Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

An Approach for Re-ordering and Scheduling of Feature-based NC Program

Ulrich Berger*, Ralf Kretzschmann*, Matthias Aner**

*Brandenburg University of Technology Cottbus
Germany (Tel: 0049-355-69-2426; e-mail: {Ulrich.Berger;Ralf.Kretzschmann}@ tu-cottbus.de).
** Daimler AG, Stuttgart
Germany (Tel: 0049-711-17-66338; e-mail: matthias.aner@daimler.com).

Abstract: Nowadays, significant deficiencies exist in the information flow and access along the NC (Numerical Control) process chain. These deficiencies are overcome insufficiently by introducing CAD/CAM systems and feature-oriented specification languages. In contrast to that, the application of new production and new machining systems require an intensive information exchange. The introduced approach enables the preparation for feature-based work plans using methods known from the graph theory. Therefore, the work plan will be mapped into a directed graph in a mathematically defined way. Now it is possible to use algorithms to find the shortest path and a Hamiltonian path inside this directed graph according to given requirements. Thus, the work plan will be re-ordered and scheduled. At the end, the corresponding NC paths will be generated and distributed to the machinery. Thence in this paper, the mathematics, the requirements and the work flow in such a system will is described. A preliminary prototype is introduced as well. As conclusion the transfer of this approach into other production technologies will be discussed.

1. INTRODUCTION

The current situation in the automotive industry is characterized by increasing customer requirements from the customer side on quality and individualization of products and upcoming pressure on product prices at the same time. Therefore, the machining of complex parts in tool and mould making and other business areas have to resist the mentioned requirements and constraints. Furthermore, new production technologies like the hybrid combination of machining and laser ablation for finishing will be introduced. Thus different products with different lot-size will be machined in a short time. The NC process chain is getting complex and dynamic and more information has to be handled and exchanged between the different phases. The programming of NC programs and scheduling of the machining operations is still a bottle-neck within this process chain. The reasons are the handicapped information exchange caused by prevalent organizational and technical obstacles for example the DIN 66025 / ISO 6983 as NC programming interface (DIN 66025, 1983). By introducing feature technology as a fundamental base has given to optimize NC program scheduling. With the help of machining feature as elemental parts of a NC program, the re-ordering of these elements can be executed in a mathematically defined way. It is possible to transfer the work plan of a NC program in a directed graph (Hamelmann, 1995). As a consequence well-known algorithm from the graph theory can be used to optimize these graphs under given requirements like time reduction. The advantage is the traceability of the work plan optimization. Present demands from the already mentioned business areas (e.g. more transparency and reducing the processing time) can be kept (Murawski, 2007). Thus, the following article presents an approach for re-ordering and scheduling NC programs based on feature technology and the application of algorithms known from the graph theory.

2. STATE OF THE ART AND RELATED WORK

2.1 NC –process chain

The NC process chain consists of three fundamental steps. At first step, the finished part (workpiece) is designed. The corresponding design phase determines the physical attributes of the workpiece with the help of powerful CAD (Computer Aided Design) software-systems.

The next step is the planning phase. It consists of further detailed sub steps. The main sub steps are the preparation of the work plan and the NC programming in order to compile the instructions for the NC machining. Therefore a work plan will be utilized to machine the designed workpiece. A work plan summarizes all information about the machining task beginning from the raw part, the selection of workshop facilities and the sequence of the machining operations. The complexity of the workpiece and the generated work plan determines the applied kind of NC programming methods. The common way is to use software supported programming methods like shop-floor-oriented programming procedure (SOP) or powerful CAP (Computer Aided Planning) and/or CAM (Computer Aided Manufacturing) software applications to generate the NC code instructions. The design interfaces of the CAD systems to the CAM systems will be realized by standardized interfaces like IGES or STEP (Eversheim, 1996). For transferring the corresponding NC programs to the shop floor, the internal data model of a CAM system has to be translated (with intermediate steps) in DIN 66025 / ISO 6983 NC instruction code (DIN 66025, 1983). This common interface describes a machining task with the help of absolute

978-1-1234-7890-2/08/$20.00 © 2008 IFAC

10.3182/20080706-5-KR-1001.0871

and relative cutter location points and additional machining and technology parameters like feed rate or cutting speed. The use of this interface influences the whole NC process chain as described in the following paragraphs.

The last step is the machining of the part by NC machines operating these generated instructions in the shop floor (Eversheim, 1996). Therefore the programs have to be distributed all over the machinery by a DNC (Distributed Numerical Control) system. The suitable programs will be distributed to the corresponding machine at the right time corresponding to the production, planning and scheduling results. The production can be controlled as a control loop with the help of PDA (Production Data Acquisition) of the whole machinery.

2.2 NC scheduling

As mentioned before, the NC programs have to be reordered and scheduled. The reordering of the work plan and consequently of the machining features will be done with the help of several criteria in a preferred order. Some examples are “same machine”, “same tool”. After re-ordering the NC programs, they have to be distributed to the machinery. This task is part of the manufacturing control or of the shop-floor scheduling. Therefore some models are developed. A well-known example is MRP II (Manufacturing Resources Planning) (Eversheim, 1996). The determining factors for the shop-floor scheduling are the machinery, the tools, the operators and restrictions regarding to the capacity and time scheduling. The detailed scheduling will be handled by semi-automatical scheduling algorithms implemented in MES (Manufacturing Execution Systems).

2.3 Problems and challenges

The NC machining process is characterized by ongoing improvement. Some indicators are the usage of multi-axis-machining and hybrid technologies like machining and laser ablation. Therefore, the NC process chain comprehends knowledge intensive processes. A new knowledge exchange is enabled within these phases with the help of integrated design and process planning by joining CAD and CAM systems and introducing the feature technology paradigm.

The information and knowledge exchange from and to the shop floor is still handicapped by using the DIN 66025. Moreover, the CAM systems do not consider all information concerning the machinery. The result is that the programs are not 100% verified (Warnecke, Valous, 1993). Furthermore, the programs are not optimized concerning the actual machining requirements and state. The reason is that the NC programs are generated for a fixed allocation of the machinery. Thus, it is hard to modify these NC programs, if the allocation will change because of unpredictable states in the machinery.

An information feedback of these modified NC programs fails because of missing or insufficient information feedback possibilities back to the design and process planning. As the result the knowledge is kept on the one hand in the design and process planning and on the other hand in the shop floor. Due to the missing link to the CAM information, recurrent problems occur (like broken die and collision), while setting up a machine in the shop floor with a new program (Warnecke, Valous, 1993).

There are several solution approaches to reduce the limitations of the DIN 66025. The most promising project was the introduction of a new NC programming language called STEP-NC (Weck et al., 2001). STEP-NC is a high level and feature oriented programming language. The target is to provide the CNC controller with more structural information about the machining process as the DIN 66025 does. First prototypes of STEP-NC controllers and software solutions for the whole STEP-NC process chain provided very excellent results concerning the information feedback. Several research projects using STEP-NC were very promising (Xu et al., 2006) (Pritschow, Heusinger, 2005). Apparently STEP-NC has been aborted because of the complexities in its practical implementation. It seems that the reasons are blockades from manufacturers of CNC controllers, machinery and CAM tools.

Nevertheless, high-level programming languages are the long-term solutions for decreasing the information deficits in the NC process chain and to enable an information feedback in the process planning. Another advantage of a high-level programming language is the improved interoperability among the machinery. The exchange of programs among the machinery is extremely handicapped because of the DIN 66025. Thus, the short-term shop-floor scheduling is hindered. As a consequence, production stops caused by machine breakdowns, which are the outcome of insufficiently set up programs or other obstruction that can not be handled in an efficient way. New solutions are needed.

3. REQUIREMENTS FOR A NC PROGRAM RE-ORDERING AND SCHEDULING SYSTEM

Generally, an approach for such a system has to re-order and schedule the programs in a traceable and customized way. Regarding to the actual machinery and production state, it must be possible to change parts of the NC program (operation scheduling) and the assignments of machine in the machinery. The fundamental basis will be the use of feature technology along the whole NC process chain. Thus, features have to be used to describe the physical design of the workpiece (CAD model) and furthermore the assigned machining operations to machine this workpiece (Hamelmann, 1995). Finally, the concrete order of the machining features will be translated into the DIN 66025 instructions. A feedback from the shop-floor must be established to guarantee an optimal assignment of machining operation to design features. An essential aspect is to enable the feedback of the operators back to the process planning about failing machining operations. In this case writing and benchmarking access to a collection of planning information is needed. Thus, the re-use of the operator knowledge and remarks for the selection of machining operation in the process planning is possible. Summarizing, the following requirements have to be kept in mind:

At first, the DIN 66025 as NC programming language has to retain as short-term solution. Secondly, a structured feature-based description and/or model for the process planning has to be developed, where it is possible to benchmark machine operations, with objective and subjective criteria in order to compare them under certain introduced machining scenarios like 'high quality', 'low cost' or 'low time'. Thus, the best practice solution should be re-useable. Thirdly, algorithms have to be developed for restructuring and scheduling a feature-based work plan under given re-ordering criteria. Therefore additional data source like PDA and structured model of the machinery will be needed. Fourthly, the information demands of the different interacting users have to be investigated in order to elaborate typical profile. One critical point to solve will be the access authorization to the different documents regarding the quality guidelines. Furthermore, the usability has to be adapted to the corresponding user profile. Fifthly, the system has to be developed as an "add-on" to the actually prevailing IT architecture. Therefore, the architecture has to be investigated and the relevant data bases have to be found and finally networked. Additionally, missing databases like TDC (technology data catalogues) and machinery databases have to be installed. The system needs reading and writing access to these identified databases. Thus information feedback can be enabled. Finally, the system should be the first step to introduce a higher-level NC programming language. Therefore the system should have a modular architecture, where several modules can be replaced by a long-term rolling out of useful modules of STEP-NC.

4. DEVELOPMENT OF THE RE-ORDERING AND SCHEDULING SYSTEM

The development of the re-ordering and scheduling system can be divided in three main steps. At first, the process planning and scheduling has to be defined in a mathematically structured way. Secondly, the workflow of the system has to be described. Finally, the scheduling system as a guidance system has to be established with access to several databases according to user profiles.

4.1 Mathematical description

The mathematical definition will be divided in two main sections. At first, the MStep will be introduced as a basic element for describing a machining task as a work plan and consequently as the NC program. Then, the transfer of the sequence of MStep into a directed graph and the application of graph theory algorithm will be investigated.

4.1.1 Defining MStep as a basic element

The process of machining a task can be subdivided hierarchically in several process plan elements (Gerken, 2000). So, the machining task as machining feature of drilling a step drilling can be divided in machining operations and machining steps. To describe the elements in a mathematical way, *Cai* defines a machining step (MStep) as a product of selected tools (Tool), technology (Tech), paths and machining features (MFeature) (Berger et al., 2005). Additionally, a machining step will be expanded with the element machine (Machine). A set of machining steps can be defined as a set of 5-tuple (1). A specific 5-tuple of MStep is called set-up (SU).

$$\begin{aligned} &MStep = \{Tool \times Tech \times Path \times Machine \times MFeature\} \\ &SU \in MStep \end{aligned} \tag{1}$$

Each set-up describes the parameter of a machining process. Consequently, each machining operation is a combination of machining steps. Furthermore, each work plan consists of a sequence of concrete set-up from MStep to machine the machining task. Unlike the STEP-NC data model machining operation, the MSTEP is defined in a more abstracted way.

4.1.2. Transfer in directed graph and application of algorithms

A complete work plan consisting of a sequence of elements of MStep can be transferred in a directed graph. A directed graph DG is defined as an arrangement of a set of notes (edges) V and a set of edges or arcs E. These arcs are connecting two notes out of the set of notes (Jungnickel, 1990). Regarding to the work plan, the set of separate MStep can be transferred in the set of notes at first. Secondly, the arcs between the notes will represent the ordering of these two MStep. An arc e = (a,b) means, that the MStep a is ahead of MStep b. Therefore time dependency of different elements from MStep can be modeled. At this moment, an arc has no quantifier. An arc emblematizes only a connection between two MStep. By introducing a quantifier the use of the arcs become an additional dimension 'cost'. This cost is a combination of two efforts to pass this arc. The first effort is the cost to apply the first machining step a. The second effort represents the cost to pass to the second step b. Thus, a target system of different criteria like machining time, machining quality, and machining energy can be defined to calculate the cost. Therefore, a need of additional information concerning the machinery is detected. Now, it is possible to change the value of a quantifier corresponding to a given scenario, which will be described by a concrete specification of these criteria. Summarizing a work plan consisting of MStep can be described as a directed graph with edges and arcs in-between the edges. Now, it is possible to use algorithms known from the graph theory to calculate significant paths through the directed graph. Two major algorithms can be identified, which are suitable for the application in the field of NC machining (Jungnickel, 1990). At first the Floyd-Warshall algorithm calculates the shortest distance (as a sum of arc quantifiers) between two nodes (machining step). Secondly, the TSP (Travailing Salesman Problem) solving algorithms could be executed in order to re-order all machining steps in a work plan to get lowest cost in total to machine all MStep in a row (as Hamiltonian path).

The Floyd-Warshall algorithm calculates the shortest distance between two nodes with the help of the transitive closure. The complexity is $O(n^3)$, where n is the amount of nodes. With the help of this algorithm, different alternatives for the same machine feature could be rated. The detailed application will be investigate later on (Jungnickel, 1990).

The TSP algorithm calculated a Hamiltonian path with the lowest sum of costs. It means, that this optimal path describes a way through the graph (work plan) to execute all machining steps at least one time regarding to the time dependence. Here is one problem to solve. The calculation of this optimal Hamiltonian path is NP-complete. Consequently, the optimal path can be calculated by combining of all MStep. But, this algorithm is not an acceptable way for a common amount of MStep. There are several algorithms, which find a local minimum for a Hamiltonian path in acceptable effort. The use of these heuristic algorithms shorts the runtime of the combinatoric algorithm drastically (Jungnickel, 1990).

4.2 Workflow and layout of the re-ordering and scheduling system

After defining the mathematical background, the workflow of the system is defined (Figure 1).

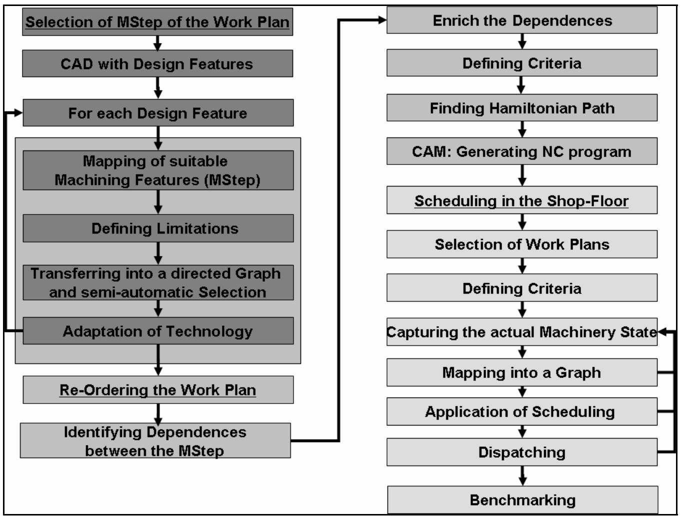

Fig 1. Workflow of the approach

The initial situation is that a work plan for machining the work piece should be generated. Therefore, the design feature-based CAD model will be investigated. For each design feature suitable alternative machining features will be identified. A machining feature consists of several MStep. Thus, a work plan can describe a sequence of MStep as mentioned before. In Figure 2, an example is given. The work plan consists of three design feature, which can be mapped into six machining features (MF). Each of the machining features will be represented by machining steps. The machining features MF1a and MF1b have a shared machining step MStep1 (e.g. roughing) and two alternative steps MStep2a (finishing 3-axis) and MStep2b (finishing 5-axis). The machining feature MF2 will be represented by one machining step. Finally, the last design feature can be represented by one shared and three alternative machining steps (MStep5a … MStep5c). To solve these alternatives, limitations for the machining steps will be given by using scenarios as mentioned before. A scenario describes a special combination of criteria to calculate a quantifier for each element from MStep and each arc. The process planer defines a machining scenario from the given scenarios profiles. The selected scenario defines ranges for each criterion. Possible criteria are machining time, tool change, and surface quality. Afterwards, the process planer can select the right alternative. The Floyd-Warshall calculates as a supporting function the "shortest path" between the additionally added notes St and En. The nodes are marking the start and the end of work plan and have no influence in the work plan. A suitable work plan as result is fat marked in Figure 2a. Finally, the selected machining steps will be aligned to the given machining task by adapting the technology parameters (feed rate, cutting speed). The first step is done.

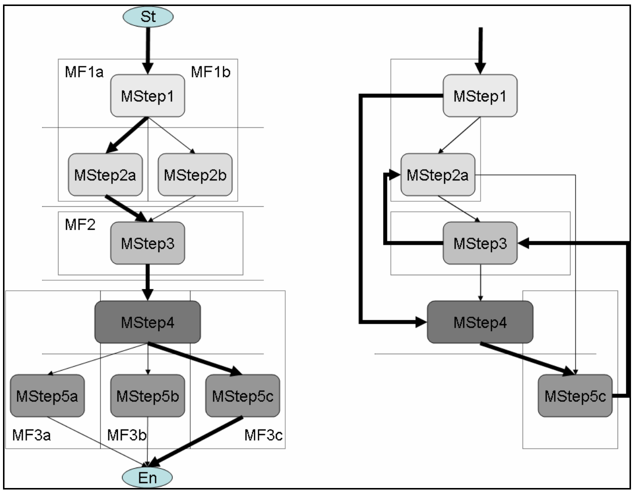

Fig 2. Example work plan (a) and directed graph (b) with Hamiltonian path (with not shown quantifiers)

The following task is restructuring the work plan in order to find a sequence of the MStep with the least sum of quantifiers between the MStep. The Hamiltonian path can describe such a path. Therefore the work plan will be transferred in a directed graph for a second time. The next step is the enrichment of arcs in the graph, which represents additionally dependence as seen in Figure 2b. Afterwards calculation criteria will be set, before calculating the Hamiltonian path. These criteria specify the quantifier a second time. Possible quantifiers are the same machine, same clamping, same tool and same type of operation. Finally, a suitable Hamiltonian path can be calculated. The grade of the path is dependent on the executed algorithm. The best path can be archived by combination all possibilities. This algorithm is NP-complete. The use of heuristic algorithms shorts the runtime radically. But is it not warranted, that they will find the best path through the work plan. A possible Hamiltonian path through the example is shown in Figure 2b. Finally a CAM model generates the NC program corresponding to the given re-ordered work plan by translating the machining steps. The optimized NC program is determined.

The last task is the scheduling of the NC programs in the shop-floor. At first, scheduling criteria and rules has to be specified. The actual machinery state in the shop-floor will be capture with the help of PDA. Consequently, the scheduling of the NC programs will be done in a closed-loop corresponding to the machinery state. Finally, the scheduled programs will be dispatched to the corresponding machine. The operator has now to possibility to benchmark the machining steps for reusing them.

4.3 Integration in the NC – process chain

The scheduling system is embedded in a guidance system and is structured into two major parts, which are integrated in already existing applications.

The first part is the integration of the approach in the machines on the shop floor. The user can access additional planning information with the help of an information system as front-end of the guidance system.

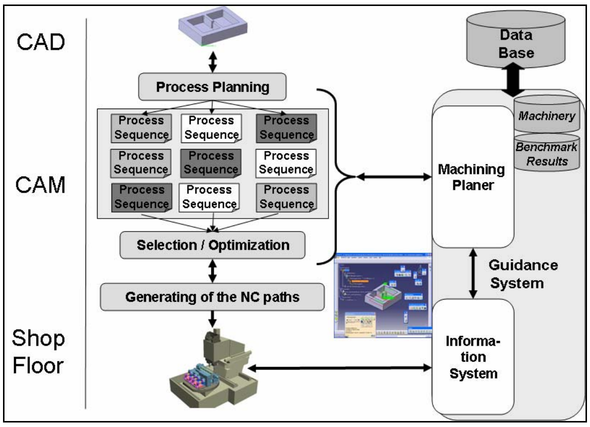

Fig 3. Embedded guidance system

The second part is located in the process planning phase. The module called “machining planer” (see Figure 3) is integrated in the guidance system and supports the process planning as mentioned before. Thus the process planer uses a normal CAM system with a plug-in, where additional information is accessible. The intended information flow is the one, coming from the design phase, the work plan and NC program has to be generated. As mentioned before, the benchmarked machining steps help the user to choose semi-automatical between different alternatives in order to find the best sequence of machining steps with certain parameters to fulfill a chosen scenario. Afterwards the work plan will be optimized by using algorithm from the graph theory. After that the corresponding NC programs will be generated by the CAM system. Finally, the NC program will be scheduled and sent via a DNC server to the CNC-controller of the machine. The operator executes the whole program in a smooth way in order to set-up the machine. If the operator detects some failure or discrepancies (like a wrong clamping), he can report these mistakes to the planning phase through the system. Furthermore, the operator can benchmark the machining with given measurement applications and criteria.

5. TECHNICAL REALIZATION

The technical realization of the concept for a NC re-ordering and scheduling system included in a guidance system is an ongoing process, which will be implemented in two steps. At first, the fundamental guidance system will be realized. This system is conceived as a client-server-application with a central server with access to several data bases and a CAM system. The mobile client fits for industrial need. A W-LAN Tablet-PC / Personal Digital Assistant will be used. The server provides an external interface to the CAM system e.g. CATIA. A 5-axis milling centre will complete the experimental setup (Figure 4).

Fig 4. Experimental setup with 5-axis milling centre and mobile Personal Digital Assistant

The user has access to the product data of the CAD module and planning data of the CAM module in this current development status (Figure 5). Secondly, the scheduling application is in progress to implement.

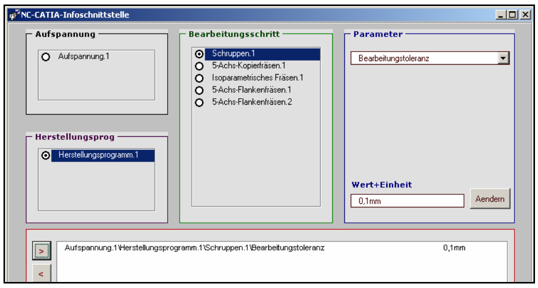

Fig 5. CAM - Information system

At first, the selection of MStep will be realized with a VB macro (Visual Basic) embedded in CATIA. The corresponding mathematical mapping rules are already defined. Therefore, additional information about tools, machinery and a database including all MStep (as TDC = Technology Data Catalogue) has to be used. The next step will be the transfer of the work plan with MStep into MS Visio (Figure 6). This tool visualizes the work plan and offers the possibilities to implement and execute VB programmed algorithm (Floyd-Warshall) for re-ordering the work plan like mentioned above. The next step will be to carry on the interface specification and the investigation of the use of the mentioned algorithms. One gist will be the decrease of runtime of this NP-complete algorithm. One possible solution will be the ‘All the nearest neighbor’ heuristic algorithm.

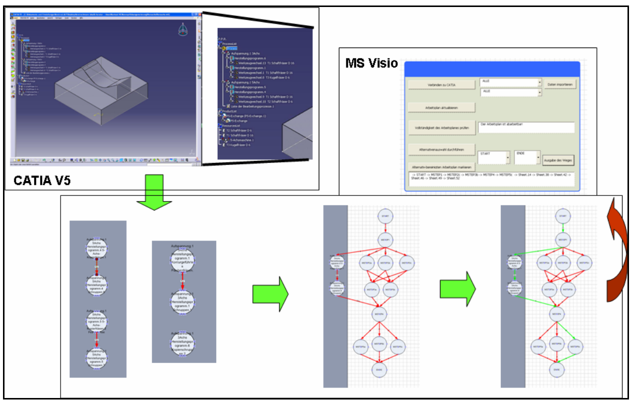

Fig 6. Prototype of the scheduling application

CONCLUSION AND OUTLOOK

Nowadays, there are significant in the NC process chain. The reasons are the different used insufficient interfaces within the process chain. Consequently, knowledge is kept in the uncoupled phase of the process chain. The deficiencies can be solved insufficiently with the help of common integrated CAD/CAM software solutions. Modifications in the shop-floor and the handling of alternative machining strategies are not supported in an adequate way. The presented approach for feature-based NC program re-ordering and scheduling is an enabler to optimize the machining of different task under a given requirement scenario. The fundamental concept will be the usage of feature-based designed and process planning. Therefore, a mathematical description of machining will be introduced. This specification describes a work plan as a sequence of machining features with alternative machining steps. These MStep are benchmarked with the help of different certain criteria. The process planer has now the possibility to select different alternative parameters for machining different areas of a workpiece corresponding to a given machining scenario. Furthermore the work plan re-ordering and scheduling approach was introduced to support the process planer. The MStep based work plan will be transferred in a directed graph will notes as MStep and arcs as quantified dependences within them. The application of the Floyd-Warshall algorithm calculates now the best choice of alternative MStep for each machining feature. Furthermore algorithms for TSP calculate the optimal sequence of the received MStep in a work plan. Thus, the optimal work plan was generated and will be transferred to the NC path generator of a CAM system. A first prototype will be implemented step by step. First results validate the approach. The next steps will be the enhancement of the prototype. Several additional databases have to be added like the data base to store the MStep and the structured machinery. Furthermore, the user profiles have to be defined and implemented instantly. The following step will be the implementation of mathematical description for bench-marking and reusing machining operations. Therefore the benchmarking criteria will be introduced and the operator will be enabled to benchmark the given machining steps with them. Furthermore, an algorithm is in progress of implementations, which suggests possible set-ups for given structured machining tasks with methods known from the artificial life (e.g. CBR – Case Based Reasoning). Finally, the mentioned transfer of the work plan into a directed graph and the application of the Floyd-Warshall and TSP algorithm will be investigated and implemented. A possible compromise between runtime and quality of the algorithm could be an adaptive combination algorithm. Thus, additional methods to combine and to connect the separated path of the machining steps will be provided. As long-term target, the replacement of the common DIN 66025 with a higher-level programming language will be contemplated. The workflow will adaptive to other production technologies. For that reason the applicability of this approach will transfer to the area of joining and assembly of complex components. In this case a machining feature will be transferred into a joining and assembly feature. These features include all necessary information about the joining technology (welding, gluing, etc.), the requirements and applicability of these technologies regarding to the joining materials. Consequently the approach will support the selection of suitable joining technologies with strategies and technology data for a given joining / assembly task with critical requirements. The mathematics of this approach will established in an intelligent cell controller and process planer for handling different alternative joining possibilities for handling composite or *multi-functional materials* in the BIW (body in white).

ACKNOWLEDGMENT

The work reported in this paper was partially supported by EC / FP6 NMP Program, "Integration Multi-functional materials and related production technologies integrated into the Automotive industry of the future" (FP6-2004-NMP-NI-4-026621).

REFERENCES

Berger, U., J. Cai, M. Weyrich (2005). Ontological Machining Process Data Modeling for Powertrain Production in Extended Enterprise. *Journal of Advanced Manufacturing System (JAMS)*, **Vol. 4, No. 1 (2005),** pp. 69-82.

DIN 66025 (1983). *Programmaufbau für numerisch gesteuerte Arbeitsmaschinen; Allgemeines*. Beuth Verlag GmbH, Berlin.

Eversheim W. (1996). *Organisation in der Produktionstechnik - Band 1 Grundlagen*. VDI-Verlag, Düsseldorf.

Gerken H. (2000). *Management von Erfahrungen mit einem Assistenzsystem für die Arbeitsplanung*. Hochschulschrift: Karlsruhe, Karlsruhe.

Hamelmann, S. (1995). *Systementwicklung zur Automatisierung der Arbeitsplanung*. VDI-Verlag, Aachen.

Jungnickel, D. (1990). *Graphen, Netzwerke und Algorithmen*. Wissenschaftsverlag, Mannheim.

Murawski J. (2007). SIMATIC IT öffnet Potential für Lean Manufacturing. In: *Unterlagen zu den Vorträgen der 38. Jahrestagung*, SAK, Siemens-Automatisierungs-Kreis, Dortmund.

Pritschow G., S. Heusinger (2005). *STEP-NC-basierter Korrekturkreis für die Schlichtbearbeitung von Freiformflächen*. Jost-Jetter Verlag, Heimsheim.

Warnecke G., A. Valous (1993). *Informationsrückkopplung zwischen NC-Fertigung und Arbeitsplanung*. Schnelldruck Ernst Grässer, Karlsruhe.

Weck M., J. Wolf, J.D. Kiritsis (2001). STEP-NC – The STEP compliant NC Programming Interface. In: *IMS Forum.*. Ascona Switzerland.

Xu W., W. Lihui, R. Yiming (2006). STEP-NC and Function Blocks for Interoperable Manufacturing. In: *IEEE Transactions On Automation Science and Engineering*, **Vol. 3, No. 3, 2006, pp. 297 - 308**.