there is a problem of lack of technological resources and qualified personnel. Therefore the EML has initiated several projects to overcome the shortages and promote clustering. In tight cooperation several solutions have been proposed. The proposed overall concept of the system includes sectoral, enterprise and technological levels (Fig. 4.1).

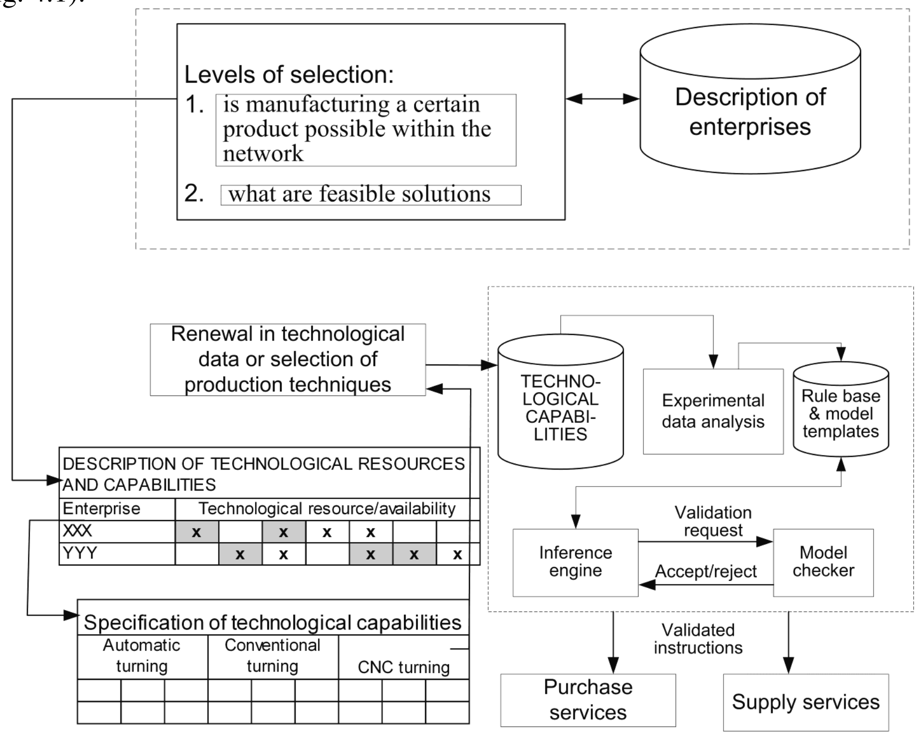


Figure 4.1 Information flow in virtual database solution for planning resource-sharing production in a technological resources network

The sectoral level involves a general description of technological features of industrial sector enterprises. The knowledge base connects also manufacturing enterprises, consultancy firms, educational organizations and universities in a certain field to handle local resources for larger subcontract orders and production volumes.

The enterprise level includes a specification and a detailed description of technological possibilities of an enterprise, increasing the export opportunities of SMEs through technological networking. This level includes data about availability of current resources.

Technological possibilities involve firstly the specifications of technological processes, e.g. turning, milling, drilling, welding, etc. followed by a selection of corresponding subclasses. When selecting a specific subclass, one has to specify some technological constraints, e.g. the bar and chuck capacity, maximal length of work piece, etc.

Some general questions of creating cooperative production network can be listed as: is manufacturing of a certain product possible within the network, what is the expected production time, what are feasible logistic solutions and rerouting possibilities in case of emergency (equipment failure)? Those questions represent the user point of view to all of three cooperation levels described and should be formalized as queries to the database.

As assumptions to solve the queries described we need:
1. A description of the technological process to be implemented in terms of machining operations and their sequencing constraints.
2. Enterprises, their technological capabilities in terms of machining operations, performance and quality characteristics of services.
3. Locations of enterprises and inter-enterprise logistics.

The incremental approach proposed for solving the production planning problems consists of three phases:
1. Deciding whether the technological process is feasible (implementable) concerning given constraints, i.e., showing the existence of some solution.
2. Reduction of the solution space by removing inappropriate firms and services. The selection criteria are the cost, deadline, trust, and location of service providers.
3. Finding the time/cost (sub-)optimal solution. It is assumed that the solution takes into account also transportation between different locations, e.g. if the quality does not satisfy the standards set.

4.2. Shared use of technological resources

The enterprise level of the network includes specification and detailed description of technological possibilities of an enterprise, increasing the export opportunities of SMEs through technological networking. Technological possibilities involve specification of technological processes, followed by a selection of corresponding subclasses. When selecting a subclass, the next step is input of adequate data, e.g. bar and chuck capacity, maximal length of work piece.

The level of problem solving can be realised by the following options:
- an opinion of a current expert system, advising management board/marketing department of an enterprise to evaluate current production potential and need for updates in technology;
- supporting the human agent ability in focussing on core manufacturing to stay competitive in business;
- supporting the outsourcing of non-core business competitive manufacturing – support in creation manufacturing network for those product modules, components or final assembly;
- an inquiry through the system, approach to scientific authorities. Universities and consultant companies have the key role, acting as authorised bodies, predicting the need for advanced technologies in a forecast of 5 years. A mapped need for investments into new technologies for the next 5 years is valuable for the community;
- data exchange or business-aid network, where participants can describe resources vacant and the supply needed. The resources in current context are defined as technological capabilities characterised by precise specifications.

Technological capabilities are considered as hierarchic associations, whereas definition of technological possibility acts as a basis for classifying. In classification four levels can be distinguished.

- Group definition. Process method serves as a basis for group definition (e.g. machining, sheet material processing, welding, casting, finishing, EDM, powder metallurgy, electro-chemical methods, engineering methods).
- Type definition. Processing mode is the basis when defining a type in the corresponding group.
- Class definition. Classification of technological possibilities is based on the technology used on certain machines (e.g. automated turning, semi-automated turning, universal turning, etc.)
- Parametric definition. Parametric definition is based on finding features characterising possibility of processing a detail on the machines of an enterprise (Fig. 4.2).

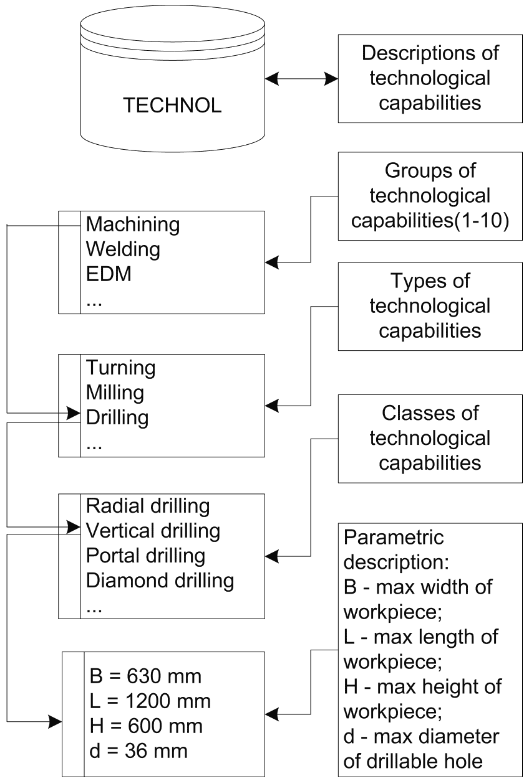


Figure 4.2 Structure of the technological capabilities database Technol

Knowledge of technological capabilities is important regarding from three aspects:

- What kind of products is the enterprise able to manufacture (product–set of machine tools)?
- What are technological capabilities of different enterprises (similarities, differences)? – co-operation can be organised as rationally as possible.
- When the technological capabilities of an enterprise in some field are fixed, then how can a product or a group of products be manufactured as rationally as possible?

Regarding co-operation networks the main goal is sharing of production stages of a complex product between similar enterprises, obtaining thus higher quality, shortening of cycle times and rational use of existing resources. In the proposed database model a product can be described by using characteristic data, e.g. for rotational parts:

- d – max diameter of processing
- l – max length of processing
- IT – quality class of processing
- Ra – surface roughness parameter

A lathe can be described by the following data:

- L – max distance between centres
- D – max diameter above support
- T – inner diameter of spindle
- TK – quality class of the machine tool
- PK – surface quality parameter derived from processing method

Technological capabilities of a manufacturing enterprise evolve based on the technological capabilities of machinery (machine tools, presses, welding equipment, etc). Technological capabilities can be defined as a set of characteristics of a device, robot, production module or system for performing some technological task. The first database version of a description of enterprises was completed in 2004 as a CD and an online version. The renewed version includes besides enterprises also educational organisations and suppliers (test version http://www.alertix.net/metnet/).

The test version of technological resources was elaborated and tested on the basis of 10 enterprises (http://www.emliit.ee/innoclus).

4.3. Modelling of competences of human resources

Innomet is a project funded by the European Community Leonardo da Vinci II programme. The project aims at developing international and trans-European methodologies by realising the Internet based human resources development system as a prototype. The project is promoted by Tallinn University of Technology. Innomet is an acronym for development of the innovative database model for adding innovation capacity of labour force and entrepreneurs of the metal engineering, machinery and apparatus sector.

The primary objective of this tool as such is to increase the responsiveness of educational institutions to business demands and to improve the access of vocational and higher educated specialists into labour market. For that purpose it is proposed to introduce an integrated virtual database system for educational and industrial needs in the sector, which includes links to existing educational opportunities, e.g. different levels of study programmes, as well as private sector qualified labour force and mapping of the industrial needs for human resources.

The main objective of the system therefore is to supply enterprises and educational institutions with the updated information related to the needs, structure and qualification of human resources as well as about the opportunities of finding/ requesting the courses needed.

The number of network partners in different countries varies, the total evaluative number being 25–30 companies and network schools. In addition, in Estonia another project has been submitted to the European Social Fund (Measure 1.1) the objective of which is to implement the Innomet system throughout Estonia involving 10 major schools and 100 companies (full-scale data and comparability). However, in different countries the scope of the project is different involving only the core network partners of the organisation.

The project and Innomet system as such identify the bottlenecks (lack of qualified labour force, development problems related to human resources) of the educational and training system vis-à-vis the existing private sector labour force needs.

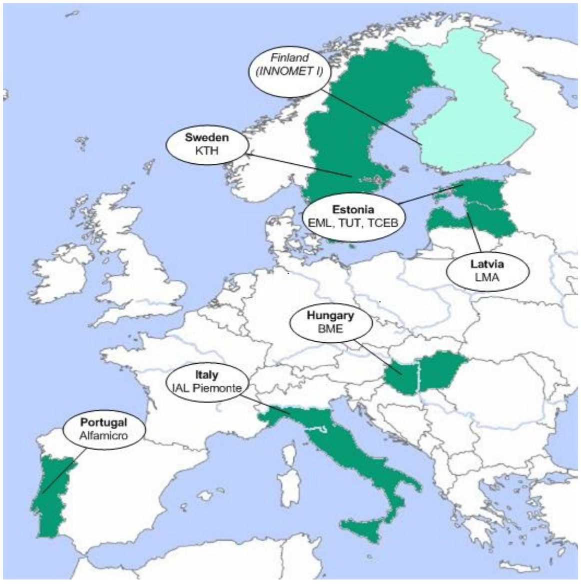


Figure 4.3 Innomet in Europe

Therefore, with this project, the quality of both education programmes and cooperation between educational institutions and private sector companies will be improved through interaction and networking. Direct impact on different target groups is the following:

- The system introduced offers a new innovative channel to improve the everyday communication and cooperation between educational institutions (professors, trainers, students), sectoral associations and companies, which are all involved in the project. In addition, professors and trainers can more easily adapt and up-date their study programmes according to the private sector labour force demand. For education and planning purposes, the co-operation platform with an information system helps to streamline higher and vocational education programmes to better respond to market needs. This will lead to a high skill and competence profile of students and trainees and better competitiveness of human resource in general.

- The system offers dynamic and up-dated recommendations in an Internet-based form for the vocational and higher education institutions (e.g. proposals of changes of study programs) having a concrete impact on the vocational and higher education system – increasing its quality and competitiveness.
- The system provides a cost efficient information exchange medium for the educational institutions (training providers) on the one hand and the companies (potential re-training receivers) on the other hand. The system on the Internet site improves direct contacts and links between vocational schools and companies in order to cooperate in terms of common research (graduation works on different levels of education), traineeships, and job offers/seeking.

In the longer term, the Innomet system on the Internet helps companies to find the possibilities for re-training and to provide constant implications to study programmes focusing on the market need for qualified specialists. Development, monitoring and drawing conclusions of knowledge, skills, experience, personal qualities motivation factors are the main merits of human resources development in an enterprise.

Qualification standards are the basis for evaluation of labour force qualification. The qualification standard stands here as the criterion of skills, knowledge and personal qualities of social (human) resources. On the assumption of particularity of every organisation or enterprise the core component for human resources development is the competence/skills card (Fig. 4.4).

2A. OPERATOR	SPECIFICATION: MACHINE TOOL OPERATOR	
Competence/ Skills	**NL (0-5)**	**EL (0-5)**
2.1 General skills		
2A.1.1 General skills of profession	5	4
2A.1.2 Management and economy	4	3
…………………………		
2A.2 Basic skills		
2A.2.1 Knowledge of specific materials	5	4
2A.2.2 Skills of reading technical drawings	4	3
…………………………	….	….
2A.3. Extra skills		
2A.3.1 Selection of working tools	4	4
2A.3.2 Knowledge of manufacturing technologies	4	4
…………………………	…..	….
2A.4 Personal qualities		
2A.4.1 Sense of duty	5	4
2A.4.2 Precision and punctuality	5	3
…………………………	…..	…..

Figure 4.4 An example of competence/skills card

Skills/knowledge to be evaluated are grouped according to professional standards. A professional standard is a paper, defining requirements of professional qualification for knowledge, skills, experience, values and personal qualities. A professional standard acts as:

- a specification of labour force qualification requirements;
- a basis for elaboration of educational organisations curricula and study programmes;
- a basis for elaboration of vocational exams as well as for certification and evaluation of professional qualification;
- a means for creating a basis for comparison of international qualification certificates.

In practice prescription of professional requirements is substantial. Professional requirements are divided into four groups beginning with more general skills and ending with specific personal qualities essential for working in a profession. The general principles of professional requirements are as follows (Fig. 4.4):

- general skills – requirements for general skills and knowledge originating from economic affairs;
- basic skills – special professional requirements for skills and knowledge;
- extra skills – special professional requirements for skills and knowledge, characterised in narrow specialisation and/or necessity for executing additional assignments at current position;
- personal qualities – expected personal identities and abilities required in a certain profession.

The definition of specific skills/knowledge depends on the field of activity of an enterprise. The definition process should be started in every particular case from job descriptions of a current enterprise.

Evaluation of skills/knowledge is the next step towards human resources development at an enterprise. For assessment a scale of grades [0…5] is used. The lowest grade is "1" and the highest "5". Grade "0" is used if the respective skill is not relevant. Both needed (NL) and existing (EL) levels are to be evaluated.

Innomet will play a significant role in engineering education management process.

Companies try to find skilled employees to fulfil their strategy. From the other side the study programmes reflect the competency of particular educational institution. Missing are coherent activities between industry and the academic world.

The real situation should be as follows.

In companies one should do all defined by the list of skills related to a particular job on the needed qualification level.

In educational institutions a student after passing a course "should know" the subject (passive skills) and "should be able to do" related to the subject (active skills).

The sum of active skills of the programme should match the lowest set of skills by the related qualification standard.

In the Innomet system there are separate processes which are tightly connected with each other (see Fig. 4.5).

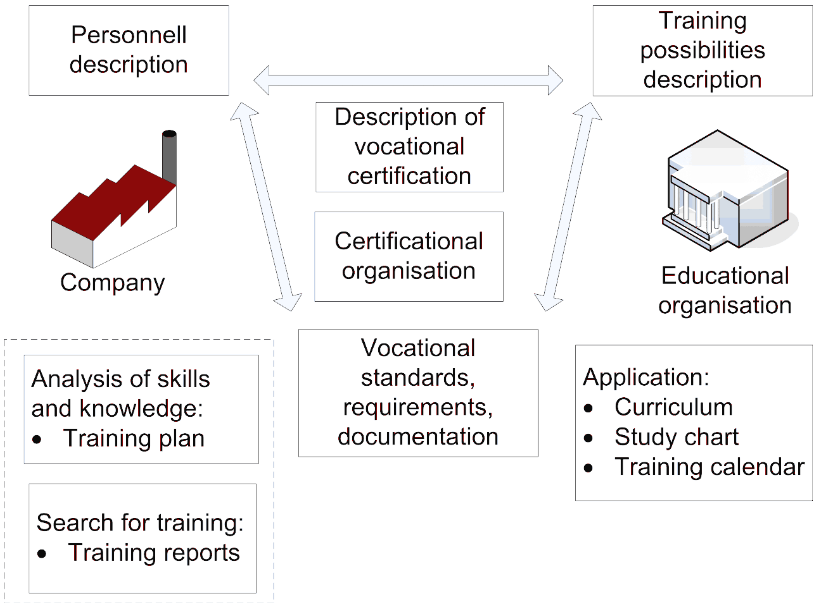


Figure 4.5 Associations in the Innomet system

These processes are:

1) Determination of the Human Resources (HR) competence and the training necessities in the company, taking into consideration the strategy of the company and operating needs.
2) Matching the training necessities with the possibilities and carrying out the real courses through the system.
3) Fixing the needs for vocational examinations and developing a national professional award system in the field of machine building and apparatus industry.

In the first stage of the process training needs are determined according to competency charts of the company. Competency charts are filled personally for each employee or vocation (e.g. CAD engineer, CNC operator, welder, etc.). The charts can be filled in through the Internet in every enterprise, with the sensitive information of the enterprise remaining undisclosed. The analysis is based on average indicators of vocations, industrial fields (toolmaking, machine-building, etc.) or on regional basis. The existing (EL) and needed levels (NL) are estimated in a scale of 0–5, where 0 means “the skill is of no importance” and 5 denotes “the skill is of high importance”. If EL<NL, there exists a need for additional training. For general professions special standard templates have been created, e.g. the results of queries concerning CAD designers in 18 Estonian enterprises are depicted in Fig. 4.6. In the template competences are divided into four groups: general, basic, special, and personal.

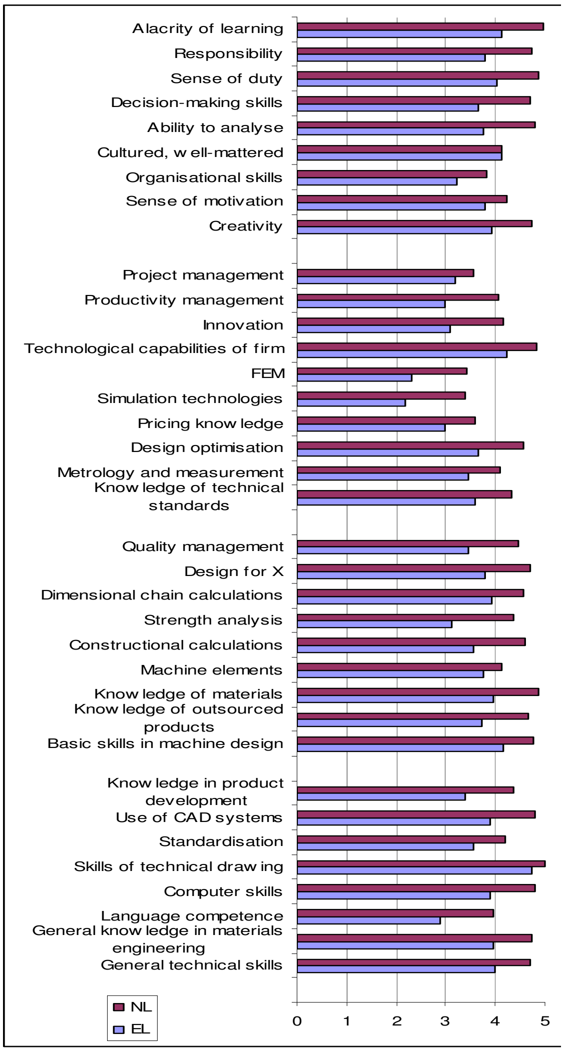


Figure 4.6 Existing (EL) and needed (NL) competences of a CAD Engineer in Estonian enterprises

The second stage includes arrangement of training courses according to the needs mapped. The input is obtained from an analysis of all Estonian educational organisations of the sector. The training activities are organised based on unified training calendar and the corresponding documentation.

On the information of Fig. 4.6 educational institutions can draw conclusions and offer corresponding training courses, e.g. a course of CAD systems could be advantageous, at the same time a course of technical drawing appears to have less potential.

Before the Innomet system was implemented vocational training courses were organised independently by taylor-made course plans. The new monitoring system makes it possible to support organisational work by adding value through different queries, statistical calculations and prediction mechanisms.

An enterprise-centred mapping and analysis of skills/knowledge is described in Fig 4.7.

A regional analysis of companies is shown in Fig. 4.8. There exist differences in estimated levels of competence between Northern and Southern Estonia for CAD Engineer profession. The overall pattern seems similar for both, however Southern enterprises value their competence more highly than Northern enterprises. Concerning CAD, Northern Estonia is more influenced by Tallinn University of Technology, whereas Southern Estonia is more tightly connected with Estonian University of Life Sciences.

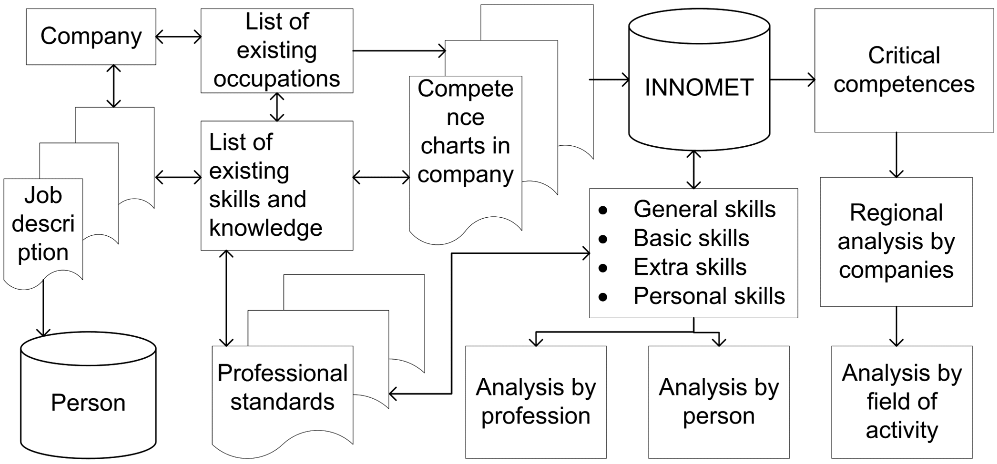


Figure 4.7 Enterprise-centred mapping and analysis of skills/knowledge

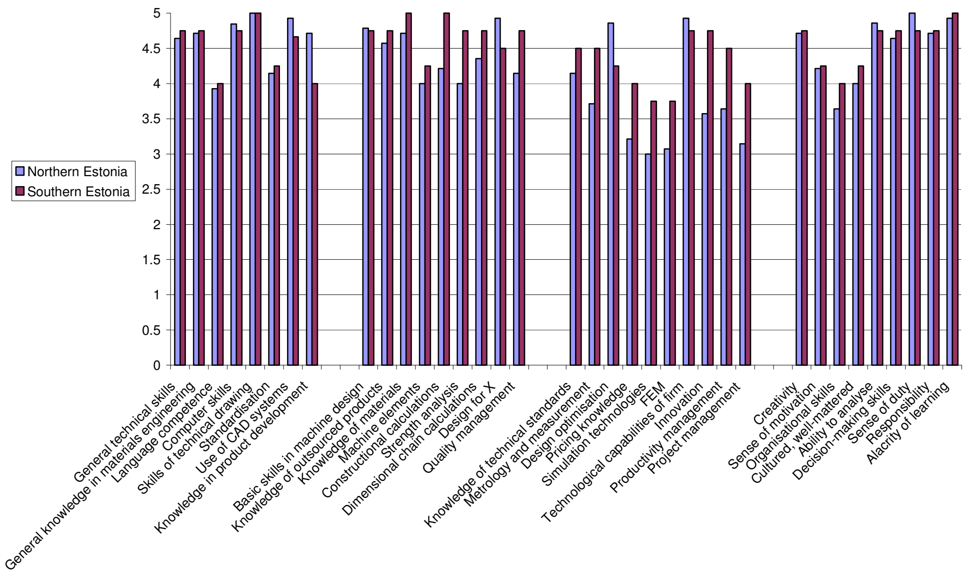


Figure 4.8 Differences in estimated existing level of competence between Northern and Southern Estonia

When the North is more confident with CAD systems, knowledge in product development, design for X and design optimisation, then the South is estimating higher its knowledge of materials, constructional calculations, innovation and project management.

A scheme of virtual database solution for factor conditions development of Porter's competitive diamond model is presented in Fig. 4.9.

In 2005/2006 several new vocational training courses were developed for industry, using the best lecturers both from universities and the industrial sector (e.g. courses 'ERP Systems', 'Modern Technologies, Materials and Measurement Techniques'). It improved considerably open dialogue between educational institutions, the private sector and other related organisations.

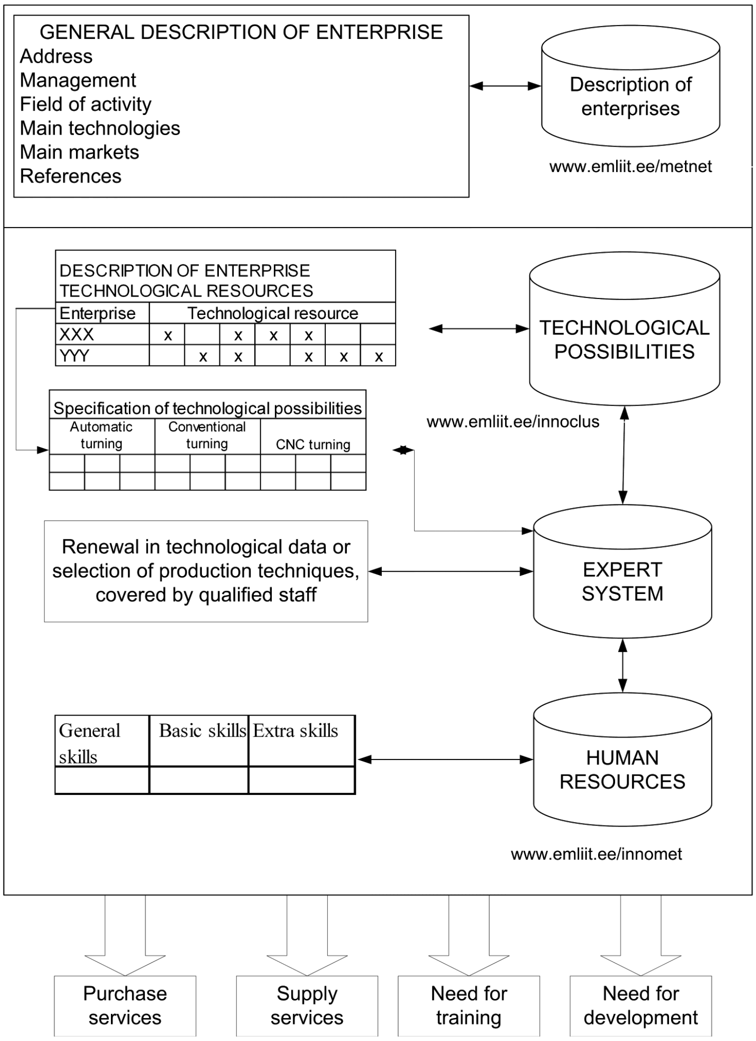


Figure 4.9 Information flow model for improving factor conditions of clusters

Better efficiency and transparency of needed education and training in the sector of machinery, metal and apparatus engineering is based on measurable private sector labour demand. Academic world can more easily adapt and update current study programmes according to the private sector labour force demand.

4.4. Conclusions of Chapter 4

The proposed model is capable for monitoring quality and quantity of technological resources in every participating enterprise of the network. Results at this phase are used to revise and develop the INNOCLUS database test version. In a long perspective when a critical mass of companies are involved the system results can support the strategic planning of technology transfer as well as it could be used as a basis for the industrial enterprises in order to elaborate co-operation networks and develop towards extended enterprises. Online resource databases allow effective cooperation of production enterprises at least in machinery. Usability of such databases can be significantly increased by adding search engines that are able to construct full production chain implementing user needs and restrictions. As shown in Chapter 3, model checking tool is one candidate for performing such chain construction task.

The main objective of the proposed model is to supply enterprises and educational institutions with updated information related to the needs, structure and qualification as well as the opportunities of finding the needed labour force. An important step towards this goal is to define and understand the needs of the manufacturing industry for training and education in manufacturing at the global level. Data regularly updated by enterprises and educational institutions will contribute to the development of a time based information system concerning human resources. This will also give companies the opportunity and benefit to upgrade employees within the latest courses of manufacturing and management based on global industry needs and with the state of the art of educational methodologies. For increasing mutual trust the professional non-profit organisations as well as local authorities should take the initiative in creation such networked systems. An important key factor is concurrent development and implementation of vocational standards, including different levels for workers, engineers and managers.

Current developments have proved interest and need for such a system, having advantages such as:

- Informativity (large and multilevel data feeds)
- Flexibility (possible to interact to changes in economic environment)
- Operativity (always relevant)
- Versatility (various tasks can be solved)
- Farsightedness (enables predicting future changes)
- Dynamism (enables to monitor processes in different time intervals)
- Universality (the system is adjustable for other industrial sectors).

The proposed system is in a phase of implementation in Estonian machinery sector. International cooperation towards development of unified templates for European labour market goes on.

5. CONCLUSIONS

The generalised conclusions of the work are the following:

1. A process monitoring model and an exemplary system was developed at MU level, where a real form of cutting wedge and real depth of cut at the given moment were transformed into real cutting data in the tool-in-process system.
   1.1. Exact measurements of the surface contact areas, average wear land widths and chip movement direction involving CCD cameras enabled monitoring. The elaborated measurement methodology made it possible to monitor tool wear development by mounting a single CCD camera into the machine tool. The main advantages of the elaborated digital video measuring system rely on a relatively low cost, portability and extended possibilities of digital image analyses, e.g. exact measuring of surface areas, average wear land lengths and perimeters. Automated measuring excludes human mistakes and, due to the images saved, permits to analyse the data later off-line, which is important when carrying out long-lasting non-repeatable machining tests.
   1.2. A dynamic model of manufacturing with two degrees of freedom was proposed for process monitoring by indirect measurements. The processing of the roughness measurements data confirmed the precision of the calculation model. Surface roughness parameters of the blank quite satisfactorily agreed with the respective data of the theoretical investigation.
2. A formal model checking technique was proposed as an extension to R/OMS tools. Providing provably safe instructions to an operator is possible only with adequate process and operator behavioural models.
   2.1. Real time model updating in this approach is performed by an integrated measurement and expert system during the process run. The final instruction decision is made only after model checkers acceptance.
   2.2. The elaborated model-checking modules are universal, can be implemented with minor changes in other automated manufacturing systems and reduce hazardous situations caused by the human factor.
3. Online resource databases allow effective cooperation of production enterprises at least in the machinery sector. Usability of such databases can be significantly increased by adding search engines that are able to propose a full production chain implementing user needs and restrictions. Results at this phase are used to develop the technological resources database test version.
   3.1. The system results can support the strategic planning of technology transfer, it also could be used as a basis for the industrial enterprises in elaborating co-operation networks and developing towards extended enterprises.
   3.2. The proposed model is capable of monitoring the quality and quantity of technological resources in machine-building enterprises of the network. Influence of human resources can be evaluated successfully when using proper taxonomy and expert estimations. The described methodology of human resources development has been thoroughly tested in five

institutions: in enterprises of diverse type (specialising in machinery, tools engineering, metal engineering and road engineering), and Tallinn University of Technology. Testing results turned to be successful and the system elaborated has proved its place as a carrier of competence development.

3.3. Results at this phase are used to revise and develop a test version of the human resource database. However, in a long perspective when a critical mass of companies are involved in the system the results could be used as a basis for educational institutions to elaborate complementary study and training programmes and modify the existing ones.

3.4. The current solution is focused on the sector of metalworking, machinery and apparatus engineering. The proposed model can be transferred also to other industrial sectors (wood processing, chemical industry, construction materials industry, etc).

Further research

1. Applicability of novel technologies in industry, estimation of preconditions for the needed technological advancement and creation of basis for that on sectoral (macro) level is the first priority.
2. Models of MU behaviour are an object of interest. Upcoming long-distance Radio Frequency Identification (RFID) technology and integration of Smart Dust concept with machining module makes it possible, in the next decade, to monitor real processes based on the models as a portable layer.
3. Adding modules of R/OMS for CAE applications needs further investigation. The formal verification for automated building of machine tool models gains importance with acceleration of computers computing capabilities, being so far the bottleneck in formal methods software development.
4. The developed database solutions were tested in a restricted area, having common cultural and language basis. Development at a multicultural level needs additional research of common understanding – development of ontology for building automated libraries assuring similar knowledge-based input from different languages.

KOKKUVÕTE

Doktoritöö "Tehnoloogiliste protsesside ja tootmissüsteemide monitooringu mudelid" keskendub väike- ja keskmise suurusega ettevõtetele sobivate lahenduste väljatöötamisele. Tehnoloogiaprotsessi tasemel on vaadeldud infovoogusid – pilootlahenduses on keskendutud lõikeprotsessi jälgimisele treipingis otseste ja kaudsete mõõtevahenditega. Näitliku lahenduse väljatöötamisel on keskendutud uute instrumendimaterjalide ja -geomeetriate testimist võimaldava tehnoloogia-seadme arendusele. Otsese mõõtmise osas on selleks loodud eksperimentaalne videomõõtesüsteem tööriista kulumise monitooringuks, milleks on välja töötatud kulumisjälje mõõtmise metoodika, aparatuur ja tarkvara. Kulumis- ja murdepindade videomõõtesüsteem võimaldab lõikeriista kulumuse mõõtmist ja monitooringut, nii et süsteemi saaks kasutada instrumentide väljatöötamisel teadusuuringuteks ning töötlevas tööstuses tööpinkide/paindtootmismoodulite monitooringuks. Mõõte-süsteem hõlmab arvutit Visual Basicu keskkonnas väljatöötatud tarkvaraga "Terik", ühenduskomplekti ning arvjuhtimispinki monteeritud optikaga varustatud CCD-kaamerat ja külmvalgustussüsteemi, mille abil on võimalik jälgida töötlusprotsessi ning määrata laastu liikumise suunda, laastu kontaktpinna pindala esipinnal, tagapinna kulumisjälje keskmist kõrgust ja maksimaalset kõrgust. Laastu kontaktpinna pindala alusel on võimalik arvutada laastu tegeliku paksenemisteguri, mis on oluline uute lõikeriistade katsetamisel ning lõikeprotsessi reaalajamudeli väljatöötamisel. Kuna uuritavad lõikekiirused on suured ja protsessi jälgimine ilma kaitseekraanita inimesele ohtlik, annab videosüsteemi kasutamine võimaluse instrumendi kulumise/purunemise põhjuste täpseks analüüsiks. Välja on töötatud mudelid, mis arvestavad instrumendi kulumist, selle mõju pinnakareduse parameetritele, mida saab omakorda hinnata müra- ning vibratsioonianduritest saadavate signaalide kaudu. Välja on töötatud metoodika otsuste verifitseerimiseks mudelkontrolli vahenditega UppAali näitel. Juhul kui andurite ja mõõte-süsteemidega jälgitavad tehnoloogilised parameetrid (temperatuur, vibratsiooni-kiirendus, instrumendi kulumine, akustiline emissioon) muutuvad mudeliga kirjeldatule mittevastavalt, käivitatakse mudelkontroll, millega verifitseeritakse olukorra lahendatavus. Lõplik otsus võetakse vastu pärast mudelkontrollilt saadud kinnitust.

Ühe tööpingi varustamine monitooringusüsteemiga ei anna ettevõttele efekti, kui teised tehnoloogiaseadmed ja töötajate kompetents jäävad samaks. Seetõttu on klastritasandil monitooringut uuritud masina-, metalli- ja aparaaditööstuse näitel Porteri konkurentsivõime mudeli tootmisprotsessi sisendtingimuste osas. Porteri mudelit saab arendada tehnoloogiliste võimaluste kirjelduse ja vastava integreeritud süsteemi väljaarendamise kaudu. Esimeses etapis on välja töötatud mudel instrumentaaltootmisettevõtete (neid on baasis registreeritud 10) tehnoloogiliste võimaluste kaardistamise kohta. Lisaks on välja pakutud metoodika inimressursi arendusvajaduste hindamiseks ja detailiseeritud esituseks. Realisatsioonina on Eesti Masinatööstuse Liidu ettevõtete kui SME-de vajadustest lähtuvalt välja töötatud süsteemi testversioon, mis hõlmab 75 ettevõtte andmeid.

Töö üldistatud järeldused on järgmised:

1. Tehnoloogiaseadme tasemel on loodud protsessi monitooringu mudel ning näitlik lahendus, kus lõikekiilu kuju ja lõikesügavus antud ajahetkel viiakse protsessi reaalajasüsteemi.
   1.1. Kontakti pindalade, keskmise kulumisjälje kõrguse ja laastu liikumise suuna täpne määramine CCD-kaamera abil võimaldab tehnoloogilise protsessi monitooringut. Väljatöötatud mõõtemetoodika lubab instrumendi kulumist jälgida ühe kaamera abil. Loodud videomõõtesüsteemi peamisteks eelisteks on suhteliselt madal maksumus, portatiivsus ja digitaalse pilditöötluse erivõimalused, nagu kulumisjälje pindala, keskmise kõrguse ja perimeetri täpne mõõtmine. Digitaliseeritud mõõtmine välistab inimlikust eksitusest põhjustatud vead ning salvestatud kujutisi saab analüüsida ka hiljem, mis on ajamahukate töötluskatsete läbiviimisel oluline.
   1.2. Protsessi monitooringuks on välja töötatud kahe vabadusastmega dünaamiline mudel, mis võimaldab arvestada töödeldava detaili varasemat pinnakaredust, instrumendi kulumise astet ning loob võimalused tehnoloogiaseadme täpsemaks juhtimiseks.
2. Protsessi ohutuse ja usaldusväärsuse vahendina on välja pakutud formaalne mudelkontrollimeetod. Kontrollitud ohutute juhiste andmine operaatorile on võimalik vaid vastava protsessi ja operaatori käitumismudelite olemasolul.
   2.1. Reaalajamudeli uuendamine viiakse selles lähenduses läbi integreeritud mõõte- ja ekspertsüsteemi abil. Lõplik juhendamisotsus tehakse üksnes pärast mudelkontrolli positiivset läbimist.
   2.2. Väljatöötatud mudelkontrolli moodulid on üldised ning rakendatavad väheste muudatustega ka teistes automatiseeritud tootmissüsteemides ning inimtegurist põhjustatud ohtlike olukordade vähendamiseks.
3. Tehnoloogiliste ressursside sidusandmebaasid võimaldavad masinaehitus-sektoris tööstusettevõtete efektiivset koostööd. Selliste andmebaaside kasutatavust saab tõsta, täiendades neid otsingumootoritega, mis on kasutaja vajadusi ja piiranguid arvestades võimelised välja pakkuma tervikliku tootmisahela. Uurimuses saadud tulemusi kasutatakse tehnoloogiliste ressursside andmebaasi testversiooni arendamisel.
   3.1. Süsteemi tulemused võivad toetada tehnoloogiasiirde strateegilist planeerimist, samuti võib neid kasutada tootmisettevõtete alusena, et välja töötada koostöövõrgustikke ning arendada neid laiendatud ettevõtete suunas.
   3.2. Väljatöötatud mudel võimaldab masinaehitusettevõtete võrgustikus tehnoloogiliste ressursside kvaliteedi ja kvantiteedi monitooringut. Inimressursside mõju saab tulemusrikkalt hinnata, kasutades sobivat taksonoomiat ning eksperthinnanguid. Kirjeldatud inimressursside arendamise metodoloogiat on testitud viies organisatsioonis. Testitud organisatsioonid olid tüübilt erinevad: masinaehitus, tööriistatootmine, metallitöötlus ja teedeehitus. Viiendaks institutsiooniks oli TTÜ. Testimistulemused olid edukad ning väljatöötatud süsteem on tõestanud oma kohta kompetentsi arendamise kandjana.
   3.3. Tulemusi kasutatakse antud faasis inimressursside arenduse testversiooni edasiarendamiseks. Pikemas perspektiivis kaasatakse ettevõtete kriitiline

mass ning süsteemi tulemusi saab kasutada haridusasutustes täiendusõppe uute kavade ja kursuste väljatöötamise ning olemasolevate modifitseerimise alusena.

3.4. Siinkirjeldatud lahendus on fokuseeritud metallitööstuse, masina- ja aparaadiehituse sektorile.

Edasised uurimissuunad

1. Uute tehnoloogiate kasutatavus sektori (makro)tasemel, selleks vajaliku tehnoloogilise arengu eeltingimuste hindamine ja baasi loomine.
2. Tehnoloogiaseadmete monitooringumudelite realisatsioon portatiivse kihina RFID tehnoloogia ja integreeritud arukate kübemete („tark tolm”) kontseptsiooni abil teeb järgmise kümnendi lõpul reaalajaprotsesside monitooringu võimalikuks.
3. R/OMS moodulite lisamine CAE rakendustele vajab täiendavat uurimist. Formaalne verifitseerimine tehnoloogiaseadmete mudelite kontrolliks on arvutiressurssi nõudev, mistõttu lahenduse kiire leidmine on sageli probleemiks.
4. Väljatöötatud andmebaasi lahendusi testiti sarnase kultuuritaustaga piiratud alal. Multikultuurse taseme erisuste arvestamine eeldab ontoloogiate edasiarendust andmekogude automaatseks koostamiseks, võimaldades eri keeltes koostatud teadmusbaasidest saadavate andmevoogude vastastikku mõistetavaks tegemist.

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Paper II

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Paper III

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Paper IV

Otto, T., Papstel, J., Riives, J. Knowledge management in the framework of technological resources network, *Machine Engineering*, 2004, Vol. 4, No. 1–2, 21–28.

Paper V

Otto, T., Vain, J. Model checking in planning resource-sharing based manufacturing. 12th IFAC Symposium on Information Control Problems in Manufacturing. *Preprints*. Vol II: Industrial Engineering. Ed. A. Dolgui, G. Morel, C.E. Pereira, 2006, 535–540

ELULOOKIRJELDUS (CV)

1. Isikuandmed

Ees- ja perekonnanimi	Tauno OTTO
Sünniaeg ja -koht	04.09.1967 Tallinn
Kodakondsus	Eesti
Perekonnaseis	Abielus
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2. Kontaktandmed

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3. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus
Tallinna Tehnikaülikool	2001	Tootmis- ja transporditehnika /tehnikateaduste magister
Tallinna Tehnikaülikool	1990	Masinaehitustehnoloogia /mehaanikainsener
Keila 1. Keskkool	1985	Keskharidus

4. Keelteoskus

Eesti	Kõrgtase
Vene	Kesktase
Soome	Kõrgtase
Inglise	Kõrgtase
Saksa	Algtase

5. Täiendusõpe

Õppimise aeg	Õppeasutuse või muu organisatsiooni nimetus
2005	TTÜ – Projektijuhtimine
2005	EML – Koolituste korraldamine
2004	Helsingi Tehnikaülikool
2003	Tartu Ülikool – Veebipõhise õppe tuutorite täienduskoolitus

6. Teenistuskäik

Töötamise aeg	Ülikooli, teadusasutuse või muu organisatsiooni nimetus	Ametikoht
Alates 2001	TTÜ	lektor
1990–2001	TTÜ	assistent

7. Kaitstud lõputööd

   Aivar Auväärt, MSc. Elektropneumaatilise õppestendi arendusprojekt. Tallinn, 2006.

8. Teadustöö põhisuunad

   Nõustamissüsteemi mudelite väljatöötamine metalli-, masina- ja aparaaditööstuse sektorile

9. Teised uurimisprojektid

   Tootmisprotsesside ja andmevoogude modelleerimine ning analüüs väike- ja keskmiste ettevõtete koostöövõrgustikus (alates 2006)

   Tehnoloogiaprotsesside võrkmonitooringu kontseptsioon ja realisatsioon (2003–2005)

   Videosüsteemi moodul tehnoloogiaseadmete monitooringuks (2002)

CURRICULUM VITAE (CV)

1. Personal data

Name	Tauno OTTO
Date and place of birth	04.09.1967 Tallinn
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Children	Tanel (born 2005)

2. Contact

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3. Education

Educational institution	Graduated	Speciality
Tallinn University of Technology	2001	Production and Transportation Engineering /MSc
Tallinn University of Technology	1990	Production Engineering/Mechanical Engineer
Keila 1st Secondary School	1985	Secondary education

4. Language skills

Estonian	Advanced
Russian	Intermediate
Finnish	Advanced
English	Advanced
German	Elementary

5. Further training

Apprenticeship	Educational or other organisation
2005	TUT – Project Management
2005	Federation of Estonian Engineering Industry – Course Management
2004	TKK
2003	University of Tartu – Tutoring for e-learning

6. Professional employment

Period	Organisation	Position
Since 2001	Tallinn University of Technology	Lecturer
1990–2001	Tallinn University of Technology	Assistant Lecturer

7. Supervised dissertations

   Aivar Auväärt, MSc, Development project for electro-pneumatic training stand, Tallinn, 2006.

8. Main research interest

   Development of advisory system models for adding capacity of the metal engineering, machinery and apparatus sector

9. Other research projects

   Modelling and analysis of manufacturing processes and data flows in SME network (since 2006)

   Network monitoring of metal-working technological processes: strategy and realisation (2003–2005)

   A video measuring module for machine tools monitoring (2002)