International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:4, No:12, 2010

Evaluating the Innovation Ability of Manufacturing Resources

M.F. Zaeh, G. Reinhart, U. Lindemann
F. Karl, W. Biedermann

***Abstract*—**Due to today's turbulent environment, manufacturing resources, particularly in assembly, must be reconfigured frequently. These reconfigurations are caused by various, partly cyclic, influencing factors. Hence, it is important to evaluate the innovation ability - the capability of resources to implement innovations quickly and efficiently without large expense - of manufacturing resources. For this purpose, a new methodology is presented in this article. Within the methodology, design structure matrices and graph theory are used. The results of the methodology include different indices to evaluate the innovation ability of the manufacturing resources. Due to the cyclicity of the influencing factors, the methodology can be used to synchronize the realization of adaptations.

***Keywords*—**Changeability, Cycle Management, Design Structure Matrices, Graph Theory, Manufacturing Resource Planning, Production Management

I. Introduction

TODAY'S manufacturing environment is considered "turbulent" since it is characterized by high international competitive pressure, rising customer requirements, an accelerated development of technological innovations as well as shortening product life cycles [1]-[3]. This forces companies to innovate frequently to be successful in this environment, especially in times of crisis [4]-[6]. Due to the resulting permanent change in products, components and technologies, manufacturing resources must be adapted and redesigned continuously.

Assembly, in particular, is affected by adaptations because it is under the influence of modifications in upstream production. Moreover, assembly is heavily impacted by quantity fluctuations. Many of the influencing factors, which cause these adaptations, show a cyclic behavior [3]. Product life cycles, technology cycles or economic cycles are examples. The cyclicity of these factors and the knowledge about the characteristics of the cycles helps to forecast adaptations at an early planning stage. Thereby, it becomes possible to determine and evaluate the required innovation ability. Hence, the requirements can be taken into consideration at the stage of manufacturing resource design. The term "innovation ability" refers to the capability of manufacturing resources to implement innovations in, for example, processes, components and technologies quickly and efficiently without large expense (it refers to the term "changeability" [7]).

A "cycle" in this article refers to a recurring course pattern (temporal or structural) that can be divided into phases. Therefore, a cycle is always connected to repetition, phases, duration, initiators and cause. In this research area, cyclic influencing factors, which cause adaptations in assembly manufacturing resources (AMR), are called "cycles".

In this article, a methodology is presented to evaluate the innovation ability of manufacturing resources. Thereby, indices, in particular, are considered. Therefore, the examination object - the AMR - is described at the beginning. The structure of the methodology is then presented before different indices for evaluation are introduced

II. Assembly Manufacturing Resources

AMRs are examined in the research area discussed in this article. "Assembly" is defined as "the application of joining processes to fabricate a connection, whereupon all handling, auxiliary and controlling processes are included" [8], [9]. Manufacturing resources are the entity of all constructions, devices, equipment and facilities that serve a company's production of goods and services [10]. AMRs, which are of technical nature, can appear at different levels of a company.

To show the hierarchical embedding of an AMR within the company, the Hierarchic Structural Model (HSM) is shown in Fig. 1. The Macroscopic Factory Levels (according to [7], [11], [12]) structure the factory from the network to the cell area. The different cell areas (e. g. assembly, production, quality control areas) are further described by the Microscopic Factory Levels (according to the hierarchical classification of resources [13]) through functional groups, components and elements.

M.F. Zaeh is head of the Institute for Machine Tools and Manufacturing Technology (*iwb*), Technische Universität München, Boltzmannstrasse 15, 85748 Garching, Germany.

G. Reinhart is head of the Institute for Assembly Technology and Industrial Management (*iwb*), Technische Universität München, Boltzmannstrasse 15, 85748 Garching, Germany.

U. Lindemann is head of the Institute of Product Development, Technische Universität München, Boltzmannstrasse 15, 85748 Garching, Germany.

F. Karl is with the Institute for Machine Tools and Industrial Management (*iwb*), Technische Universität München, Boltzmannstrasse 15, 85748 Garching, Germany (phone: +49-89-289-15496; fax: +49-89-289-15555; e-mail: florian.karl@iwb.tum.de).

W. Biedermann is with the Institute of Product Development, Technische Universität München, Boltzmannstrasse 15, 85748 Garching, Germany.

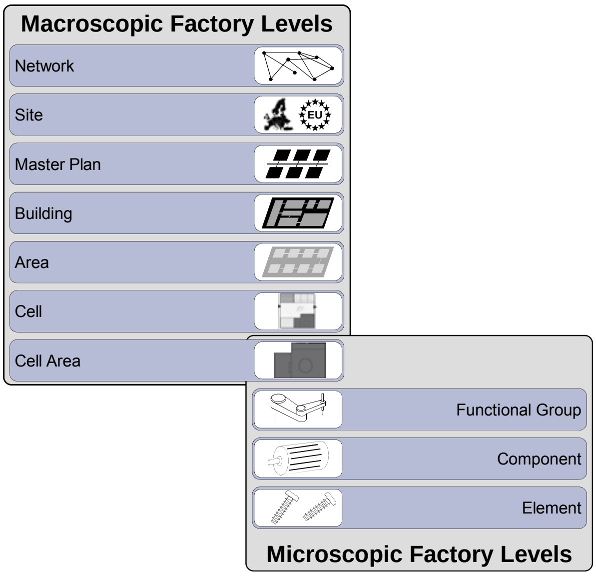


Fig. 1 Hierarchic Structural Model according to [11]-[13]

The evaluated AMRs are assembly cells (e. g. a welding or a gluing cell). They are hierarchically arranged on the cell area (see Fig. 1). Within the cells at issue at least one joining process must be performed. This process can be supported by an unlimited number of handling, auxiliary or controlling processes. An example of an AMR is given in Fig. 2.

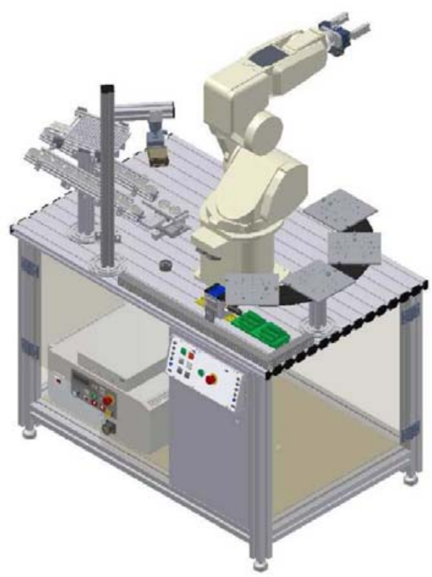


Fig. 2 Example of an AMR (picture: Festo AG)

III. Methodology to Evaluate Innovation Ability

The methodology to evaluate the innovation ability of the manufacturing resources consists of five steps (see Fig. 3) [14]. In the first step (1a), the influencing factors are identified and characterized. The second step consists of system modeling (1b). Then cycles are mapped to the model of the AMR in the third step (2). The forth step includes the displaying of the adaptations (3) and in the fifth step the evaluation of the innovation ability is carried out (4). If components are cut or new components added during the display (3), the model has to be adapted to the new structure of the AMR.

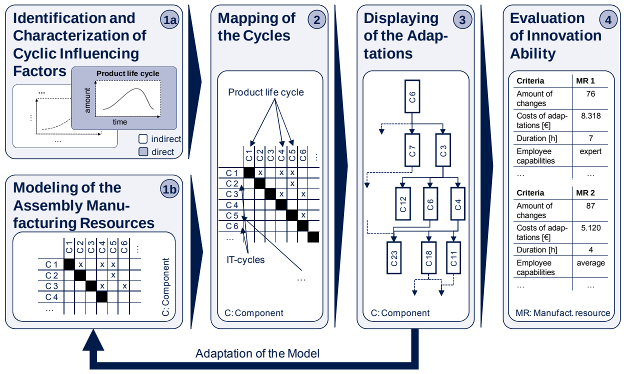


Fig. 3 Structure of the methodology

The methodology can be used for comparing different AMRs (e. g. during the production planning phase when the AMRs are designed and chosen). Companies can also define company specific minimum requirements regarding innovation ability. These can be used for the specification book. The methodology also helps to reduce the time to market since the AMRs can execute adaptations faster and easier when equipped with the required innovation ability. The adaption time can also be reduced because innovation inhibiting components are identified by the methodology. Thus, these components can be redesigned or exchanged.

The particular steps of the methodology are presented in the following paragraphs.

A. Identification and Characterization of Cyclic Influencing Factors

In the first step of the methodology, the influencing factors of the examined AMR must be identified. These factors can be categorized by different criteria. For this purpose, three different classes were defined. First, there are cyclic and non-cyclic factors [15]. The comprehension of cycles particularly supports forecasting adaptations. Second, the factors can be distinguished by their origin. They can be internal or external in their nature referred to the company [7]. Some factors can be both internal and external. For example, a technology cycle is external when the technology is developed outside of the company (e. g. at an university). Technology cycles can be also internal if the technology is developed within the company to accelerate the development process to achieve competitive advantages. While internal cycles can be influenced, the possibilities to influence external cycles are limited. Third, the factors can be differentiated by their influence on the AMRs. Direct factors directly cause adaptations on AMRs. Indirect factors cause adaptations via direct factors.

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:4, No:12, 2010

Fig. 4 shows the influences of the different factors on AMRs. The product life cycle is a direct cycle because its quantity fluctuations can immediately generate adaptations. In contrast, the economic cycles are indirect cycles as they do not directly cause adaptations. They can cause quantity fluctuations and thus have an impact on the product life cycle.

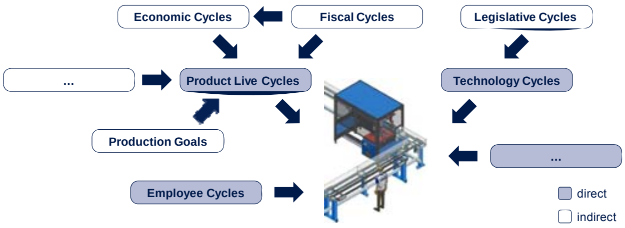


Fig. 4 Influencing factors and cycles (central picture: Zorn GmbH)

After identification, the cycles must be characterized to determine when the adaptations should be executed. Hence, only direct cycles are described taking the indirect cycles and the influencing factors into account. For example, the characteristics of technology cycles might be communicated by the technology planning department to determine which technology should be applied and when [16].

B. Modeling of the Assembly Manufacturing Resources

The second step consists of modeling the system. For this purpose, design structure matrices (DSM) are applied. DSMs are a powerful tool to reduce the complexity of unclear systems [17]. The DSMs are generated at the component (e. g. pneumatic cylinder) level (see Fig. 1). Hence, the components of the system have to be identified and listed in a matrix. Following, the relationships and connections between the components must be noted. Fig. 5 shows an exemplary DSM.

x: Connection between Components	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	...
Component 1		x		x	x		
Component 2					x		
Component 3				x		x	
Component 4							
Component 5						x	
Component 6							
...							

Fig. 5 Example of a design structure matrix (DSM)

Within this research project, a new method to create the DSM was developed [18]. It helps to reduce the data acquisition time by hierarchical modeling. In an executed case study, the time effort was reduced up to 65 %.

C. Mapping of the Cycles

The third step consists of mapping the direct cycles to the influenced components. Therefore, the components that are affected by the cycles must be determined. Due to these cycles, components have to be directly changed. For example, a gripper has to be redesigned if a new product needs to be assembled in the AMR because of the product life cycle.

D. Displaying of the Adaptations

During this step, the effects of the changed components on the system are visualized. Since these components affect others, the resultant adaptations within the whole AMR are displayed. Therefore, graphs [19] are used (see Fig. 6). The graphs are built based on the DSM from the left to the right side. Component 6 in Fig. 6 (e. g. a gripper) must be changed. This causes further adaptations (components 3, 7, 4 etc.) within the AMR (e. g. of the robot, steering, pneumatic). If a component is related to an adapted component (a relation or connection is noted in the DSM), then it is not visualized in the graph so long as no adaptation is evoked. Thus, the nodes show components that are changed, added, replaced or adjusted.

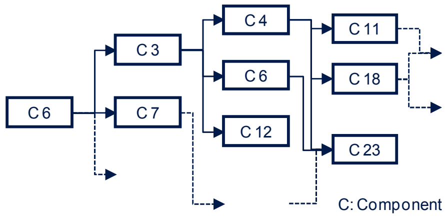


Fig. 6 Example of an adaptation graph

When building these graphs, different data has to be gathered to create the indices in the next step. First of all, the adaptations have to be described precisely (e. g. the tasks that have to be done for the adaptations). Moreover, further data (e. g. duration and costs of the adaptations) has to be provided. If new components need to be added or existing components deleted, the DSM of the model has to be adjusted [20].

E. Evaluation of Innovation Ability

Within the last step, the innovation ability of the AMR is evaluated. Therefore, different indices, such as costs and duration, are calculated. Chapter IV focuses on these indices. Moreover, the adaptations are planned in this step to reduce non-operation periods and costs. This procedure is presented in chapter V.

IV. Indices to Evaluate Innovation Ability

Two kinds of indices are needed for the evaluation of innovation ability. The first kind determines which components support or inhibit the adaptations. The second kind evaluates the innovation ability of the whole system. In this paper, the most important indices are presented. Each time the method is used, the right indices have to be chosen and weighted to deduce actions.

A. Indices for Components

These indices are utilized to find critical components in the system. They can help to identify innovation inhibiting components in the early stages of the AMR design process. Hence, those components can be redesigned (maybe by creating standardized interfaces). For identification, two different calculation methods exist. On the one hand, the whole model (DSM) is considered. To evaluate these indices, the excel-based software Loomeo is used. On the other hand, indices are calculated based on the graphs visualizing the adaptations.

The indices can, for example, be used to compare different components or to define minimum requirements in a company. The following paragraphs give an overview of different indices.

1) Number of Loops

This index counts the number of loops of a component [21]. A loop is a closed cycle of nodes (components) and edges (relations between components). This index is calculated regarding the whole DSM and helps to identify central components. The higher the index, the stronger the component is embedded into the system. Hence, special attention has to be paid when adapting this component, particularly on the impact on the system.

2) Activity / Passivity

"Activity" refers to the number of outgoing edges from a component. "Passivity" refers to the number of ingoing edges [21]. Therefore, the activity shows the direct impact of the regarded component on other components. The passivity indicates the direct impact of other components on a specific component.

These indices can either be calculated regarding the whole DSM or by using graphs. When using the DSM, the indices have the same characteristics since the matrices are omnidirectional. When utilizing the graph, the components on the left side have to be counted for passivity. For activity, the components on the right have to be counted (see Fig. 6). Hence, the activity shows the impact of components on the system. Therefore, it helps to identify critical components.

3) Number of Connections

This index is the number of all connections from one component to other components. Two types of this index exist. Either the direct connections are counted alone or the indirect connections are counted as well. The DSM or the graph, where only the initiated adaptations are shown, can again be applied as a basis for the calculation. When applying the DSM, this index should be considered in combination with other indices. If a component has many connections without causing adaptations on other components (for example due to standardized interfaces), it exhibits high innovation ability.

4) Duration of Adaptation

The "duration of adaptation" shows the time required to execute the adaptation. The longer it takes to fit a component, the less it supports the adjustment. The index counts the durations of all adaptations concerning a component. The durations must be specified when creating the graphs. Another possibility could be to use databases where standard processes for implementing adaptations are deposited. Hence, this index supports the identification of components that are critical to adapt due to a long duration of adaptation.

5) Employee Capabilities

This index differentiates between different kinds of persons which can execute the adaptations. It is estimated by the planner. Based on the complexity of the adaptation, three different levels of capabilities are recommended for estimation: expert, average and layperson. These capabilities again have to be specified when generating the graphs.

6) Costs of Adaptation

The costs of adaptation are all of the costs regarding a component, which are the product of all adjustments (e. g. material, workforce). These costs are, for example, estimated based on historical data or personal knowledge.

7) Share of Total Costs

This index displays the share of the total adaptation costs of one component. Hence, the adaptation costs of one component are divided by the costs for all adaptations.

B. Indices to evaluate the innovation ability of the system

The indices to evaluate the innovation ability of an AMR are calculated based on the graphs. They can be used to compare different AMRs, to define company specific minimum requirements or to install the right degree of innovation ability in an AMR. The following paragraphs display the most important indices.

1) Number of Adaptations

With this index, the components to be adapted are counted. The higher is the number, the more components have to be adjusted, changed, replaced or added.

2) Range

The "range" is the percentage of the adapted components of all components. To calculate the range, the adapted components are divided by the number of all components. It helps to estimate the impact of the adaptation on the whole system. A high range might be an indicator to purchase a new AMR. Nevertheless, this decision cannot be made without considering further indices (e. g. total costs).

3) Total Duration

This index illustrates the whole duration of all adaptations which have to be executed. Hence, all times to implement the adaptations are summed.

4) Employee Capabilities Needed

This index expresses the kinds of employee capabilities that are needed to carry out all adaptations. To summarize these capabilities, they are grouped according to expert, average or layperson and details are given concerning their percentage of the total duration.

5) Downtime

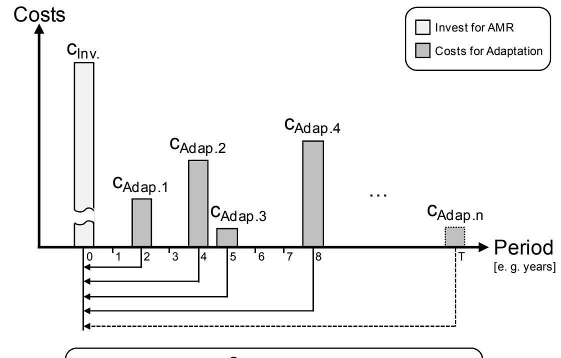
The "downtime" is sum of all adaptations (durations) along the longest lasting path in the graph. This expresses the time that is needed to fulfill all adaptations. During downtime, the AMR cannot be used. This index is similar to the critical path in project management [22].

6) Total Costs

The total costs are all costs that are caused by all adaptations. Hereunder, all material, labor and downtime costs are summarized.

7) $NPV_{Adaptation}$

To take the time delay of cost into account, all can be aggregated into an index called $NPV_{Adaptation}$ (see Fig. 7). It discounts all costs to a single point of time (e. g. time of investment). It is similar to the usual Net Present Value (NPV) [22]. However, only costs of adaptations are regarded.



$$NPV_{Adaptation} = \sum_{i=1}^{n} \frac{c_{Adapt.i}}{(1+r)^t}$$

Fig. 7 Calculation of $NPV_{Adaptation}$

The $NPV_{Adaptation}$ is the most important index. It helps to compare different invests that can be implemented in an AMR to increase the innovation ability during the designing process. If two different characteristics of a hypothetical AMR need to be compared, this index can be used. AMR_L shows low innovation ability (see Fig. 8). In contrast, the innovation ability of AMR_H is high. Since increasing the innovation ability causes costs, expenses for AMR_H are higher than for AMR_L ($c_{Inv.,H} > c_{Inv.,L}$). Because of the higher innovation ability, $NPV_{Adaptation}$ of H is smaller than of L ($NPV_{Adapt.,H} < NPV_{Adapt.,L}$). So, if the sum of $c_{Inv.,H}$ and $NPV_{Adapt.,H}$ ($\sum_H$) is smaller than $\sum_L$, the additional expenses required to increase the innovation ability should be spent.

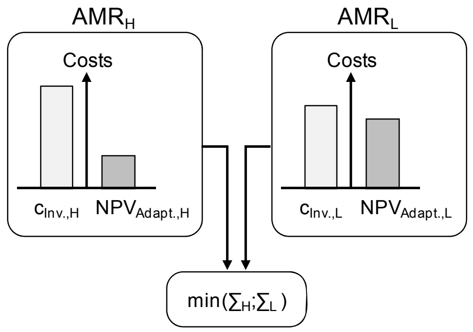


Fig. 8 Choice of an hypothetical AMR out of two possible characteristics

C. Conclusion Regarding the Indices

When evaluating an AMR, the right indices have to be chosen. The choice depends on the AMR or company specific requirements. Usually, decisions (e. g. which kind of AMR to purchase or if an AMR should be adapted or disposed and a new AMR bought) cannot be made on one index. Therefore, several indices have to be considered.

V. Planning of the Adaptations

The presented methodology (see Fig. 3) provides more advantages than do the evaluation of the innovation ability and the identification of innovation inhibiting components through indices. First, the necessary adaptations can be executed in a harmonized manner. The cyclicity of the factors helps to forecast different adaptations. Hence, one can figure out which adaptation has to be carried out when and therefore identify which adaptations are close to each other. For example, it could be that adjustments on the AMR have to be executed due to a new product (product life cycle) or due to a new technology that must be implemented (technology cycle) within the near future. Then, the usual $NPV_{Adaptation}$ and the $NPV_{Adaptation}$ for the simultaneous execution of the adaptations can be calculated to determine the savings. Following, the difference of the two NPVs can be compared to the additional costs for the synchronization of the cycles (e. g. for the implementation of a face lift to lengthen the product life cycle or the internal development of a technology to increase the technology' maturity in order to implement it earlier in an AMR [3]). Moreover, this synchronization helps to reduce downtimes.

Second, the downtimes can be even further reduced by considering maintenance rates or the live cycles of the components that must be given when creating the graphs. Therefore, it can be estimated when the components have to be maintained or exchanged. These works should again be executed parallel to the adaptations.

Third, the time-to-market can be reduced since innovation inhibiting components can be identified and be made more changeable or be replaced by more changeable components. Hence, adaptations on the AMR can be executed more quickly and products can also be put on the market more quickly.

VI. Summary and Outlook

Today's manufacturing environment is heavily turbulent. Manufacturing resources have to be adapted frequently due to numerous factors. Many of these factors are cyclic. Based on this initial situation, a five-step methodology was presented in this article taking cyclic influencing factors into account. In the first step, the influencing factors that cause adaptations on manufacturing resources are identified and the cyclic factors are characterized. Simultaneously, the resource is modeled in the second step using the DSM. The third step consists of the mapping of the identified cycles to the influenced components of the resource. The impacts of the cycles are shown in the fourth step using graphs. The innovation ability is evaluated in the fifth step. For this purpose several indices were presented. The indices aim at two objectives: some identify innovation inhibiting components and others evaluate the innovation ability of the whole manufacturing resource. Depending on the regarded AMR the right indices have to be chosen. Usually, not one single index should be regarded when making a decision.

The methodology is temporarily implemented in a software tool. This will support the planner of manufacturing resources to use it with low effort. Furthermore, the indices are automatically created. Moreover, the methodology is currently applied in the automotive industry to evaluate the innovation ability of an assembly cell. The application also helps to specify the indices (e. g. when to take which index and to figure out dependencies between different indices). For this purpose, different indices are calculated and their expressiveness regarding future and past adaptations determined.

ACKNOWLEDGMENT

We extend our sincere thanks to the German Research Foundation (DFG) for the generous support of the work described in this paper. The research project is part of the subprojects B5 ''Design of changeable production resources'' and A2 "Modeling and analysis of discipline-spanning structural criteria and their impacts on product development processes" of the Collaborative Research Centre 768 ''Managing cycles in innovation processes - Integrated development of product services systems based on technical products''. The goal of the Collaborative Research Centre 768 is to reduce the knowledge gap regarding cycles and cyclic influences.

REFERENCES

[1] E. Abele, J. Elzenheimer, T. Liebeck, T. Meyer "Globalization and Decentralization of Manufacturing," in "Reconfigurable Manufacturing Systems and Transformable Factories," A. I. Daschenko, Ed. Berlin: Springer, pp. 3-14, 2006.
[2] Y. Koren, U. Heisel, F. Jovane, T. Moriwaki, G. Pritschow, G. Ulsoy, H. van Brussel "Reconfigurable Manufacturing Systems," ClRP Annals Vol. 48, Nr. 2, pp. 527-540, 1999.
[3] M. F. Zaeh, G. Reinhart, J. Pohl, S. Schindler, F. Karl, C. Rimpau "Modelling, Anticipating and Managing Cyclic Behaviour in Industry," 3rd International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV), Munich, 2009, Germany.
[4] J. Schumpeter "A theoretical, historical and statistical analysis of the capitalist process," New York: McGraw Hill, 1939.
[5] B. Aschhoff, T. Doherr, H. Löhlein, B. Peters, C. Rammer, T. Schmidt, T. Schubert, F. Schwiebacher "Innovationsverhalten der deutschen Wirtschaft - Indikatorbericht zur Innovationserhebung 2007," Mannheim: ZEW, 2008.
[6] D. Spath, J. Warschat, K. Auernhammer, A. Domeringer, M. Bannert "Integriertes Innovationsmanagement - Erfolgsfaktoren, Methoden, Praxisbeispiele," Stuttgart: Fraunhofer IRB, 2003.
[7] H.-P Wiendahl, H. A. ElMaraghy, M. F Zäh, H.-H. Wiendahl, N. Duffie, M Kolakowski "Changeable Manufacturing: Classification, Design, Operation," in "Annals of the CIRP 56 (2007) 2," J. Corbett et al., Ed. Exter (UK): Polestar Wheatons, 2007.
[8] Deutsches Institut für Normung, Ed. "DIN 8593: Fertigungsverfahren Fügen - Teil 0: Allgemeines, Einordnung, Unterteilung, Begriffe," Berlin: Beuth, 2003.
[9] Deutsches Institut für Normung, Ed. "DIN 8580: Fertigungsverfahren - Begriffe, Einteilung," Berlin: Beuth, 2003.
[10] Verein Deutscher Ingenieure, Ed. "VDI 2815: Begriffe für die Produktionsplanung und -steuerung," Düsseldorf: VDI-Verlag, 1978.
[11] E. Westkämper "Digital Manufacturing in the global Era," 3rd CIRP sponsered Conference on Digital Enterprise Technology, Setúbal, 2006, Portugal.
[12] P. Nyhuis, M. Kolakowski, C. L. Heger "Evaluation of Factory Transformability," CIRP 3rd International Conference on Reconfigurable Manufacturing Systems, Ann Arbor, 2005, MI /USA.
[13] M. F. Zäh, J. Werner, M. Prasch "Changeable Means of Production," in "First CIRP International Seminar on Assembly Systems (ISAS 2006)," E. Westkämper, Ed. Stuttgart: IRB, pp. 33-38, 2006.
[14] M. F. Zäh, G. Reinhart, F. Karl "Zyklenorientierte Montagebetriebsmittelbewertung," wt Werkstattstechnik online, vol. 100 (2010) H. 9, Düsseldorf: Springer-VDI-Verlag, 2010, submitted for publication.
[15] M. F. Zaeh, G. Reinhart, F. Karl, S. Schindler, J. Pohl, C. Rimpau "Cyclic influences within the production resource planning process," in "Production Engineering - Special Issue: Part I: Changeable, Agile, Reconfigurable and Virtual Production," M. F. Zaeh, G. Reinhart, Ed. Vol. 4, Nr. 4, 2010, pp. 309-317.
[16] G. Reinhart, S. Schindler, J. Pohl, C. Rimpau "Cycle-Oriented Manufacturing Technology Chain Planning," 3rd International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV), Munich, 2009, Germany.
[17] T. R Browning "Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions" IEEE Transactions on Engineering Management, vol. 3, pp. 292-306, 2001.
[18] W. Biedermann, B. Strelkow, F. Karl, U. Lindemann, M. F. Zaeh "Reducing Data Acquisition Effort by Hiearchical System Modelling," in "Proceedings of the 12th International DSM Conference," D. C. Wynn, M. Kreimeyer, K. Eben, M. Maurer, U. Lindemann, J. Clarkson, Ed. München: Hanser, pp. 309-318, 2010.
[19] D. B. West "Graph Theory," 2nd ed. London: Prentice-Hall International, 2001.
[20] K. Eben, W. Biedermann, U. Lindemann "Modeling Structural Change over Time – Requirements and First Methods," in "Proceedings of the 10th International DSM Conference," M. Kreimeyer, U. Lindemann, M. Danilovic, Ed. München: Hanser, S.15-23, 2008.
[21] M. F. Kreimeyer "A Structural Measurement System for Engineering Design Processes," München: Dr. Hut, 2010.
[22] H. Kerzner "Project Management for Engineering Design," Hoboken, NJ: Wiley, 2009.
[22] D. R. Hansen, M. M. Mowen, L. Guan "Cost Management: Accounting & Control," 6th ed. Mason (USA, OH): South-Western Cengage Learning, 2009.

Prof. Dr.-Ing. M. F. Zaeh is head of the *iwb* (Institute for Machine Tools and Industrial Management). He studied mechanical engineering at the Technische Universität München with internships at a tool and die shop, a machine tool builder and an automotive supplier. Recommended by Professor Dr. Joachim Milberg, his Diploma thesis was awarded the student prize of the VDW, the German Machine Tool Builders´ Association.

Michael Zaeh started his career in the year 1990, assuming a position as a graduate research assistant at the Institute of Machine Tools and Industrial Management of the Technische Universität München (*iwb*) where he received his doctorate in the year 1993 with a thesis on a dynamic process model for circular sawing. From 1994 until 1995, he was head of a department under the new Director of the Institute, Prof. Dr. Gunther Reinhart.

In 1996, Michael Zaeh joined Gleason-Pfauter Maschinenfabrik GmbH, a builder of machine tools for manufacturing of gears, where he worked in the research laboratory and in the design department during the first year. He was later promoted to head of the order management department. Since 1997, he has been a member of the management group. From 1998 until 2002, he worked in an ERP-system-implementation project at four production sites and three sales agencies of the Gleason Corporation. During this period, he lived in Rochester, NY, USA, for two years and he also worked in South Korea, Great Britain, Brazil and Japan.

In the year 2002, Michael Zaeh accepted the position of full professor for Machine Tools and Manufacturing Technology. Prof. Dr. Michael Zaeh is a member of acatech, the German academy of technical science, of the WGP (German Scientific Society for Production Technology), of the WLT (Scientific Society of Laser Technology) as well as of several other institutions.

Prof. Dr.-Ing. G. Reinhart is head of the *iwb* (Institute for Machine Tools and Industrial Management). After studying mechanical engineering with the emphasis on design and development at Technische Universität München, he worked on his doctoral degree in assembly automation until 1987. Afterwards, he started his industrial career with the BMW Group, initially as head of the handling and welding engineering department and subsequently as director of the body paint shop. In 1993, he returned to the University and became a professor for Assembly Technology and Industrial Management.

From March 2002 to February 2007, Professor Reinhart took a sabbatical to accept the position of Director of Technology and Marketing at IWKA Corporation, a large German supplier of plant equipment and packaging technologies. Since 2007, Professor Reinhart has been, together with Professor Michael F. Zaeh, in charge of the Institute for Machine Tools and Industrial Management (*iwb*). He is also chairman of the Bavarian Cluster for Mechatronics and Automation and a member of many scientific societies and associations (WGP, WLT, CIRP, AIM and acatech). He has approximately 300 publications in leading trade journals to his credit and is author or editor of seven books and two series. He has also supervised the doctoral theses of approximately 100 research investigators.

Prof. Dr.-Ing. U. Lindemann is head of the Institute of Product Development. He studied mechanical engineering at the "Universität

Hannover" with a main focus on thermal process engineering. After graduating, he worked at the "Universität Hannover" as a Research Associate of Prof. Dr.-Ing. K. Ehrlenspiel at the "Institut für Maschinenelemente und hydraulische Strömungsmaschinen" from 1974. The research focus was cost driven product development. When Prof. Dr.-Ing. K. Ehrlenspiel became the head chair of "Konstruktion im Maschinenbau" (later: Institute of Product Development) at the Technische Universität München, he followed him to Munich and got his PhD in 1979.

In the following years, he had leading positions at Renk AG, Augsburg in divisions like mechanical engineering design and product development. In 1992, he became the chairman of MAN Miller Druckmaschinen GmbH and had the responsibility for production, logistics, quality, services, personal and factory planning. He had the interim responsibility for some products of the parent company MAN Roland AG.

In 1995, Prof. Lindemann became head of the Institute of Product Development at the Technischen Universität München as successor of Prof. K. Ehrlenspiel. Prof. Lindemann is director of the collaborative research center 768 ''Managing cycles in innovation processes – Integrated development of product services systems based on technical products'', vice-president of the design society, member of acatech and member of the senate of the Technische Universität München.

Dipl.-Ing. F. Karl was born in 1982 and studied mechanical engineering at the Technische Universität München, Germany, and the Tallinn University of Technology, Estonia. Since April 2009, he has worked as a scientific assistant at the Institute of Machine Tools and Industrial Management (*iwb*), headed by Prof. Dr.-Ing. G. Reinhart and Prof. Dr.-Ing. M. Zaeh. His field of research is cycle-oriented manufacturing resource planning.

Dipl.-Ing. W. Biedermann was born in 1982 and studied mechanical engineering at the Technische Universität München. Since December 2007, he has worked as a scientific assistant at the Institute of Product Development, headed by Prof. Dr.-Ing. U. Lindemann. His field of research is structural complexity management.