machining process planning, NC (numerical control),
graph theory, heuristic algorithm

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APPROACH FOR THE DEVELOPMENT OF A HEURISTIC PROCESS PLANNING TOOL FOR SEQUENCING NC MACHINING OPERATIONS

Abstract

This chapter deals with the process planning for sequencing NC (numerical control) machining operations. This task of selecting and ordering of machining operations is still done manually in principle. In order to overcome this problem, an approach for enabling the automatic preparation of work plans with methods known from the graph theory is introduced in this chapter. Therefore a work plan is mapped into a directed graph in a mathematically defined way. Based on that, it is possible to use algorithms to find the shortest path and a Hamiltonian path inside this directed graph as optimal sequenced solution under given requirements. Thus, the work plan is structured and re-ordered. Finally the corresponding NC machining code will be generated and distributed to the machinery.

1. INTRODUCTION

The current situation for mould and die makers is characterized by increasing requirements from the customer side on quality, prices as well as individualization of products. As a consequence, the enterprises are forced to shorten the product lifecycles in order to react faster to customer demands. In general, the design and the manufacturing process planning phase as well as the manufacturing process become more and more the critical in the product lifecycles. One essential process step is the machining of components and work pieces to the given requirements from the production definition and designing phase. Therefore the manufacturing cost, the manufacturing time and the product quality are strongly dependent on the used manufacturing technology. A lot of innovations were introduced in the last decades in this scope (e.g. multi-axis machining and hybrid combination of milling and laser ablations for high precision finishing). Furthermore, enhanced CAD/CAM system allows very complex calculation for optimized cutter location paths to assure a high surface quality of a work piece. As a consequence more machining strategies have to be considered in the process planning

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phase. As a consequence, the NC (numerical control) process chain is getting more complex due to the fact that more information has to be handled and exchanged between the different phases of the process change. Nevertheless, the effective NC programming is still a bottle-neck within the process chain. The reason is the mangled information exchange caused by prevalent organizational and technical obstacles like the use of the ISO 6983 as NC programming interface [1]. It was shown by Brunnermeier in 2002, that the US automotive spend 1 billion $ to fix data error caused by interoperable interfaces [2].

A solution to overcome these problems is the establishment of the feature technology that enables the process planning and the exchange of NC work plans to the machinery [3] [4] [5]. The process planning knowledge can be included in the corresponding machining features and operations. Nevertheless, the sequencing (selecting and ordering) as well as acknowledgement of suitable machining features and operations to given design feature as a mapping function is still done manually with the help of the experience of the process planner. Consequently, the objectives of automatic process planning are the time savings comparing to a manual planning and the use of the whole available machinery. Thus, a lot of different automatic process planning methods and approaches were introduced in the last decades. However, these so-called expert systems are limited, because of their small fields of application and their difficult handling. The knowledge acquisition is also a bottleneck.

To overcome these limitations, a new innovative approach for using algorithm known from the graph theory for sequencing machining operations is presented in this chapter. The selection and re-ordering of these knowledge-based machining operations can be executed in a mathematical defined way. It is possible to transfer a work plan (consisting of the machining operations) in a directed graph [6] for further processing by using further mappings. As a consequence, well-known algorithms from the graph theory can be used to process and optimize the directed graph with an objective cost function (e.g. time reduction) in a traceable way [7].

The chapter is organized as follows: The state-of-the-art is presented in the next section. Arising problems and challenges of the NC process chain will be introduced as well as the automatic process planning in the NC process chain is outlined. As a result, this section concludes with the statement of problem formulation of the sequencing problem. Consequently, the third paragraph deals with objective and requirements of a new approach based on the actual state of the art. The new approach for sequencing of machining operations based on algorithm known from the graph theory are introduced in fourth paragraph in a detailed way. The evaluation of the demonstrator of the approach is done by using a carefully selected benchmark part in the fifth paragraph. Finally, the conclusion and outlook is presented in this chapter.

2. STATE OF THE ART AND RELATED WORK

The actual state of the art of the NC process chain is presented in this paragraph in the scope of carefully selected literature. At first, the general NC process chain is introduced. Afterwards actual challenges and problems in the process chain are discussed and their solutions are presented. Then, the process planning methods to generate NC work plans and NC programs are investigated in detail. Finally, the problem statement of the sequencing problem has defined.

2.1. NC process chain

The NC process chain consists of three steps (see Figure 1). In the first step, the part (work piece) including manufacturing requirements is designed with powerful CAD (Computer Aided Design) software systems [8]. Afterwards, the following process planning phase consists of further detailed sub process steps that are arranged in two levels. The first planning level describes the preparation of a work plan in the scope of NC machining. Thus, a work plan is used to compile the instructions for the CNC (computerized NC) machine controller. The work plan includes all information about the machining task. That includes in detail the raw part and the work piece geometry, the allocated shop floor equipment (tools, machines, clamping) and the sequence of elementary machining operations. A NC programming tool is used to create such work plans. The NC programming method depends on the complexity of the work piece and the work plan. Common used methods are shop-floor-oriented programming procedure (SOP) and powerful CAP (Computer Aided Planning) and/or CAM (Computer Aided Manufacturing) software tools. Afterwards, the work plan (with the sequence of machining operations) is compiled into NC programs based on ISO 6983 based NC instructions or ISO 14649 data structure [1] [4].

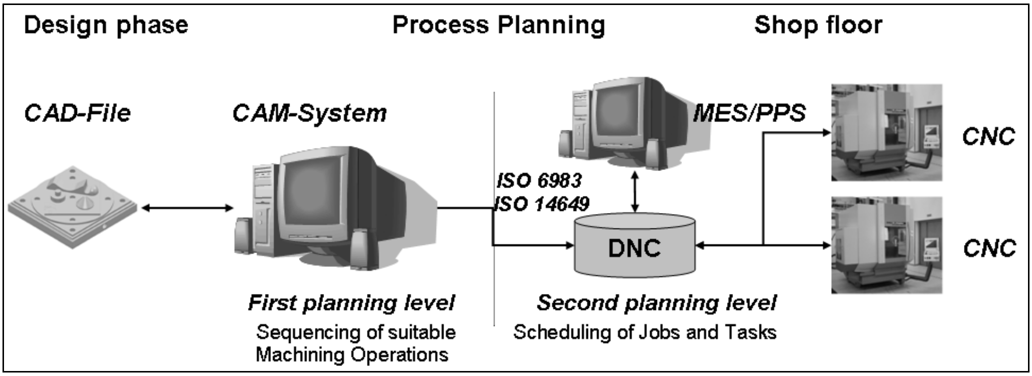

Fig. 1. Identifying different planning levels in the (STEP-)NC process chain

Thus, the first planning level describes the selection and ordering of machining operations including the machining parameters (e.g. tools, machine, technology, path, etc.). The planning horizon is the work piece with all geometric and technical elements. Additionally, the available machining operation strategies and technologies belong to the planning horizon.

The second planning level schedules the generated NC programs based on the work plans according to the current manufacturing situation at the shop floor at the right time according to the production, planning, and scheduling results. This task is performed by MES (Manufacturing Execution System) and/or PPS (Process Planning System) using DNC (distributed NC) [9]. The planning horizon is in this case the current job scheduling and capacity planning. Finally, the part will be machined by NC machines executing these generated instructions in the shop-floor as the last step of the process chain [9].

2.2. Challenge and problems in the process chain

The NC machining process is characterized by permanent technical enhancements in the last decades. Thus, Figure 2 sums up the most influencing factors which will be divided into organizational and technical factors.

The organizational factor deals with the operator on the machine and the NC programmer as well as the process planer. The organizational separation of the shop floor and the process planning departments lead to information lacks due to the use of standard interfaces for exchanging information between process planer and operator. Furthermore, manually done process planning is very time consuming. A lot of different information has to be handled by the operator and programmer due to the information overload caused by the availability of new machine, technologies, materials and method.

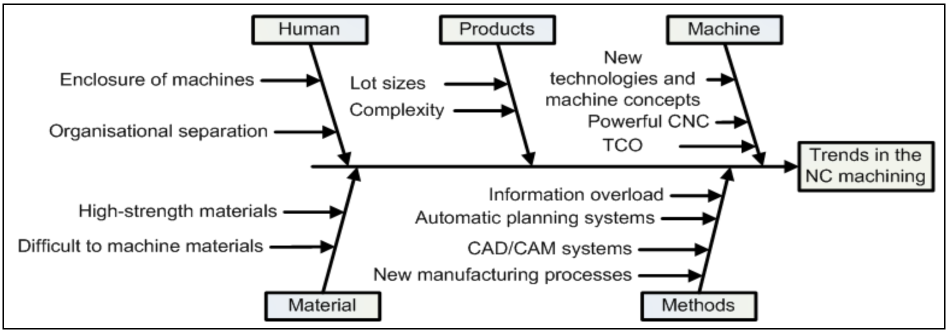

Fig. 2. Complexity along the NC process chain [7]

The technical factors focus on the manufacturing process of complex products with variable lot sizes. This can be by new machining technologies (e.g. like multi-axis-machining and hybrid technologies) for the machining of new resources with different cutting characteristics (e.g. expensive nickel for turbine blades). As a result, complex programs have to be generated. By doing so, more potential programming errors have to be avoided in the CAM system. Nevertheless the CAM generated NC programs are not 100% verified [10]. Thus a modification of the non human-readable programs is necessary, while setting up the machine.

Summarizing the factors, the NC process chain comprehends more knowledge intensive processes. Thus, new methods (fifth factor) like the use of integrated design and process planning by joining CAD and CAM systems and the feature technology paradigm [5] were introduced. Unfortunately, the automatic rule-based process planning algorithms are limited to small machining application fields. These so-called expert systems are very difficult to handle.

As discussed earlier, the traditional NC process chain is facing new complexities. Thus, Xu presented the required capabilities for a new generation of CNC machining in order to meet the increasing costumer demands [23]. Comparing the ISO 6983 interface base process chain to the requirements, the common used NC process chain fails. Thus, the disadvantages of the "G/M" code were discussed extensively in the literature [3]. The ISO 6983 describes only the cutter locations, which will be interpreted by the controller of a CNC machine. An ISO 6983 based program is comparable with an assembler program that describes "what-to-make" and not "how-to-make" [3]. As a consequence the ISO 6983 programs are very huge even for smaller parts. Furthermore, the interoperability among the machinery is reduced because of machine/vendor specified modifications of the ISO 6983 language. Finally, modifications of these programs are very hard to handle in the shop floor due to the fact that the programs are not traceable and non-human readable. The antiquated ISO 6983 influences and also hinders the process planning activities. New solutions for the process planning and NC programming are needed. The introduced projects can be divided in an additional solution for the ISO 6983 and in replacing programming language. The integration of information systems in the CNC-controller (e.g. shop floor oriented programming procedure) or NC code optimizer are belonging to the additional solutions. The most promising project is the introduction of a new NC programming language called STEP-NC (ISO 14649 data structure) [3]. STEP-NC is a high level and feature-based NC interface which is comparable with high level programming language. The target is to provide the CNC controller more structural information about the machining process as the ISO 6983 does. Therefore, the bi-directional information flow is enabled in the NC process chain. Finally, the following question has to be solved in context to the process planning:

- Which of the machining operations sequence will be selected to machine the work piece?
- How the selected machining operation will be ordered to meet the manufacturing objectives in an optimized way?

To answer these questions, different approaches for the process planning are presented in the following sections.

2.3. Process planning in the NC process chain

The objectives of the process planning are the sequencing of machining operations in order to machine the given work piece and the scheduling of machining jobs at the shop floor. As already introduced, these activities are divided into two levels that are supported by the CAM, the CAP and the MES. Nevertheless, these activities are very difficult and time consuming. Therefore a need for introducing automatic process planning, in order to decrease the time consuming programming and planning activities is identified. Several planning methods were introduced in the last decades for automatic process planning tools [11]. Thus, the following paragraph is dealing with the first planning level that sequenced the machining operations. A survey of methods for the scheduling of machining jobs in the second planning level are although presented for the sake of completeness.

It was proved in the late 80th that the automatic process planning can be done with the help of a computer algorithm [12]. But, this problem and especially the scheduling job problem are described as NP-hard [13]. As a consequence, various approaches are dealing with this problem in scope of the generation of work plan for the NC machining and scheduling of jobs into the shop floor. In Figure 3, an overview of suitable methods for the sequencing of machining operations is presented. The direct rule-based process planning is an example of an optimizing planning method. As representative example, Sormaz developed a system for rule- and feature-based process selection. This system uses more then 32 rules for mapping so-called design feature of a work piece into the suitable machining feature. Possible mappings are stored several machining technology data bases. The knowledge representation is a XML based data model. The concept is supported by a virtual simulation of the selected features in order to generate valid NC program code [14]. The rule-based process selection is limited in handling conflicting rules.

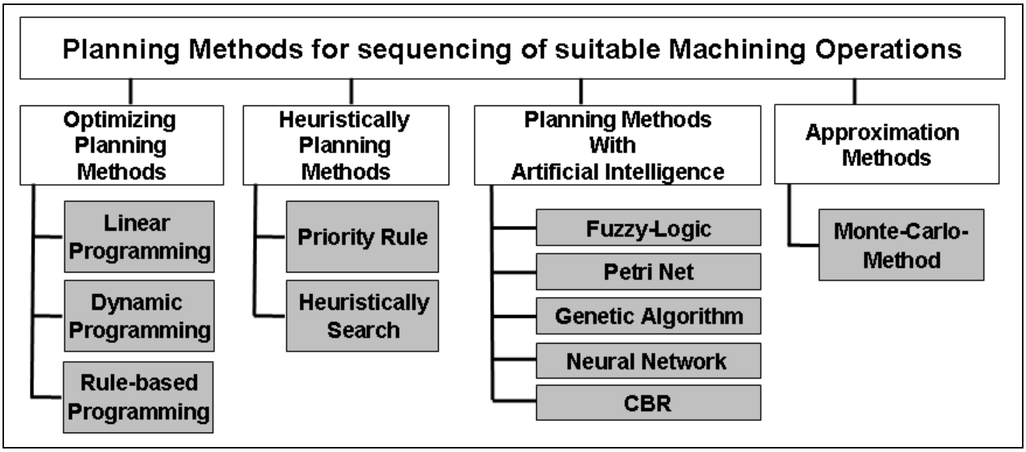

Fig. 3. Planning methods for the sequencing of suitable machining operations

A representative example of a heuristic planning method is introduced by Hellberg. Hellberg defined so called “work piece intermediate states” as a kind of planning history for a step-by-step process planning. The objective of the approach was to overcome the limitations of the direct rule-based planning. In this context, different rules are also introduced which determine the application of the machining operations. The planning history enabled the planning of different alternatives. Thus, a backtracking in the already defined process plan is possible in case a planning branch is not successful [15]. Finally, an overview of representative process planning methods that are using Artificial Intelligence (AI) are summarized in table 1.

Tab. 1. Representative process planning methods based on Artificial Intelligence

Methods	Application
Fuzzy-Logic	Multi-parameter decision making with uncertain parameter values
Petri-Net	Modelling the resource allocation of machining operation planning
Genetic algorithm	Finding new solution by combination of already known sequencing solutions
Neural network	Selecting technology parameters
Agent based process planning	Planning in distributed environments for allocating resources
Case-based-reasoning (CBR) [16]	Mapping of new design feature to already given design feature by comparison; afterwards the selected machining features are sequenced manually

For the sake of completeness, a survey of methods for the scheduling of machining jobs in the second planning level is investigated by Blazewicz [11]. Some representative methods are multi-agent systems for reacting for dynamic changes and disturbances at the shop floor. Neural network for scheduling different jobs on machines are introduced, too. The use of simulated annealing in combination with genetic algorithm for scheduling different jobs on several machines was proposed by Zhang et al. [17]. Finally, scheduling problems is managed by solving optimization function that represents an overall cost function of planning situation.

In conclusion, there were introduced a lot of different process planning methods for sequencing of machining operations and scheduling of jobs in the shop floor. The knowledge representation and processing is done with methods known from the AI (artificial intelligent) e.g. neural networks and genetic algorithms. Optimization approach based on heuristic algorithm and dynamic programming are often used too. The selection of the suitable knowledge representation and processing depends on the several criteria.

Nevertheless, the high amount of introduced methods for the sequencing of machining operations, actual market surveys provided by CIMdata showed that the CAM-Systems do not support the automatic process planning in a satisfactory way [18] [19]. In detail, CAD-CAM-Report investigated the offered CAM systems of the largest NC vendors in 2006 Dassault Systèmes (13,8% market share), UGS PLM Solutions (13,5%), PTC (7,3%) and Delcam (6,8%). It was proved that feature-based programming is the state-of-the-art. However, the CAM systems often suggest different alternatives of the selection and sequencing of the machining operations given by features. So, the planner has still to select manually one alternative out of them as the machining operation selection. Afterwards, several CAM systems support the planner in ordering the selected machining operation to given requirements (e.g. FeatureCAM).

As a result, the process planning at the first planning level is still done manually. The process planner has to acknowledge and select the machining feature and machining operations corresponding to the design feature of the work piece still done in a manual way. This activity is very time consuming. The objective is here the automatic sequencing of machining feature and machining operations regarding to a given work plan and given machining requirements. The benefits are the time saving in the generation of work plans.

In the scope of job scheduling, heuristic algorithms are already used for the automatic job scheduling at the second planning level [9].

2.4. Mathematical formulation of the problem statement

The statement of problem for sequencing machining operations can be formulized as follows: Let a NC work plan *WP* (1) consists of several machining operations *MO* which are ordered (machined) chronologically by the relation *C*.

$$WP = (MO, C);\ C \subseteq MO \times MO;\ mo_n\, C\, mo_{n+1} \tag{1}$$

Let *p* (2) being a function that generates a work plan *WP* corresponding to a given the work piece description *WD* and manufacturing requirements *RM* (e.g. surface quality, machining time, etc.).

$$p : (WD, RM) \rightarrow WP \tag{2}$$

Several assessment functions have to be defined in order to assess now the generated work plan. The fundamental base is the definition of an assessment setting *AS (3).* Thus, an *AS* consists of work piece and manufacturing related assessment criteria *AC* and their assigned weight *AW* for each criterion. The assigned relation between both is represented by the relation *R*.

$$AS = (AC, R, AW);\ R \subseteq AW \times AC;\ aw R ac \tag{3}$$

Let *ot* (4.1) being a function that calculated the machining effort of a machining operation *MO* to a given assessment setting *AS* in the operation time. Let furthermore *at* (4.2) being a function that calculated the effort to change a machining setup of *MO1* to the next *MO2* in the work plan in the ancillary time.

$$ot : (MO \times AS) \to \Re;\ ot(mo, as) \mapsto \Re \tag{4.1}$$

$$at : (MO \times MO \times AS) \to \Re;\ at(mo_1, mo_2, as) \mapsto \Re \tag{4.2}$$

Let *e* (5) being a function that calculated the machining effort of a complete work plan *WP* to a given assessment setting *AS* consisting of the effort in the operation and ancillary time. The function calculates now the effort for a sequence of *m* non-parallel machining operations *MO*.

$$e : (WP \times AS) \to \Re; e(wp, as) \mapsto \sum_{k=1}^{m} (at(mo_{k-1}, mo_k, as) + ot(mo_k, as)) \tag{5}$$

The overall objectives of the process planning at the first planning level are the time saving by computing an optimal work plan and the effort reduction of machining the complete work plan. Thus, the following objective function (6) with given assessment setting *AS* and *m* machining operation has to computed when a work plane is generated with the function *p* (2).

$$\min e(wp, as) = \min \sum_{k=1}^{m} (at(mo_{k-1}, mo_k, as) + ot(mo_k, as)) \tag{6}$$

The total effort can be reduced by the selection and ordering of machining operations as described in (6). For the sequencing of *m* non-parallel machining operations, the total numbers of solutions are *((m)!)*. Thus, two aspects are important. At first, suitable machining operations that meet the given requirements has to be selected and secondly, the machining operations have to be ordered in a way that the lowest changing effort in total can be achieved.

3. OBJECTIVES AND REQUIREMENTS FOR SEQUENCING OF MACHINING OPERATIONS

The presented state-of-the-art methods and approach are not implemented in the common CAM systems. It was shown by the CAD-CAM-Report investigation that the methods remain in the research and prototype stadium [18] [19]. The introduced automatic rule-based process planning algorithms are exclusively successful in preparing work plans in small machining applications fields. However these so-called expert systems are very difficult to handle as mentioned before. As a result, the process planner selects the machining operation due to his subjective experience. Neural network based approaches are common today, but the computation result is not traceable [20]. Furthermore, Hellberg has shown that genetic algorithms are not usable to find acceptable sequencing result in comparison with heuristic algorithms [15]. The CBR (case-based reasoning) based algorithm by Gerken is also not usable, because it is based on subjective validation. As a consequence, the planner used an often used but not optimal sequencing proposal. To overcome this gap between research and application, an innovative and easy-to-use approach has to be introduced by considering the following requirements. The objective of the approach is to solve the equation (6).

The main objective of a new solution is to select and re-order the work plan in a traceable, customized and optimized way. The fundamental basis is the use of process knowledge provided by the personnel involved in the NC process chain and process monitoring. As a result, the use of feature technology [5] along the whole NC process chain is utilized. Design features have to be used to describe the physical design of the work piece (CAD model). The assigned best-practice machining features as well as operations are used to represent the machining of the work piece [12]. A feedback from the shop-floor must be established to guarantee and validate an optimal assignment of machining operation to design features. An essential aspect is to enable the feedback of operators to the process planning about unsuccessful machining operations. Summing up the objectives and requirement are the following [7]:

- Shorten the programming time by automatic process planning tools and algorithms
- Enhancement of the utilization and consideration of the available machining equipment (machine, clamping/fixtures, tools) and the functions of the CAM system
- Preparation of work plan to the given user defined design requirements (surface quality, roughness) and manufacturing criteria (cost, time, quality) by solving equations 6
- Introducing an objective effort calculation procedure in order to assess machining operations and machining features
- Enabling knowledge acquisition and representation to develop a knowledge data base (KB) for gathering process planner experience for re-use in automatic process planning
- Using a suitable knowledge representation for the knowledge data base (KB)
- Developing a traceable knowledge processing for generating the work plans
- Implementing the approach on the knowledge based NC programming system [1]

The following assumption has to be defined in order to develop the approach: In order to machine a design feature, several various machining features with several machining operations are possible. These machining features are specified by CNC machines, clamping/fixtures, tools, technologies and strategies settings based on machining operations model. The machining operations are assessable with several weightage assessment criteria like machining time, surface quality, roughness, collision potential etc.

4. APPROACH FOR MACHINING OPERATIONS SEQUENCING

4.1. Keynotes and methodology

The keynotes of the intended approach are the computation of assessed and alternative machining operations in order to build up a work plan. The machining operations are stored in a data base that will represent the planner expertise and knowledge in a structural way for re-use. Furthermore, metrics are used to evaluate the machining operations depending upon their machining characteristics. These assessed machining operations are used in order to select and order suitable machining operations for a given work plan in an optimized way. Feature based technology and a directed graph as knowledge representation are used for showing the alternating work plans. For this case, algorithm known from the graph theory are applied to process the information that is stored in the directed graph. The scheduling the machining operations is a NP-hard problem and are handled by heuristics algorithms that are making the run-time short [13]. Finally the approach is integrated in the current NC process chain. The overall benefits are the time-saving in the process planning and the cost saving. The benefits are achieved by considering all the available machining technology with enhanced process planning algorithms.

The focus of the approach is on the machining process planning for feature-based work piece. The work piece are machining with geometrically defined cutting edge is conforming the DIN 8589 [21]. The demonstrator is focusing on milling features.

The development methodology of the approach for sequencing of machining operations is similar to the design of an expert and/or knowledge-based system [22]. An expert system emphasizes the decision making of a human being based one his own knowledge representation and processing. Consequently, various suitable knowledge representation and processing methods are investigated for the approach to identify suitable methods for the designing of the sequencing system approach.

4.2. General functional principle

The functional principle is outlined in this section. In this regard, the Figure 4 is comparing the state-of-the-art (top) and the new approach (button) in NC process planning.

Nowadays, the process planner selects for each design feature of the work piece the corresponding machining features and operations with the help of his personnel experience. This methodology has certain demerit i.e. the loss of planner expertise in the case the planner leaves the department. The overall objective of the approach is the re-use of expertise knowledge for the sequencing of machining operations. Thus, the general function of the approach is the customized but automatic mapping for a work piece description (list of design features) into a work plan (list of machining operations) in a mathematically defined way. The mapping is done into three sub steps as outlined in Figure 4 (bottom) in detail.

At first the feature-based CAD model with all constraints in the used design features are imported into the system. This interface could be supported by a STEP based CAD interface. Afterwards, the design features are grouped (I) by defined sorting criteria (e.g. same kind of feature) as seen in Figure 4 (graph a).

The next step is the application of the structuring function (II). Therefore, the imported design features have to be mapped into suitable machining features with machining operations. A central data base that stores all previously made mappings from previous work plans are used for that. Now, one machining feature can be represented by several alternative (various) sequences of machining operations (see Figure 4, graph (b)). The target is now the reduction of the alternative operations in each horizontal level. Consequently, an overall assessment criterion called effort is needed. Thus, the structuring algorithm selects the combination of machining operations which has the lowest horizontal effort in total is shown in Figure 4 (graph b, fat marked arcs). Afterwards, the order of the selected operations need to be changed, due to the fact that operations on the same machining, using the same clamping and/or tool can be machining one after the other in order to save effort for changing setups. Consequently, additional constraint has to be added to the directed graph (see graph c, dotted arcs).

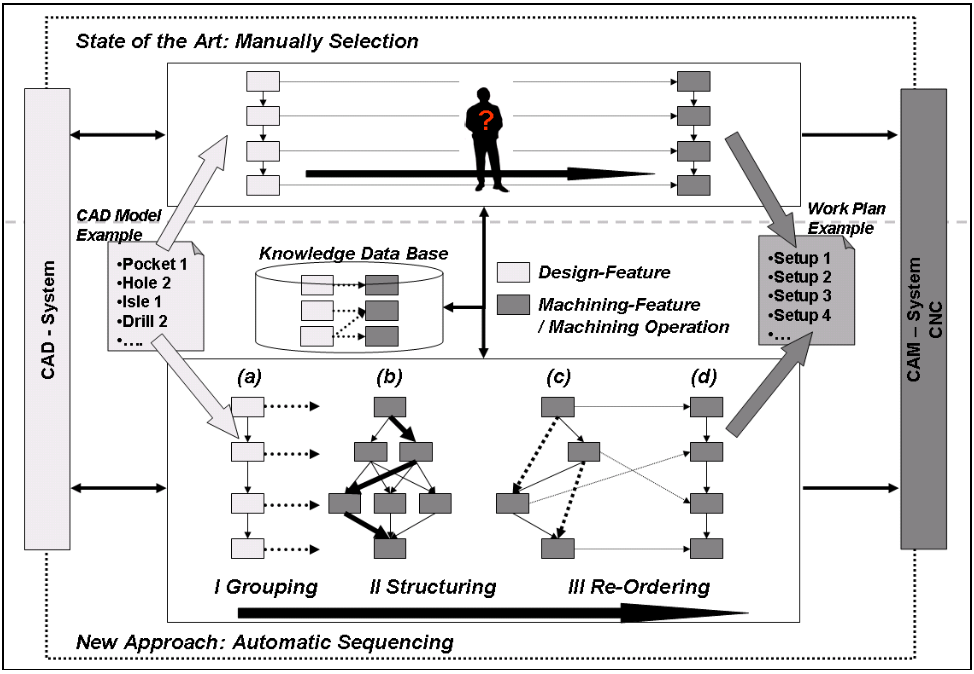

Fig. 4. Functional principle of approach in comparison with the state-of-the-art

Finally, the third step is the mentioned re-ordering (III) of the sequence of the selected machining operation in order to save effort. As a result, a sequence of machining operations corresponding to the given design features and to the process planner defined criteria (see graph (d)) was generated. In the last activity, the machining operation list is provided to the CAM system that generates the corresponding NC program based on ISO 14649 or ISO 6983.

Several issues have to be defined in order to realize this introduced functionality. At first, a suitable knowledge representation is determined for the work plan. Furthermore, the data base structure and the assessment criteria for machining operations are defined. Moreover, the effort and effort calculation rules that are based on the assessment are determined to enable the selection of alternative machining features and operations. The next step is the investigation of suitable algorithm to process the introduced functions (I-III). Finally, an overall architecture of such an approach is determined and a work flow is specified in order to transfer it to the real application as a demonstrator.

4.3. Overall architecture and modules

A modular architecture was chosen to design the architecture of the approach. Consequently, each module represents a distinct functionality of the approach. The approach consists of four modules that are integrated in the current IT architecture of a commonly used NC process chain (as seen in Figure 5). The main task is done by the first module called "Process Planning Tool". This module generates a work plan by sequenced machining operations. Thus, the module accessed the CAD system to receive the work piece description. Furthermore, an interface to the CAM-System is enabled to process the sequence of machining operations. As a result, the work plan is compiled to a NC program and is sent to the machinery at shop floor level.

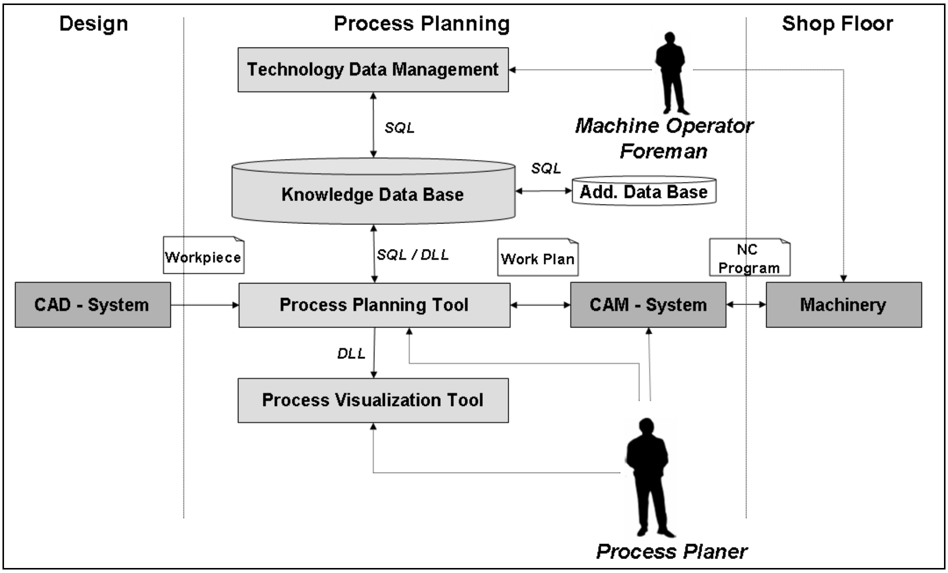

Fig. 5. Architecture and Modules of the approach

The next module "Process Visualization Tool" is introduced to enable a traceable work plan generation by illustrating the current work plan in a graphically. The process planner can easily interact with the system and can influence the work plan generation.

The objective of the approach is the use of assessed machining operations. As a consequence, two additional modules are introduced. The first one stores the assessed operations which are selected by the process planer in a data base. This data base represents the third module "Knowledge Data Base". The knowledge data base has access to the additional database (e.g. information and parameter setting about tools and machines). Secondly, the machining operations are assessed. The fourth module "Technology Data Management" enabled easy to use assessment of the machining operations by the operators and foremen. Thus, the process planers expertises are assessed in the shop floor with the expertise of the operators and foremen. These assessment results are stored and re-used for the next work plan generation

4.4. Model for work plan representation

The selection of a model for the representation of work plans is discussed in this section. Feature-based concepts are well known established structures for defining the work plan [5] [16] [23]. Cai and Gerken defined the machining process plan elements in a hierarchical way as shown in Figure 6. A work plan for machining a work piece consists of several machining features which are representing the machining of each design feature of the work piece description. As an example, the machining of a drilling machining feature is divided hierarchically in further machining operations and finally in further cut as shown in figure 6. Each machining operations consist of the used tool, the machining technology and the path strategies. Furthermore, each machining operations includes a list of parameters to store the assessment results (3) (4.1) as introduced in the chapter 2.4. In detail, the machining technology includes information about the used CNC machine, spindle speed, feedrate and tolerances. The path strategy includes information the way the tool path is calculated (number of axis, kind of strategy and so on).

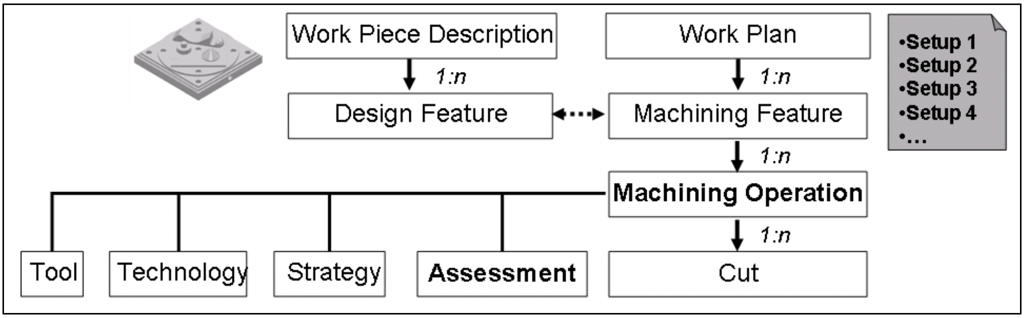

Fig. 6. Work plan representation based on machining operations

In conclusion, the machining operation represents the basic element of a machining work plan. Furthermore, a machining feature is represented by further machining operations. Additionally, the VDI2218 introduced feature mapping for assigning features in different applications scope [5]. This methodology is addressed to connect the design and the corresponding machining features. An entity “Assessment” is linked to the element machining operation in order to store the assessment of a machining feature and operation. Finally, the work plan representation is implemented in the demonstrator as Entity-Relation-Ship-Model of the used data base.

4.5. Model for work plan processing

The objective is to find a suitable concept that addresses the operations of grouping, structuring and re-ordering. Consequently, several common used knowledge processing structures are investigated and presented in this section. Afterwards, the used processing algorithms are introduced.

At first, requirements are determined for the structure and suitable but available concepts are benchmarked. Due to the fact that alternative work plans are used to machine the same machining tasks, the following requirements of a structure are defined [7]:

- Representing a work plan by several machining features and machining operations

- Handling time dependency among machining operations
- Outlining different alternatives in a work plan
- Handling and assessing machining operations
- Application of traceable algorithms for grouping, structuring and re-ordering

Therefore, the following knowledge representation and knowledge processing concepts known from the Artificial Intelligence (AI): neural networks, genetic algorithm, formal rules-based languages and methods based on the graph theory [24] are investigated. The result of the investigation is shown in Table 2.

Tab. 2. Representative process planning methods based on Artificial Intelligence

Methods	Investigation result
Neural networks	• Have to be trained through special training algorithm • Failed due to the non-traceable information processing [24]
Genetic algorithms	• Character coding is suitable for finding new solutions • Not efficient in the scope of sequencing machining operations [15]
Formal, rule-based languages	• Formalize a given well structured domain under discussion • Missing algorithms for processing structures like work plans
Graph theory	• Modelling time dependency with time conditioned arcs between nodes • Different paths inside the graph represents alternative work plans • Introducing efforts for passing nodes and arcs for assessing work plans • Enable to use of algorithms (e.g. Floyd-Warshall and Travelling Salesman Problem solving algorithm) for processing work plans [7]

Concluding the investigation, the graph theory and the corresponding algorithms fulfilled the requirement. Thus, the graph theory and the algorithms are used to represent the alternative work plans and for modelling the introduced function of grouping the design feature, as well as structuring the work plans and finally ordering the machining operations.

Thus, a work plan with all alternative machining operations can be transferred to a directed graph *DG* which is defined as an arrangement of a set of nodes (edges) *V* and a set of edges or arcs *E*. These arcs are connecting two nodes out of the set of nodes [6].The set of machining operations are represented by the set of nodes. The arcs between the nodes represent time-related dependences between two machining operations. An arc $e = (a,b)$ means, that the machining operation a has to be machined before the machining operation b. There are existing two different time dependences that have to be modelled. The first one represents the machining related dependency which is caused by the use of different machining technologies. For example, the roughing of a pocket must be done before finishing. The second time dependence models the geometric dependency for machining operations. It means that a drilling inside a pocket has to be machined at first for example. Summing up the work plan mapping, an example of an alternative work plan is given in the Figure 7. Here, different alternative machining features and operations for the design features are shown. These design features are ordered in a vertical way. Consequently, the alternative machining features and corresponding machining operations are ordered in a horizontal way, where each line represents alternative machining operations, which is to be performed to generate the work plan. In this context, three aspects are introduced in a directed graph in order to assign and process the alternative work plans [7]:

- Assessment of machining operations with criteria that have to be determined
- Introduction of effort calculation rules (4.1, 4.2) for the machining of an operation and the changing of setups between two machining operations
- Defining of algorithms which realizes the function of grouping, structuring and re-ordering with the help of the assessed machining operations

Firstly, two criteria set are introduced for assessing machining operations that are represented by arranging the set A*C* (3) (7.1). The first set *ACM (AC machining)* includes criteria for assessing the machining characteristics of the machining operations. This set *ACM* includes criteria like tool wear, run time, machining costs, surface quality and roughness. Some of these criteria are feature-size independent (e.g. roughness, surface quality) and some are depending on the geometric size of the feature. Therefore, an additionally linked CAM system computed this information (e.g. run-time). The second set *ACC* (*AC changing*) includes criteria for assessing the setup changing between two setups of sequenced machining operations. This set *ACC* includes criteria for changing the geometric position of machining operations, the used tool, the used clamping, and the used machine for each operation setup.

Secondly, assigned weights *AW* (3) have to be determined in order to define calculation rules of the effort in the work plan. The main driver is the customizing of the effort calculation. Thus, manufacturing scenarios are introduced. Each of them represents a weight setting according to the given overall manufacturing metrics (time, cost, quality). Thus, the effort can be calculated by adding the product of the corresponding assessed criterion out of *ACM* and *ACC* with the corresponding assigned weight out of *AW* to a total sum. Therefore, the assessment setting is represented as defined in (7.2). Now, the effort function *ot* (4.1) for assigning a machining operation is described by the equation (8). Furthermore, the effort function *at* (4.2) for assessing the changing between two machining operations setups as edge is defined as shown in equation (9).

$$AC = (ACM \cup ACC);\ AS = (ACM \cup ACC, R, AW) \qquad (7.1)(7.2)$$

$$ot : (MO \times AS) \rightarrow \Re;\ ot(mo, as) = \sum_{n=1}^{p} (aw_n * acm_n(mo)) \qquad (8)$$

$$at : (MO \times MO \times AS) \rightarrow \Re;\ ot(mo_1, mo_2, as) = \sum_{u=1}^{v} (aw_u * acc_u(mo_1, mo_2)) \qquad (9)$$

Thus, the overall function (6) can be defined in equation (10). This function has to minimize the effort of a work plan consisting of *m* non-parallel machining operations, which are assessed by *p* machining characteristics for each machining operation and *v* assessed setup changing characteristics. This introduced multi-factor effort calculation enables multi-parameter decisions like selection of machining operations, because all decision parameters are mapped with the help of weights into one parameter (effort) decision. Furthermore, the effort calculation depends on the customized manufacturing scenarios that are determined by the customized weight settings.

$$\min(e(wp,as)) \mapsto \min(\sum_{k=1}^{m}(\sum_{u=1}^{v}(aw_u * acc_u(mo_k, mo_{k-1})) + \sum_{n=1}^{p}(aw_n * acm_n(mo_k)))) \quad (10)$$

Finally, algorithms known from the graph theory are used to compute significant paths through the directed graph with the help of the introduced effort calculation rules. The overall objective is to find a solution of the equation (10). Thus, two major algorithms can be identified that are suitable for the application in the field of NC machining [1]:

The Floyd-Warshall (FW) algorithm calculates the shortest distance (as a total sum of arc efforts) between two nodes (machining operations) with the help of the transitive closure [6]. Thus, different alternative machining operations for the same machining feature can be rated. Consequently, the function structuring of the approach is realized with the time complexity $O(n^3)$, where n is the amount of nodes.

The TSP (Travelling Salesman Problem) solving algorithms can be executed in order to re-order all machining operations in a work plan and to get the lowest effort in total to machine all machining operations in a row (as Hamiltonian path). The TSP is NP-hard [6]. Consequently, an optimal Hamiltonian path (HP) can be calculated after comparison of all machining operations combinations. This algorithm has a high time complexity $O(n!)$, where n is the amount of nodes. Thus, several algorithms (Christofides algorithm, nearest / farthest insert algorithm, greedy algorithm, all nearest neighbours algorithm, double minimum-spanning-tree, space filling curve heuristic) are finding heuristic solution for a Hamiltonian path in acceptable runtime [6] [25]. Therefore, the function of re-ordering are realized with a heuristic algorithm.

The Table 3 sums up the explored and used algorithms. It is shown, that a common sorting algorithm for the grouping are used due to the low complexity. Furthermore, the FW and TSP (as heuristic solution) are used of realizing the function II) and III).

Tab. 3. Exploring different algorithm to realize the approaches function I)-III)

Function	Algorithm	Result	Time complexity
(I) Grouping	Sorting algorithm	1 order	*$O(n^2)$, n nodes, e.g. Quick sort*
(I) Grouping	Permutation	n order	*$O(n!)$, n nodes*
II) Structuring	FW algorithm	1 order	*$O(n^3)$, n nodes*
II) Structuring	Variation	a^b order	*$O(a^b)$, a alternatives per each nodes, b nodes, n = a * b, b = const.*
III) Re-ordering	TSP algorithm	1 sequence	*$O(n!)$, n nodes; without heuristics*

4.6. Workflow for the knowledge-based NC programming system

Now, the workflow of the proposed approach is defined based on the introduced mathematical background. The work flow of a specimen work plan is presented in Figure 7 as well as the work flow is presented in a detailed way in Figure 9. The defined workflow is divided into three already mentioned operations (I-III). The objective of the approach is the generation of a work plan for machining a given work piece. Therefore, a feature-based CAD model with design features is investigated.

At first, the design features are imported from the CAD system and ordered. This ordering is computed by a sorting algorithm that groups by similar feature types. Now, the first step is of grouping as shown in Figure 4 (a). The second step is the mapping of the design feature list into suitable alternative machining feature and operations which are reduced later on. Thus, an example for a work plan (Fig. 7) is taken to describe this second and the third step: The example CAD model description (Figure 7 left) consists of three design features (DF), which can be mapped into six machining features (MF). Each one of them is represented by machining operations (MO). These mappings are stored in the knowledge data base. Going into the detail, the machining features MF1a and MF1b have a shared machining step machining operation MO1 (e.g. roughing) and two alternative steps MO2a (e.g. finishing 3-axis) and MO2b (e.g. finishing 5-axis). The machining feature MF2 is represented by only one machining operation. The last design feature can be mapped into three alternatives machining feature (MF3a, MF3b and MF3c). These MF are sharing one machine operation MO4 (e.g. roughing) and three alternative machining operations (MO5a, MO5b and Mo5c).

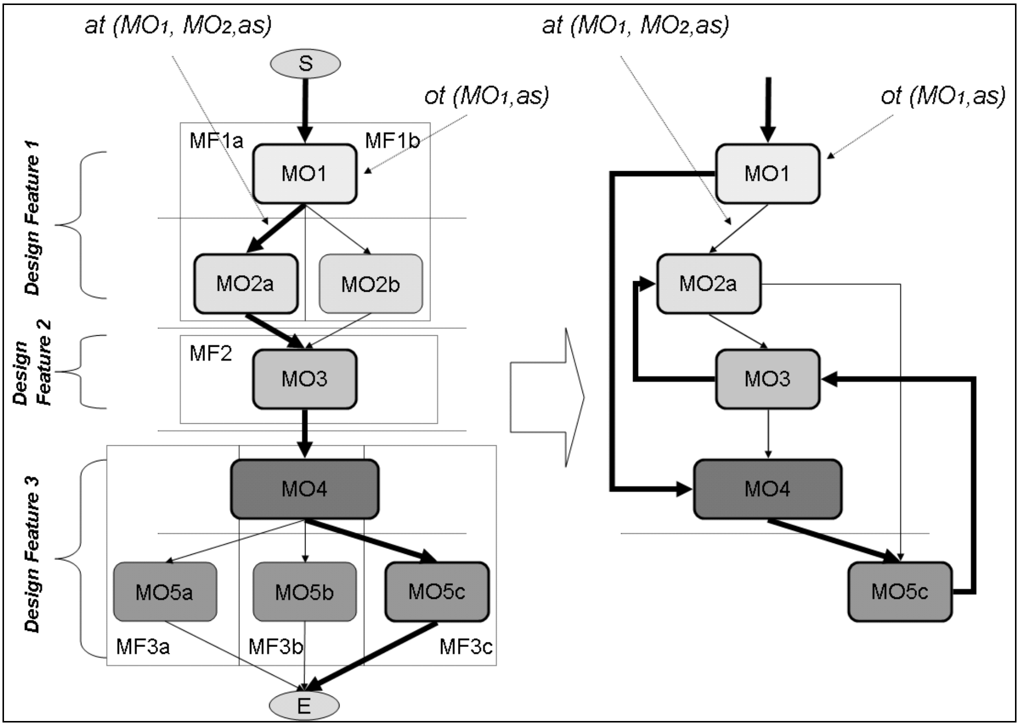

Fig. 7. Specimen work plan as directed graph (left) with Hamiltonian Path (right)

Two sets are defined in order map a list of design features into the corresponding alternative machining operations and to apply the effort calculations rules (8)-(10). At first, the set of manufacturing requirements *RM* for the technology and strategy parameters of each machining features and operations are determined by the process planner corresponding to the available resources at the machinery and the requirement to the given job. The second set is the weights *AW* which defines the used manufacturing scenarios for calculating the effort of work plans. Now, the suitable machining operations corresponding to the given machining features are selected for each mapped machining features. The mappings are stored in the knowledge data base. The next step is the effort calculation for each node (machining operation) and arc (dependencies) with the help of a CAM system for the feature-size dependent criteria and the introduced calculation rules (8)-(10). Afterwards, the process planer selects the best-fit alternative machining operations with the FW algorithm that calculates the "shortest path" inside the graph automatically. Therefore, the additional start node "S" and an end node "E" are added (as shown in Figure 7). As a result, the marked machining operations in a horizontal line represent the operations with the lowest effort to the requirements *RM* and weights *AW* in Figure 7. Thus, a suitable work plan is structured and bold marked in the Figure 7 (left). After this the structuring of the work plan is done (Figure 6 b).

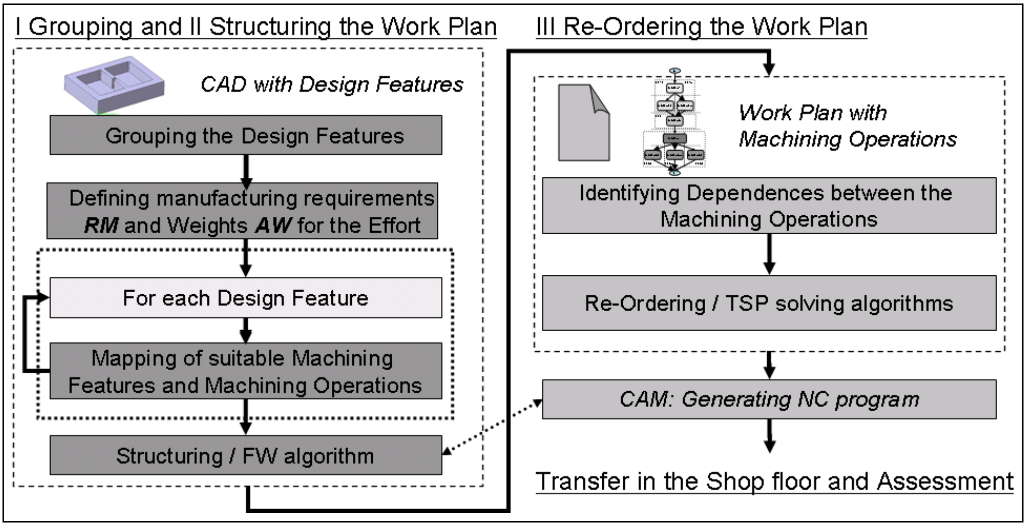

Fig. 8. Work flow of the approach

The last step is the re-ordering for determining the sequence of machining operations with the least sum of effort between the machining operations in total to meet the equation (10). This work plan is the optimal work plan to the given requirements *RM* and weights *W* by the process planner. The Hamiltonian path (HP) describes such a work plan as path. Therefore, the work plan has to be enriched with additional arcs that represent additional machining and geometric dependencies as shown in Figure 7 (right). All arcs and node are assessed with the calculation rule *ot* (8) and *at* (9). Afterwards, a suitable HP is calculated. The quality of the path is dependent upon the executed algorithm. As already discussed, the best path can be archived by the combination of all possibilities that caused with high computation time. The use of heuristic algorithms shortens the runtime drastically. A possible HP in the example is shown in Figure 7 (right, fat marked). Thus, the last step is done as shown in Figure 6 (d). Finally, the optimized NC work plan is found and translated into the corresponding NC program by a CAM system. The scheduled NC programs are dispatched to the machinery. Thus, the operator has now the possibility to assess the machining operations for re-using them.

4.7. Sequencing algorithm approach

Three different functions are assigned by automatically executed algorithm based on the presented workflow. The first function of grouping (I) the design feature is done with a sorting algorithm. It is proposed to use the common quick sort algorithm. The second function structuring (II) is realized by the Floyd-Warshall algorithm presented above and that is described in [6]. The Floyd-Warshall minimized the effort of machining features by selecting these machining operations with the lowest effort *ot (8)* in total of theses machining feature. Thus, the second part of the objective equation (10) is minimized.

The third function of re-ordering (III) machining operations is done by computing a Hamiltonian path (HP) as described above. Calculating a HP is a NP-complete problem. Therefore TSP (Travelling Salesman Problem) solving algorithm is used to compute the HP [6] [26]. As already discussed heuristic algorithm are reducing the runtime for finding solution of a Hamiltonian path in acceptable runtime by assumption, in order to shorten the amount of investigated solution [6] [25]. As a consequence, the complexity is decreased [25]. It is shown that it is not possible to validate the quality of the HP of a heuristic result in a mathematical way. But it was shown by Reinelt by empirical experiments that heuristics algorithm has fixed quality borders to validate the difference to the optimal solutions.

```
// Init. of the Variables
allNodes[]
path[] = EMPTY, paths[][] = EMPTY
restNodes[] = EMPTY, possibleNodes[] = EMPTY
lastNode = EMPTY, startNode = EMPTY
// Selecting each Node in the Graph as a starting nodes of a HP
FOR EACH Nodes startNode FROM IndependentNodes (allNodes[],allNodes[])
   path[] = startNode,
   restNodes[] = allNodes[] – startNode,
   lastNode = startNode
   // Computation of the next Node which will be visited after the last note in current sequence
   WHILE restNodes[] NOT EMPTY
      // Determining all possible Notes with a connection of the last note in current sequence as a Set
      possibleNodes[] = ConnectingNodes (lastNode, restNodes)
      // Determing all Notes that are also independent from the Set
      possibleNodes[] = IndependentNodes (possibleNodes[], restNodes[])
      //Determining the Note with the shortest Distance now from the Set
      lastNode = ShortestDistance (possbibleNodes[], lastNode)
      path[] = path[] + lastNode
      restNodes[] = restNodes[] – lastNode
   LOOP
   // Storing the HP corresponding to the starting Node
   paths[startNode][]=path[]
LOOP
// Selecting the shortest path
Path[] = shortestPath (paths[][])
```

Fig. 9. Source code the used heuristic algorithm ANN

For the presented approach, the "All nearest neighbour" (ANN) algorithm are used, due to the fact that the ANN is as simple and efficient heuristic algorithm. The main idea is the sequencing of machining operations (nodes) in a way that the effort between two operations is as low as possible. As a consequence, the setup changing effort is as low as possible for each operation pair. However, the first part of the equation (10) is minimized in a way that the effort function *at* is minimized for each operation couple. Nevertheless, deadlocks are possible due to the fact that the nearest suitable node (machining operation) can influence other nodes. Therefore, different dependencies are added between the nodes representing geometric and machining dependencies. Thus, the following heuristic algorithm which is used is shown in Figure 9:

In general, the algorithm selects a shortest path by calculating different HP in each outer iteration loop (starting at line 7 in the source code) corresponding to all possible starting nodes in the directed graph. Afterwards the shortest HP of them is selected. The objective of this algorithm is to reduce the desired possible nodes, which can be selected as next node in the iteration loop. Therefore three functions are used in the inner iteration loop (starting at line 12 in the source code). The first function (a) *ConnectingNodes* selects all possible nodes which are accessible from the last selected planning node. Afterwards, this selection is reduced to all nodes which are independent in the scope of machining and geometric by the function (b) *IndependentNodes*. The resulting nodes are those which can be accessed without having a deadlock. The next step is the selection of node with the shortest connection (via the effort) to the last planning node. This task is done by the function (c) *ShortestDistances*. As a result, the nearest node was selected for each in each inner iteration loop. The outer iteration loop for each starting node is finished when all nodes in the graph are included. Afterwards, the shortest HP from all HP is selected with the function (d) *shortestPath*. Finally, this HP represents the sequence of the machining operations with the least sum of efforts in total

4.8. Benefits and discussion

The chapter concludes with a critical discussion about the benefits and advantages as well as room for improvements. The main advantage of the approach is the traceable and customized generation of work plan by sequencing machining operations. Thus, the benefits are the time saving and the consideration of the whole machinery equipment for the process planning. After modifying the customized manufacturing requirement *RM* it is possible to try out different alternative work plans. As a result, the need for new machinery equipment can be felt and finally evaluated in relation to the effort and benefit of the new equipment. Furthermore, the planning knowledge of the planner in selection technology and strategy for each machining feature and operations is stored in a central knowledge data base in a structural way. Additionally, the expertise of the operator and foremen is used to assess the sequenced machining operations. The re-use of expert knowledge for all involved employee along the whole NC process chain for further process planning activities is enabled.

Nevertheless the approach has several rooms for improvements that have to be discussed and focus in further stages of development. At first, unknown design features are not processable because of missing mappings in the data base. So, these features and mappings have to be created. Secondly, the approach is usable for common used feature based work plans. Free-form features are very difficult to handle. Thirdly, the approach needs a CAM system as backbone for computing the run time of each individual machining operation. This function can have a high effort, when considering complex and hugh work plans. Fourthly, the ANN algorithm used a heuristically assumption to re-order the machining operations. The equation (10) can be solved by minimizing the “local” effort between two machining operations couples. In general, the algorithm assumed that the global minimum of all efforts is a sum of all minimized local efforts. Finally, the approach doesn’t consider the current job scheduling at the shop floor, but the integration into MES is possible in further steps.

5. TECHNICAL REALIZATION AND EVALUATION

5.1. Technical realization

The approach is implemented step-by-step as demonstrator. The demonstrator consists of the four individually introduced software modules of the approach. The module "Process Planning Tool" is implemented using Visual Basic (VB). The current state of the planning tool realized the import of CAD models in order to map the design features into machining features and machining operations. Then, the reduction of alternatives is computed by the FW function. Actually, the introduced ANN algorithm (chapter 4.7) is implemented and applicable. Thus, all three function of grouping, structuring and re-ordering are implemented. The further three software modules are also implemented. The "Process Visualisation Tool" is used to represent the alternative work plans as a graphical net in MS Visio and as Gantt chart in MS Excel. Thus, the process planner can easily retrace the process planning with the help of the charted work plan and Gantt chart. The "Knowledge Data Base" is also implemented in MS Access and includes 21 tables based on the introduced feature based knowledge representation. These tables are storing all relevant information for the mapping of design features into assessed machining features and operations. Furthermore, it is possible to store the computed work plans in the data base. The last software solution "Technology Data Management" enabled now, the machine operator or foreman to assess/rate the generated work plan with the machining operations with an easy-to-use form-based interface to the knowledge data base.

As the last step, the interface to the CAM system is planned in order to automatic exchange of the work plans. This will be implemented as soon as possible in order to close the information flow in the approach and NC process chain.

5.2. Evaluation of the approach

The evaluation is being done by the process planning for the machining of the NCG (NC Gesellschaft) Benchmark Part 2004 (see Figure 10).

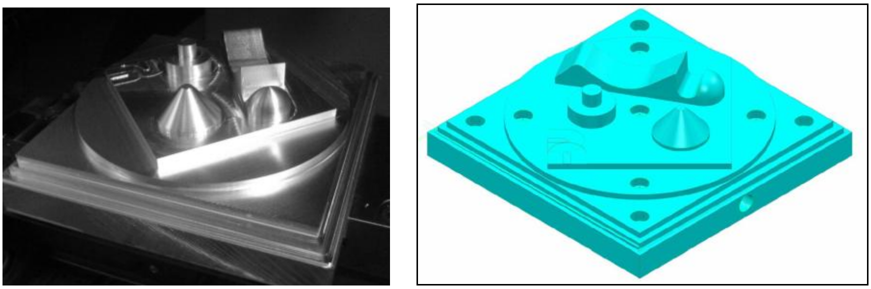

Fig. 10. NCG Benchmark Part 2004 (machined and CAD model [27])

This benchmark part consists of several design features. Thus, the corresponding machining features are already assessed and stored in the data base of the demonstrator. The demonstrator has applied with an example work plan consisting of six design features (as shown in Figure 11). At first, the grouping (a) is done. Afterwards the six design features are mapped to the machining features (b) with the help of the stored mappings in the data base. After that, theses machining features are mapped (c) again into several machining operations corresponding to the content of the knowledge data base and to given limitations (e.g. using 5 axis and all tools). Afterwards, the weights *AW* for the effort equation are defined. With the help of the given criteria sets *ACM* (tool wear, machining costs, collision potential, surface quality, roughness) and *ACC* (machine, clamping, tool, geometric position), the alternative machining operations are benchmarked. After that, the structuring is done. The result is the high-lighted machining operations which are divided into roughing and finishing operation. Now, the temporary work plan is re-ordered (d). This function is realised the help of the introduced ANN. As shown in Figure 11, the finished work plan comprehends now a new order of machining operations. All the independent roughing operations are grouped together. An effort saving (for changing the setups - *at*) of over 35 percent was archived to the given requirements, limitations, and weight *AW* of the manufacturing scenario in this simple example. The first trials showed the applicability of the directed graph to model different alternative work plans. The applicability of the FW and the ANN is also validated. But further test follows in order to confirm the first evaluation results.

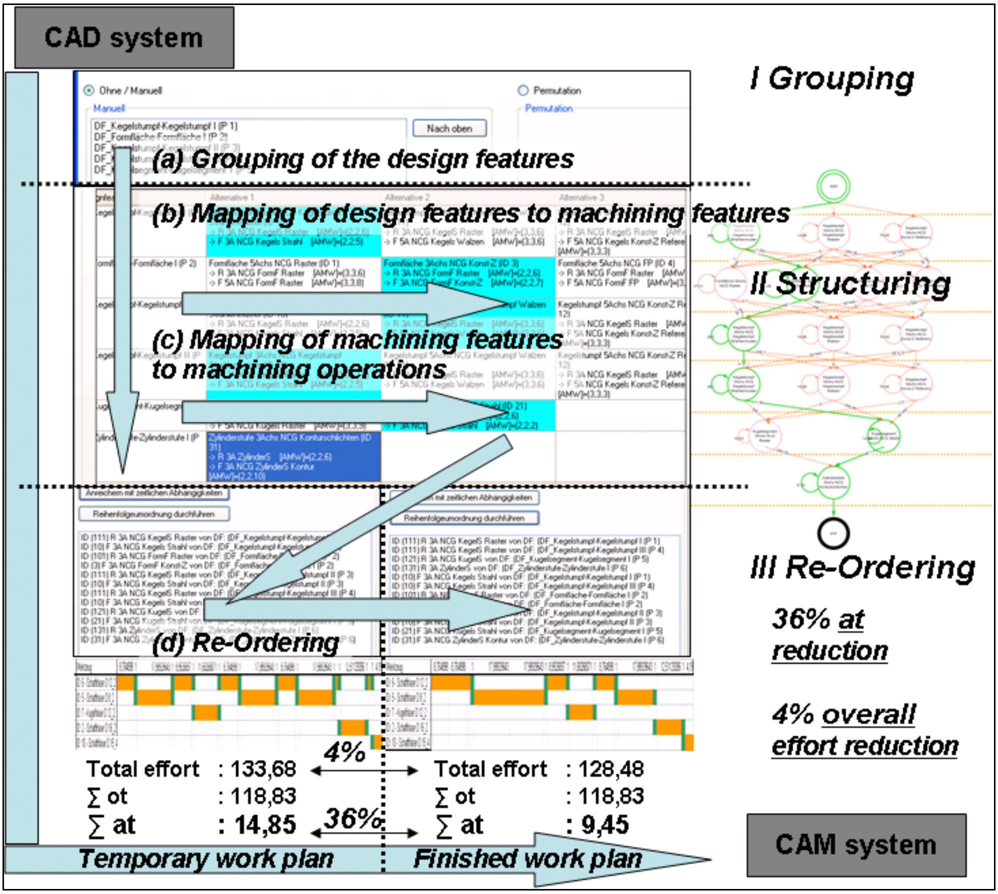

Fig. 11. Example evaluation for effort saving

6. CONCLUSION AND OUTLOOK

Nowadays, there are existing significant deficiencies in the information flow along the NC process chain caused by the use of insufficient interfaces within the process chain. Consequently, knowledge is kept in these uncoupled process chain phases. The deficits could be solved by common integrated CAD/CAM software solutions and particularly by the introduction of the feature technology based interface. Nevertheless, necessary modifications in the shop-floor are not supported in an adequate way. Furthermore, there are still deficits in the automatic preparation of work plans. So, the need for a new time saving solution for automatic re-using of expert knowledge was pointed out. The objectives as well as the requirements were formulated.

The presented approach focuses the automatic sequencing of machining operations under given customized manufacturing scenario. The main idea is the use of feature technology and assessment. Best practice strategies as expert knowledge are stored in a knowledge data base with feature-based knowledge representation. Therefore, a mathematical description of work plans based on feature technology was introduced. This specification describes a work plan as a sequence of machining features with alternative machining operations. These operations are rated/assessed with the help of different assessment criteria. The introduction of manufacturing scenarios with weight for each criterion enabled the planer to assess the different machining operation in a customized way. Thus, the process planer has now the possibility to select different alternatives parameters for machining different areas of a work piece regarding to a given machining scenario. Furthermore, the selection process is automated by using the three defined functions (I) grouping, (II) structuring and (III) re-ordering. So, different mathematical descriptions were investigated and rated. Finally, the graph theory was selected with the applied algorithm (FW; TSP) so as to meet the defined requirements (see paragraph 3). As a consequence, the machining operations based work plan is transferred into a directed graph. The nodes represent machining operations and the arcs are representing the quantified efforts dependencies within them. Now, the application of the Floyd-Warshall algorithm is enabled. It was proved, that the FW calculates the best choice of alternative machining operations for each machining feature in order to reduce machining effort for each machining features. Furthermore, a heuristics algorithm (ANN) computes the optimal sequence of the selected machining steps in order to reduce the effort for changing setups. The approach concludes with the critical discussion of benefits and possible improvements as well as limitations. The implemented demonstrator showed in first test with a NCG benchmark part that the automatic process planning based on the FW and heuristic TSP algorithm is possible and enabled. A time reduction in the process planning and machining was achieved. The effort reduction of over 4 percent in the example work plan underlines the supposition. Further tests are being followed to confirm the first evaluation results.

A next step is to finalize the implementation of the demonstrator. Therefore, several data bases (e.g. machinery) are added to the knowledge data base. Moreover, algorithms have to be identified in order to map the design features into machining features. Finally, the approach will be included into job scheduling methods related to actual machinery situation such as MES (manufacturing execution system). In conclusion, the presented approach supports the process planner by providing the functionality of the automatic sequencing of suitable machining operations corresponding to a given manufacturing scenario. It is noteworthy that all the objectives and requirement which were addresses are fulfilled.

References

[1] ISO 6983: *Numerical control of machines - Program format and definition of address words, ISO* (International Organization for Standardization), 1983.

[2] BRUNNERMEIER, S.; MARTIN, S.: *Interoperability costs in the US automotive supply chain, Supply Chain Management*: An International Journal, Volume 7, Number 2: pp. 71-82(12), 2002.

[3] XU, X.; WANG, L.; RONG, Y.: *STEP-NC and Function Blocks for Interoperable Manufacturing* IEEE Transactions on Automation Science and Engineering, Vol. 3, No. 3, July 2006.

[4] ISO 14649-1: *Industrial automation systems and integration - Physical device control - Data model for computerized numerical controllers*, ISO (International Organization for Standardization), 2003.

[5] VDI 2218: *Information Technology in Product Development - Feature Technology*, VDI-Gesellschaft Entwicklung Konstruktion Vertrieb, 2003.

[6] JUNGNICKEL, D.: *Graphen, Netzwerke und Algorithmen*, Wissenschaftsverlag, Mannheim, 1990.

[7] BERGER, U.; KRETZSCHMANN, R.; NOACK, J.: *An approach for a knowledge-based NC programming system*, Proceedings of the 5th International Conference on Informatics in Control, Automation and Robotics, Portugal, May 12-16, 2008.

[8] EVERSHEIM, W.: *Organisation in der Produktionstechnik-1. Band*, VDI-Verlag, Düsseldorf, 1996.

[9] KLETTI, J.: *Konzeption und Einführung von MES-Systemen*, Springer-Verlag Berlin, 2007.

[10] WARNECKE, G.; VALOUS, A.: *Informationsrückkopplung zwischen NC-Fertigung und Arbeitsplanung*, Schnelldruck Ernst Grässer, Karlsruhe, 1993.

[11] BLAZEWICZ, J.; DOMSCHKE, W.; PESCH, E.: *The job shop scheduling problem: Conventional and new solution techniques*, European Journal of Research 93, 1995.

[12] HAMELMANN, S.: *Systementwicklung zur Automatisierung der Arbeitsplanung*, VDI-Verlag, Aachen, 1995.

[13] WEIMING, S.; HAO, Q.: *Agent-based Dynamic Scheduling for Distributed Manufacturing*, Process Planning and Scheduling for Distributed Manufacturing, Springer-Verlag, London, 2007.

[14] SORMAZ, D., N.; ARUMUGAM, J.; GANDURI, C.: *Integration of Rule-based Process Selection with Virtual Machining for Distributed Manufacturing Planning*, Process Planning and Scheduling for Distributed Manufacturing, Springer-Verlag, London, 2007.

[15] HELLBERG, K.: *Methoden zur automatischen Erzeugung von Arbeitsgangfolgen*, VDI-Verlag, Düsseldorf, 1993.

[16] GERKEN, H.: *Management von Erfahrungen mit einem Assistenzsystem für die Arbeitsplanung*, Dissertationssschrift TU-Berlin, 2000.

[17] ZHANG, C.; LI, P.; RAO, Y.; LI, S.: *A New Hybrid GA/SA Algorithm for the Job Shop Scheduling Problem*, Evolutionary Computation in Combinatorial Optimization, pp. 246-259, 2005.

[18] CIMdata, Inc.: *NC Software and Services Market Assessment Report Version 16*, [Online], Available: http://www.cimdata.com/. [27 July 008].

[19] CAD/CAM/Report: *CAM-Systeme werden intelligenter*, CAD/CAM/Report 7+8,Volume 25, 2006.

[20] DURAN, O.; RODRIGUEZ, N.; CONSALTER, L., A.: *End Milling: A Neural Approach for Defining Cutting Conditions*, Proceedings of the 4th International Workshop on Artificial Neural Networks and Intelligent Information Processing, Portugal, May 12-16.2008.

[21] DIN 8589: *Manufacturing processes chip removal*, DIN Deutsches Institut für Normung e. V. - Normenausschuss Technische Grundlagen (NATG), Bezugsquelle Beuth Verlag GmbH, 2003.

[22] LENZ, A.: *Knowledge Engineering für betriebliche Expertensysteme*, 1. Auflage, Deutscher Universitätsverlag Wiesbaden, 1991.

[23] CAI, J.: *Development of a Reference Feature-based Machining Process Planning Data Model for Web-enabled Exchange in Extended Enterprise*, Dissertationssschrift, Shaker Verlag, Aachen, 2007.

[24] GÖRZ, G.: *Handbuch der Künstlichen Intelligenz*, Oldenbourg, München, 2003.

[25] SCHMITTING, W.: *Das Travelling-Salesman-Problem*, Dissertationssschrift, Münster, 2006.

[26] REINELT, G.: *The Travelling Salesman Computational Solutions for TSP Applications*, Springer-Verlag, Berlin Heidelberg, 1994.

[27] NC-Gesellschaft: *Anwendung neuer Technologien: NCG 2004- Prüfrichtlinien und Prüfwerkstücke für hochdynamische Bearbeitungen (HSC), Teil1: Fräsmaschinen und Bearbeitungszentren*, 2000.