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# SETUP OPTIMIZATION BASED ON VIRTUAL TOOLING FOR MANUFACTURING IN ORDER TO PROVIDE AN INTELLIGENT WORK PREPARATION PROCESS

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## ABSTRACT

The setup process and the linked configuration of point of origins, workpiece position and tool ranges require high calculative effort including multiple simulation runs during the work preparation process. The presented contribution deals with a demonstration of automatic setup optimization including validation of setup parameters using multiple virtual tooling machines as simulation models. The developed system offers a production-supported setup tool to select useful machines. The production jobs based on an optimized production schedule and the system provides a valid machine setup for collision free and rapid production of workpieces compared to the conventional manual simulation process to determine valid setup parameters for tooling processes. This contribution contains the focus on implementing tooling setup by a test environment as experimental design.

## 1 INTRODUCTION

In order to improve the setup of tooling there are several approaches using simulation-based optimization in combination with a virtual tooling machine for milling processes. The conventional case during the work preparation process is to create the product design using CAD tools, converting the CAD data in NC-programs by using CAM tools (CAD stands for Computer-Aided Design which consists of 3D-models of physical machine parts and NC stands for Numerical Control which contains the movement commands of the machine). The last step is to simulate these programs using a virtual tooling machine to validate points of origin, tool range, and workpiece positions in order to prevent accidental collisions. This leads to a confident production process. For that, several sub-systems are committed to a service platform which is controlled by a multi-user agent. The associated research project is called *InVorMa (Intelligente work preparation based on virtual tooling machines)* as part of the leading edge cluster *it's OWL* which is supported by the Federal Ministry of Germany. The system builds an intelligent work preparation process for the user in- and outside of companies.

The interface contains a web interface and interfaces between the systems to organize production order. Machine selection and the setup optimizer are provided by a database.

The system builds an intelligent experimental design in order to validate production and machine parameters using distributed resources and a simulation model which describes the real behavior of a milling machine. The simulation model is designed as numerical CAD-based and multibody-based model connected with a real control unit. The simulation systems contains the design of a real existing machine and the machine parts show relative movements between tools, tool magazine, workpiece and periphery system parts of a real tooling machine. The simulation is the core of the system because it is used to identify parameters which lead to rapid production time as collision-free parameters and gives the information to change NC-commands for a working production process. This experimental process using the virtual tooling process is performed manually which underline the importance to generate valid setup parameters. This contribution extend these procedures as automatic process in order to support work preparation.

As collisions during machining lead to high financial damages, the underlined simulation software has to map physical tooling machines exactly into a model. Thus, the used virtual tooling machine has been implemented as a one-to-one representation including virtual numerical control and virtual PLCs. For this reason, performing a simulation run is a very time-consuming process. Since this aspect makes it unfeasible to employ classical approaches for simulation-based optimization in this application, an NC parser was implemented. This tool makes it possible to predict the machining time of a given NC-program by considering travels and axis velocities in a couple of seconds. Contrary to the virtual tooling machine, this tool is not capable of computing collisions.

This contribution starts with the introduction to explain the motivation and is followed by section two containing the related work in the research areas focused on research results from the project treated in the past. Section three presents the system architecture of the entire project. Section four shows the results of the given production scenarios optimized by NC parser in order to state the potentials of setup optimization. Additionally a concrete scenario is presented, where different workpiece orientations lead to collisions during the simulation. Section five closes with a conclusion and presents an outlook for future research.

## 2 RELATED WORK

Related approaches and research activities in the given area of setup optimizer implementation to generate valid setup parameters based on virtual tooling contain the proof of concept as well as initial experiments to identify useful procedures. Initial ideas arose to implement a system according to the role model of simulation based optimization, which consists of using metaheuristics as an optimizing component and the virtual tooling machine for simulation as well as a parameter validation component.

A comparison of several metaheuristics using a benchmark function is shown in Weber, Boxnick and Dangelmaier 2014 (Weber, Boxnick and Dangelmaier 2014). The chosen metaheuristics was at first the particle swarm optimization (PSO) algorithm, similar to the algorithm from Kennedy and Eberhart (Kennedy and Eberhart 1995). The PSO algorithm offers necessary usability to configure in terms of search procedure within a large solution space.

One advantage of the PSO algorithm is the opportunity to extend the algorithm successfully to handle asynchronous, full-synchronous and semi-synchronous optimization processes in order to be prepared for stochastic node failures as well as distributed systems and resources (Reisch et al. 2015). In this way, the optimized parameter results can be evaluated by several computer resources simultaneously so that the simulation runs can be completed faster (Reisch et al. 2015).

Further tests and experiments using embedded PSO algorithms as part of a simulation-based optimization process to identify best workpiece position inside of the machine’s working area is shown in (Weber, Mueß and Dangelmaier 2015). Because of the high computational effort required in order to use a virtual tooling machine for simulation, and the increasing computing time and high numbers of simulation runs, a pre-processing approach was developed in order to estimate best setup areas for the workpiece considering NC-program commands (Weber, Mueß and Dangelmaier 2015). Instead of simulating the complete tooling machine, a replacement model is used which maps the machine workpiece area as well as tool change points and tool paths (Weber, Mueß and Dangelmaier 2015). It is shown that the targeted concept combining metaheuristics and machine simulation in the context of work preparation develops a meaningful system.

The implementation of the extended and configured PSO extension in combination with a so-called NC parser is shown in (Weber 2015) to minimize tool paths between work piece position and tool change point. The results verify the use case of the integration of a given NC parser as a pre-processing system tool to identify these workpiece positions, which leads to minimized machine and idle time in the NC-cycles. The advantages of using NC-parser for pre-processing is to rapidly determine the setup position based on NC-commands to reach minimized production time. But material removals, tool change duration and collision detection is not part of this system. This leads to the further development to combine the pre-processing with selection of best solution candidates (which determines setup position with minimized production duration) to validate these selected candidates by the full machine simulation.

The contributions (Mueß et al. 2015 and Laroque et al. 2016) deal with the development of the cluster-based PSO extension. The PSO and the NC parser determine time-efficient setup positions. The quantities of solution candidates are still high so the cluster algorithms detect solution candidates. The best solution candidates from each cluster are validated by the machine simulation, so the quantity of simulation runs should decrease. The presented contribution is associated with the further development and realization of the cluster based PSO extension embedded in the complete system using the full distributed tooling simulation.

Related to the usage of virtual tooling machines, the contribution of (Jönsson, Wall, and Broman 2005) deals with the development a real-time simulation of tooling machine (water jet cutting). The approach is more oriented on the machine development research. Also in the focus of development of simulation model for a description of near-real-world interactions between machine structure, control system and the cutting process is given by the contribution of (Lee et al. 2015). But these contributions offer no search procedures in order to determine production parameters to verify the production jobs.

The research project named *SimCAT* offered research activities in the area of simulation and integrated optimization of manufacturing processes (University of Karlsruhe 2006). Further it is described a bidirectional connection between a real NC-control and the simulation tool *Simulink* (*MathWorks, USA*). The dynamic behavior of the tooling machine and its travel-paths is embedded in a Finite-Element-Method-simulation. Furthermore the project offers research activities about the optimization of tool design. The focus of this research activities is more the improvement of the simulation of the behavior of the machine and the production processes. The determined parameters are fed into the development of tooling machines (University of Karlsruhe 2006).

Manufacturing parameter improvement such as accurately workpiece geometry considering machine defects and workpiece setup is shown in the contribution of (Martin, Dantan, and D'Acunto 2011). The shown study is focused on results reached by using a three-axis tooling machine. The machine and tool architecture is given by a numerical model that bases on kinematic models.

The following contributions are closer to the area of workpiece and clamp positions: In order to identify optimal fixture positions for workpiece and workpiece clamps there are several activities using simulation or mathematical models as well as metaheuristics. As sample there is the contribution of (Kaya 2006) that offers as solution the application of genetic algorithm. A further sample it a discrete elastic contact model to solve the fixture layout problem, shown by (Li, B. and Melkote 1999).

## 3 SETUP OPTIMIZER ARCHITECTURE AND SYSTEM DESCRIPTION

The setup optimizer is a sub-project in the total system. The framework is the cloud architecture and interfaces are web-based multi-user agents and databases. The complete system will be offered as a service platform. Other subsystems are the production optimizer and intelligent machine selection. The production optimizer contains a mathematical model of production for the planned production program which leads to an optimal time schedule, job order and lot size plan.

In combination with the planned machine occupation time, an intelligent machine selection is executed. The machine selection is an ontology-based knowledge management system which determines the most practical work space area and the matching tooling machine (Rehage and Gausemeier 2015). The virtual tooling machine is the base element for the setup configuration which is focused in this contribution by the setup optimizer in interaction with the simulation scheduler. The total system including interfaces is feasible as an embedded system in a cloud environment (Rehage et al. 2016). Figure 1 shows a schematic overview about the system.

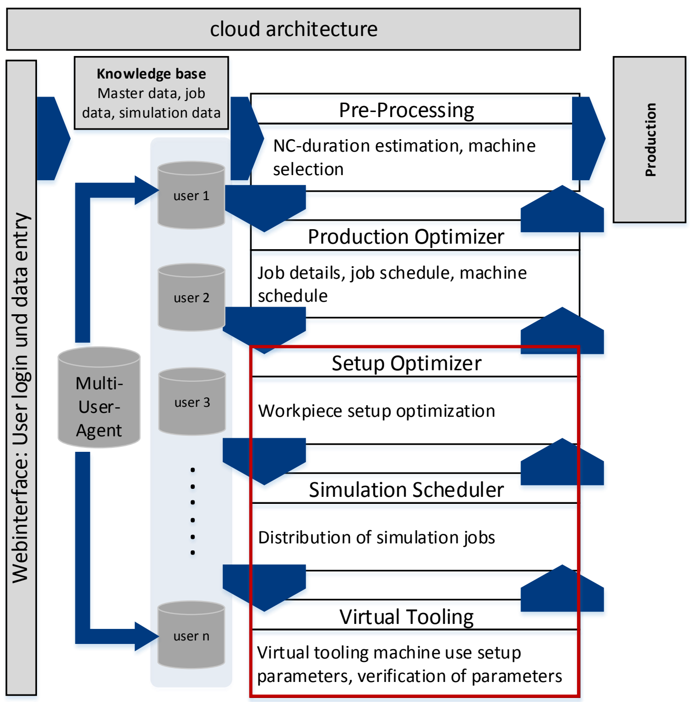



Figure 1: Schematic overview of the service platform.

In Figure 1, the focus of this contribution is marked in red. In order to provide optimal setup parameters for the workpiece position in the working area of tooling machine, the setup optimizer consists of an extended particle swarm algorithm which contains the opportunity to execute optimization jobs asynchronously (see Reisch et al. 2015). The PSO generates solution candidates that represent position coordinates of the workpiece on the machine table. The PSO algorithm is linked with the NC-parser as fitness component to identify the best position coordinates in terms of minimized NC-durations.

In order to exploit the rapid run time of the NC parsing process, unintentional collisions between workpiece, clamps or tools are ignored. The best solution candidates are further processed by the K-means cluster algorithm decreasing the number of computations required to find valid, esp. collision free, solutions. The number of clusters depends on the number of resources, such as the number of non-occupied simulation models represented by virtual tooling machines. The solution candidates from each cluster are sorted by the fitness value and there is the assumption that if the fitness value leads to valid position coordinates, the direct neighbor is also valid. If the best fitness candidate leads to an invalid parameter, total solution candidates of this cluster are also invalid. The best solution candidate of the cluster will be used and the simulation scheduler distributes the position coordinates to the virtual tooling machines instances. The virtual tooling machines will examine the solution candidates of the clusters if there are collisions. The valid parameters were given back to the database for future production processes.

In order to clarify the necessity of determining valid setup data for the tooling machine, Figure 2 shows two productions processes based on milling technology. The left one shows the workpiece and clamp before production process has begun. The middle one shows a workpiece destroyed after using disadvantageous setup parameters and the right one shows the valid process result. The results shown to the right in Figure 2 are sought by the system focus in this contribution including minimized production time. The results in Figure 2 are given by using the virtual tooling machine from the company named "DMG Mori AG" (Germany) and the workpiece is an example given by the company for show casing.

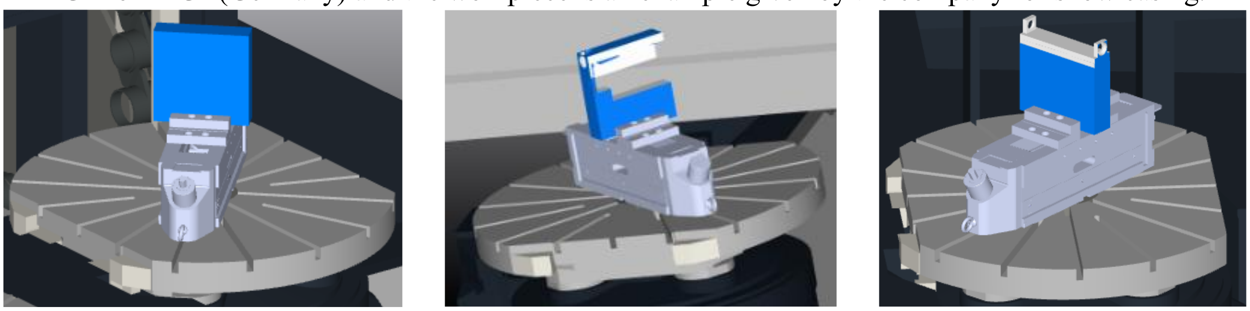


Figure 2: Raw material and workpiece after different setup parameters and production operations.

## 3.1 Technical Aspects

In order to define the positions in the workspace as potential solution candidates, a so called "position frame" is necessary which contains the coordinates information as well as orientation of the workpiece and clamps. The counterpart to setup the workpiece on the machine table, the docking frame is implemented. Docking frame and position frame are special information which are contained in the special data format so that the virtual tooling machine (simulation) recognize graphical information about tools, machine, workpieces and clamps to enable an exact 1:1-simulation of the production process. In detail, position frame and docking frame are 3-dimensional vectors representing coordinate systems such that the position frame exactly matches the docking frame. The total information data is a XML-based file format. The setup optimizer changes during the optimization process the position frame dataset of the workpiece and clamp and consequently the NC-program has been also adapted to new position and orientation information to avoid unintentional collisions of machine, tool and workpiece.

For that the setup optimizer read in the NC-data information and change the NC-commands to match the new production setup. Especially the point of origin of the workpiece as NC-program information has to be adapted for new workpiece setup. Table 1 shows an example of a workpiece position rotation and the impacts of the NC-program setup as well as position information changes. The rotation angle is 45 degree and the NC-Command are specified for the control unit developed by the company "Siemens AG" (Germany). Table 1 show on the right side the coordinates of the position of the virtual workpiece in the working area of the machine after and before a 45 degree rotation of the workpiece as setup session example. The left side explains the necessary cycle differences of the NC-program which are organized automatically by the setup optimizer. This example shows how the program change the NC-program when different setups are generated by the experimental design.

Table 1: Exemplary reconfiguration of position information and NC-commands after setup changes.

| **NC-program cycles before reconfiguration** | **Docking frame and zero point before reconfiguration** |
|---|---|
| N1240 CYCLE800(1,"TC1",0,27,100,0,-15,90,0,90,0,0,0,0)<br>…<br>N1380 CYCLE800(1,"TC1",0,27,-100,0,-15,-90,0,90,0,0,0,0) | …<br><PositionFrame rotationMatrix="1 0 0;0 1 0;0 0 1" translation="0 0 0" id="0" /><br>… |

| **NC-program after reconfiguration (45 degree workpiece rotation)** | **Docking frame and zero point after reconfiguration (45 degree workpiece rotation)** |
|---|---|
| N87 AROT Z45<br>…<br>…<br>N1240<br>CYCLE800(1,"TC1",0,27,70.7107,70.7107,<br>-15,135,0,90,0,0,0,0)<br>…<br>N1380 CYCLE800(1,"TC1",0,27,-70.7107,-70.7107,-15,-45,0,90,0,0,0,0) | …<br><PositionFrame<br>rotationMatrix="0.70710678118654779<br>-0.70710678118654724 0;0.70710678118654724<br>0.70710678118654779 0;0 0 1"<br>translation="5.74250757 0 -0.1" id="0" /><br>… |

## 4 EXPERIMENTS AND RESULTS

### 4.1 Experiments Using the Setup Optimizer to Determine Time Savings by Translational Workpiece Movements

In order to show the meaningfulness of the approach, several setup parameter of the workpiece position are tested. For that there are two experimental series: The first three experiments present the impacts of different setup positions using the tooling machine simulation (Cases I, II and III). The changed NC-program caused by the parameter variation is tested by the NC-parser in terms of the cutting time (machining time) and non-productive secondary machine time. Especially different setup angles (0 degree, 45 degree and 90 degree) to install the workpiece rotating on the machine table leads to time savings. The parameter values are chosen randomly to proof the theoretical aspects behind the total idea of this contribution.

The given tool change coordinates of the machine as well as implemented in the NC-parser environment is x = -228.972 mm, y = 0.0 mm, z = 200.00 mm, A = 0.0, B = 0.0. Three translation axis x, y and z and two rotational axis A and B are defined for a five-axis-milling machine as simulation model (virtual tooling). The results are shown in Table 2 and the workpiece orientation is illustrated in Figure 3 to support the discussion of the system and proof of concept. The time is measured in seconds by the NC-parser.

In order to investigate the potential of moving a given workpiece on the machine table translationally, we considered two NC-programs which differ in their machining time. These cases are numbered as IV, V, VI, VII, VIII, and IX. Based on the original program, we introduced in both cases additional tool changes so that cutting times remain constant whereas secondary times increase. The original version of NC-program 1 contains one tool which leads to a rather short secondary time of 15.402 seconds since very few travels to the tool change point are to be processed. NC-program 2 contains in its original version eleven tools showing a secondary time of 72.270 seconds. We set up settings with five and twelve tools for NC-program 1 and settings with 20 and 30 tools for NC-program 2. The underlying initial secondary times can be seen in Table 3 and Table 4. In order to find out which time savings may be achieved by moving a workpiece, we performed particle swarm optimization employing 20 particles and 50 generations on the NC parser.

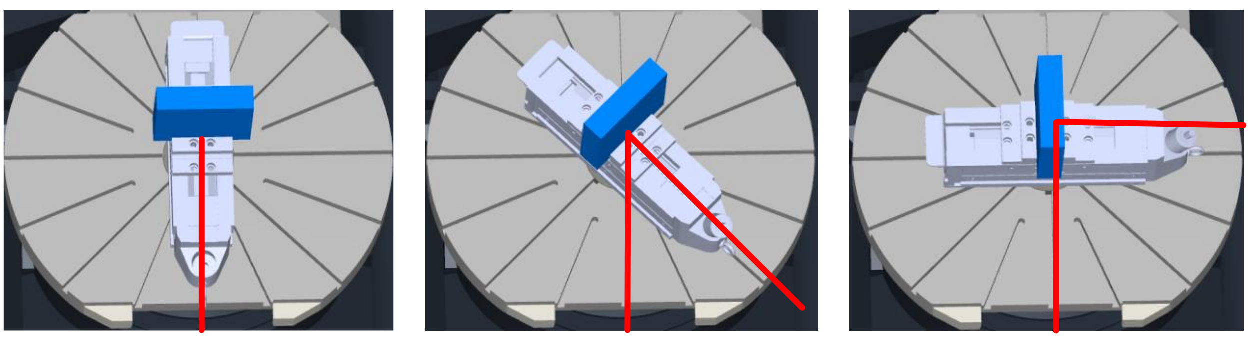
### 4.2 Experimental Results

The results in Table 2 show that case II, which means the rotation of 45 degrees leads to time savings for the cutting time as well as total production time. Compared to the initialized status of the standard workpiece setup (case I). In comparison to case III, the total production time is 0.65 % lower, but the cutting time determines a contrasting development (2.98% higher). That means, the setup position has definitely influence on cutting time as well as secondary time containing tool changes. The secondary time declines in case III by 26.79 %. The setup workpiece position treated in case III determines unintentional collision (see Figure 1 middle) that would damage tool and workpiece which means that this setup will be dropped. In total comparison of the use cases, case II is the promising result.

Table 2: Results of the comparison of three setup positions of the workpiece.

| | **Case I: 0 degree workpiece setup position (initialized status), NC-program 1** | **Case II: 45 degrees workpiece setup position, NC-program 1** | **Case III: 90 degrees workpiece setup position, NC-program 1** |
|---|---|---|---|
| Total time [s]: | 134.299 | 125.115 | 124.292 |
| Cutting time [s]: | 118.897 | 109.803 | 113.082 |
| Secondary time [s]: | 15.402 | 15.312 | 11.210 |
| Collision status [-]: | No collisions | No collisions | Collisions and tool damage |
| Time savings: | No savings compared to case II and III | 7,65% cutting time savings and 6.8% total time savings compared to case I. | 0,65% total time savings and 26.79% secondary time savings compared to case II. 2.98% cutting time lost compared to case II. |

Figure 3 shows the orientation of the workpiece fixed in the clamp of the Case I, II and III including the different orientation angles (see red marked line).



Case I: 0 degree Case II: 45 degrees Case III: 90 degrees

Figure 3: Variation of workpiece setup orientation.

Table 3 features the results of the explained experiments considering NC-program 1. Obviously, introducing random tool changes within the NC-program does not change the cutting time. Moreover, the cutting time remains the same by optimizing the position of a workpiece. Thus, contrary to rotational movements on the table, translational changes of a workpiece are just capable for minimizing the secondary time. For this reason, one achieves only an improvement of about 1.7 % considering case IV where one tool is used because on the secondary time makes just 11.5 % of the total time. As the cutting time remains the same irrespective of the number of employed tools, introducing tool changes increases the amount of secondary time. Hence, translational movements of a workpiece become more significant. This can be seen in case V where an improvement of 4.2 % is achieved and in case VI where even 7.3 % time saving is observed.

Table 3: Results of Optimizing Workpiece Position (NC-program 1).

| | **Case IV: Initial NC-Program: 1 tool** | **Case V: NC-program 1 with 5 tools** | **Case VI: NC-program 1 with 12 tools** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Initial Total time [s]: | 134.299 | 161.779 | 211.410 |
| Initial Cutting time [s]: | 118.897 | 118.897 | 118.897 |
| Initial Secondary time [s]: | 15.402 | 42.882 | 92.513 |
| Best Total time [s]: | 131.099 | 155.181 | 197.019 |
| Best Cutting time [s]: | 118.897 | 118.897 | 118.897 |
| Best Secondary time [s]: | 12.202 | 36.284 | 78.122 |

The results presented in Table 4 match with the observations of the previous experiments. In case VII, the secondary time makes about 2% of the total time. Thus, only an improvement of 0.2% is reached by optimizing the position of the workpiece. Considering 20 tools, where 3.7% of the total time is secondary time, 0.6% time saving is observed optimizing the positions. In the third case where 30 tools are employed, the optimization leads to a time saving of 1.7%. Here, the secondary time makes 5.5% of the total machining time.

Table 4: Results of Optimizing Workpiece Position (NC-program 2).

| | **Case VII: Initial NC-Program: 11 tools** | **Case VIII: NC-program 2 with 20 tools** | **Case IX: NC-program 2 with 30 tools** |
|---|---|---|---|
| Initial Total time [s]: | 3588.517 | 3651.431 | 3721.277 |
| Initial Cutting time [s]: | 3516.247 | 3516.247 | 3516.247 |
| Initial Secondary time [s]: | 72.270 | 135.116 | 205.030 |
| Best Total time [s]: | 3578.047 | 3629.320 | 3658.689 |
| Best Cutting time [s]: | 3516.247 | 3516.247 | 3516.247 |
| Best Secondary time [s]: | 61.800 | 113.074 | 169.442 |

These results show clearly that translational changes of a workpiece are capable for reducing secondary machining times because travels between a workpiece and the tool change point are saved. The cutting time is not changed by any movement of the workpiece on a machine table. Figure 4 gives an overview about the total comparison of the performed experiments.

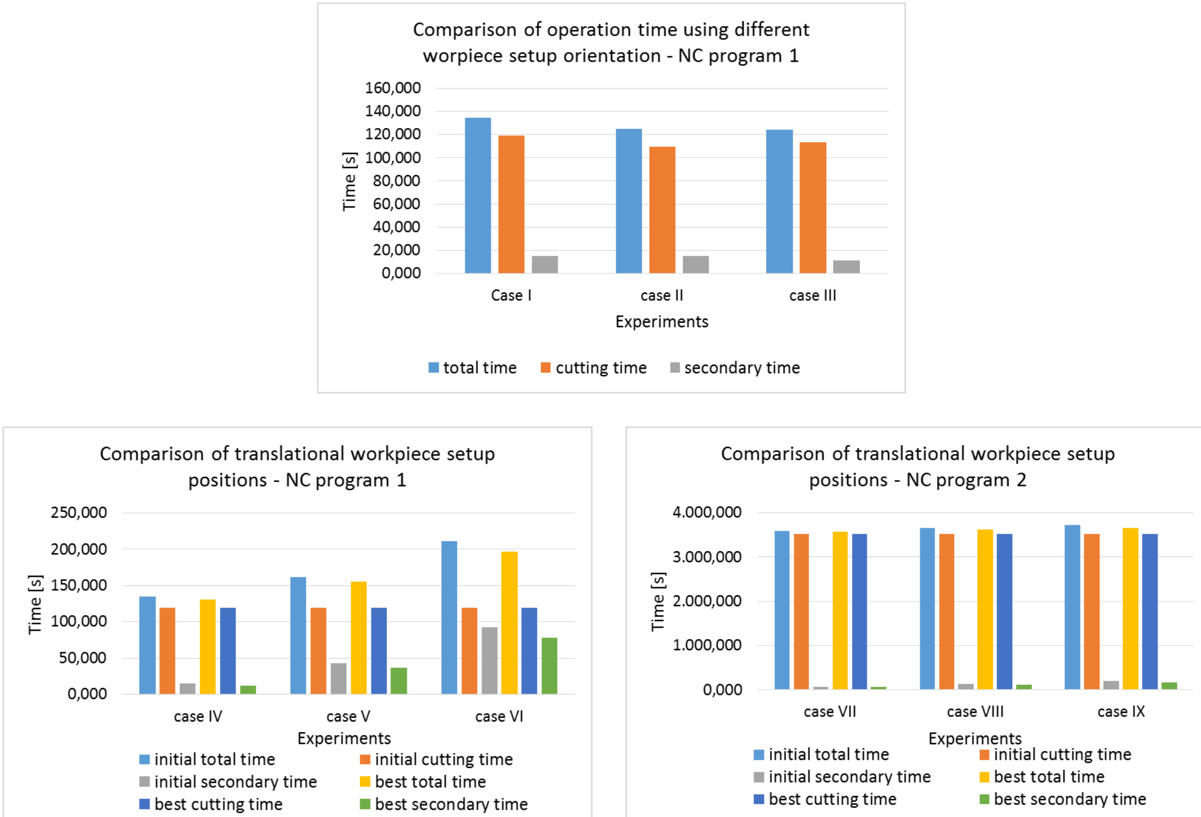



Figure 4: Overview about the comparison of the experiments from case I to case IX.

## 5 CONCLUSION AND OUTLOOK

This contribution underlined the potential of setup optimization in tooling machines based on exact simulation. We showed for a special case that workpiece rotations are capable for reducing the cutting time of milling machines significantly. Moreover, secondary time can be saved by changing the workpiece position translationally which becomes crucial if many tool changes occur in an NC-program. Based on the presented results more possibilities of optimizing NC machining are to be investigated. For that, it is planned to introduce initial tilt movements in order to take advantage of different axis velocities in an optimal way. Contrary to this contribution where just machining time is optimized, it is planned to consider further key figures like build size and energy consumption. Additionally, more experiments considering different machine models are needed in order to prove the generality of the show results.

Furthermore, it is planned to develop a program which is able to adjust the NC-program when improved workpiece setup positions are reached. In order to prevent unintentional collisions there are opportunities to accept more disadvantageous production times mixed by cutting and secondary time when setting specified calculated rotational and translational shifts of the workpiece. The simulation model of the tooling machine will evaluate automatically these rotational and translational positions.

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