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Manufacturing System Design with Virtual Factory Tools

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During the analysis and design of manufacturing systems, companies are challenged by existing restrictions and the running production. To deal with these key issues, different virtual factory approaches and tools have been widely implemented in recent years. By employing modern approaches and tools, a manufacturing system can be adapted effectively as changes occur. Virtual Reality (VR), one of the most important approaches, is now applied to the scientific and the industrial fields. Current studies of VR applications are mainly focusing on the design of products, but not manufacturing systems. This paper presents VR as an innovative and collaborative design platform for manufacturing systems, which enables a holistic use of virtual factory tools. Based on this platform, three applications have been implemented, which are addressed at different levels of a manufacturing system. Furthermore, the noise simulation and the virtual machining have been visualized in a Cave Automatic Virtual Environment (CAVE).

Keywords: Virtual Reality, Manufacturing System, Virtual Factory Tools, CAVE, Visualization

Subject classification codes: include these here if the journal requires them

1. Introduction

Customer demands as well as legal requirements are changing in a rapid manner. Facing these challenges requires a fast and systematic method to adjust production systems (Schönsleben 2009). In the context of worldwide competition, the productions of innovative and low-cost products, within an appropriate manufacturing system, are becoming a crucial part in the product life cycle. As one of the virtual factory tools, Virtual Reality (VR) takes a significant role as it deals with definition, modelling and validation of manufacturing systems (Smith and Heim 1999).

Changes in a manufacturing system occur at several levels and in different domains. An adaption in one section often influences several others. The total number of new designed factories is declining in both developed and developing countries. Therefore, to adapt established manufacturing systems is more important now due to the increasing changed requirements (Kühn 2006).

Considering this scenario, a systematic planning of necessary changes in a manufacturing system is essential for two major reasons. One, the impacts of changes in an established manufacturing system has to be analysed and rated in a holistic manner. Downtime in factories should be prevented. Two, the efficiency of analysing and planning has to be improved to cover the increasing change demands. In order to meet these challenges, the virtual factory has considerable potential to meet the every changing demand.

This paper is organized as follows. The VR framework is introduced after discussing related work. Then, three virtual factory tools are presented, which cover different application fields in the range of manufacturing system design and improvement. A use case shows a combination of sound simulation and planning of engineering changes (ECs). Two applications are visualized in a Cave Automatic Virtual Environment (CAVE). The last section concludes the paper and provides an outlook.

2. Related Work

2.1 Description of a Manufacturing System

Today’s production is a networked process, in which more production units are included, so that a comprehensive investigation of the manufacturing system is necessary. Depending on the chosen views on a manufacturing system, the associated problems vary. To focus each of these different problems, the whole manufacturing system is divided into several hierarchical levels (Wiendahl *et al.* 2010).

According to the cluster and classification of the major production units, six production levels are identified and scaled in a top-down fashion. In Figure 1, they are shown as production network, production location, production segment, production system, production cells, and workstation (Westkämper and Hummel 2009). Not all levels are considered in this paper, only levels four through six are taken into account. The production system level consists of production cells as elements. Several machines and workstations can be clustered as production cells. The interaction among those levels and their elements are taken into account. At the workstation-level, for example, the interaction among machining processes and tools is a point of interest.

2.2 Definition of the Virtual Factory

Based on common understanding, the digital factory is a data- and information-centred method, but a virtual factory is constructed by using computer generated models. In this paper, the term virtual factory covers both meanings. It is defined as a virtual environment, which contains geometric models of factories, machines, and humans. In addition, measurements, simulation, visualization, VR, evaluation, data management, etc. are included as well. The modelling of a manufacturing system enables further simulation and visualization. Machining operations, assembly processes, and material flows for example are based on a consistent database (Weimer *et al.* 2008).

Broad virtual factory implementations of product design, factory layout design, and production processes are discussed by many authors (Zhong and Shirinzadeh 2005, Zhai *et al.* 2006, Cecil and Kanchanapiboon 2007). However, a holistic view upon manufacturing systems is not provided by using virtual factory tools. Different levels of manufacturing system represented in prior section are addressed by using virtual factory in this paper.

2.3. Current Use of VR

According to Chawla and Banerjee (2001), a virtual environment "provides a framework for representing a facility layout in 3D, which encapsulates the static and the dynamic behaviour of the manufacturing system."

A direct link of simulations to an immersive, virtual environment, allowing user interaction and changes during simulation processes, offers high potential for exploring complex interactions between users, objects, and operations (Dorozhkin *et al.* 2010). Therefore, VR is a reliable platform for several virtual factory tools and suitable to support a wide range of applications. They are, for example, production planning, product design, and the technical qualification of employees (*Oliveira et al.* 2007). Cecil and Kanchanapiboon (2007) decompose the software applications in the field of manufacturing system into three sub-areas:

- factory-level prototyping
- virtual assembly environments
- virtual prototyping of lower-level activities

At the factory-level, VR is used in the majority of the applications to support modification and simulation of existing shop floors or to improve the design of new layouts (Kesavadas and Ernzer 1999). A well-designed layout is the basis on which idle time and bottlenecks in a manufacturing system can be prevented. Improving the parts flow through a shop floor or a factory is another key issue, which can be solved by using those measures (Cecil and Kanchanapiboon 2007).

At the workplace-level, VR is used to analyse single cells or more assembly processes within a workstation (Chryssolouris *et al.* 2000). According the related problems occurring in a physical assembly situation, the comparison of several virtual approaches leads to suitable benchmarks. By identifying constraints and oblique problems in early design stages, other possibilities can be improved (Sharma *et al.* 1997).

In lower-level manufacturing processes, simulations and software tools like CAD/CAM are widely distributed in industry today. But just a few of them can be simulated properly in a virtual environment (Cecil and Kachanapiboon 2007).

3. A VR Framework for Manufacturing System Design

In this chapter a VR framework is introduced which is illustrated and divided into three main phases: modelling, application, and adaption (see Figure 2). In the modelling phase, the acquired necessary data is described as models, e.g., a geometric model or a mathematical model. In simulation phase, the processes and interactions in real manufacturing are simulated. It provides the information for the following adaption phase. This framework achieves to facilitate the virtual factory tools for manufacturing system design and enables an integrated use of them in a virtual environment.

3.1. Modelling

In the modelling phase, a data basis is prepared considering further use. Usually it starts with geometric and mathematical modelling. Then a VR model is generated. During geometric modelling, different objects in a manufacturing system are considered, such as the machines, person, parts, transports, materials etc. Due to the large data volume, several levels of detail (LOD) are used in order to depict the objects according to the top-down approach. For example, in the engineering change application, the LOD is kept at the production cell level and the parts, cutting tools or work pieces are not taken into account. Mathematical modelling provides then the description of processes, for example, the algorithms to calculate material flows.

Furthermore, additional information from the manufacturing system is described and integrated into the completed geometric/mathematical models as a comprehensive VR model. By using different VR platforms, this VR model is visualized and manipulated. This set-up defines a so-called virtual environment, in which the different applications are implemented. This environment enables the interaction between users and virtual objects as well.

3.2. Application

In an application phase, two main components should be included: simulation and visualization. Simulation is the kernel of the whole work flow. Based on the modelled virtual world, it rebuilds the manufacturing processes and provides essential information for visualization and VR. Users are able to obtain more realistic perception in a virtual environment. In other words, the simulation gives a virtual model "life."

Due to the complexity of the processes in manufacturing systems, the information obtained from the tools mentioned above is also complex. They are not intuitive and are difficult to understand. Visualization makes the viewing and analysing of complex data in VR easier. Users are allowed to find the useful information for customized needs and are able to use them more efficiently. Therefore, visualization is a key method supporting analysts to verify models, understand simulation results and communicate them to non-technical audience.

3.3. Adaption

According to the analysis results from applications, the manufacturing system will be adapted. A VR-supported Continuous Improvement Process (CIP) workshop is used to implement such adaption. An application-related discussion of this method is not provided in this paper. Figure 3 shows this method. For more details we refer to Aurich *et al.* (2009).

The workflow in Figure 3 starts with a data entry, which includes essential production and process data for generating an appropriate virtual environment. Not only available geometric models of machines and facilities, but also the simulation results, measurement data or other manufacturing data are integrated. Within the virtual environment a CIP workshop is performed in five steps: 1) detection of problems, 2) analysing selected problems, 3) developing improvement measures, 4) realizing the measures with workers, and 5) evaluating the results. Following the successful implementation of the workshop the results are immediately transferred to enable the realization of these improvements in a physical production environment.

4. Implementation

In this chapter, three applications are introduced, which are addressed at different levels of manufacturing systems. All these applications have been implemented by using the introduced framework. The modelling level is generally introduced and shows fewer differences among these applications. At the application level, different simulations and visualizations have been implemented to achieve different objectives.

4.1 Modelling

The modelling level consists of geometric modelling and modelling of the manufacturing system. A standardized procedure for creating VR models is proposed to provide a basic prerequisite for the efficient reuse via databases. To identify the appropriate objects out of the database, the objects must have a comparable and standardized structure. This common structure is granted by a detailed process model which consists in general of two steps: the geometric modelling and the matching of additional information.

The geometric modelling describes, for example, the shapes, materials and textures for objects in virtual environments, which includes the room, the machines, the transport and the support elements etc. Thereby, a virtual environment is always a composition of different objects. Some objects are often recurring during several planning cycles. To facilitate the creating of virtual environments and to avoid doubling work, these standard objects are saved in one database. From this database, objects can be extracted to be reused in different processes of manufacturing system design.

By using modelling software “3ds Max®”, the numbers of polygons at the CAD objects are optimized for the balance of visual effect and computing performance (see Figure 4). Not all of the objects are modelled directly in this paper, for example, the indexable insert and the insert holder are provided by the manufacturer in order to ensure a high level of detail.

Additionally, the modelling of manufacturing systems provides a database for information of objects as well as the interrelationships between them. Such data contains for example machine object features, layout information, or dynamic process information. Hence, the standardized procedure is based on default classes to describe object attributes in a common way. By following these rules, a complete and comparable description of the model attributes can be provided without overlooking some input information.

These models are finally integrated together into a VR model and exported using the Virtual Reality Modeling Language (VRML) standard or OBJ format. In case of VRML standard, a VRML editor such as VrmlPad is used to construct sensors, events or other interactions in a VRML file. At the same time, Java and JavaScript are embedded into VRML. Java 3D is used to manipulate the OBJ file. As result, it enables the modification of geometry, interactive user interface, performing a simulation and building data interfaces. After these steps, the data for simulation and visualization is prepared.

4.2 Application

To discuss different issues in manufacturing systems, three applications are shown in this chapter. They are noise investigation, engineering change management and a virtual cutting tool with chip formation simulation. All of them are based on the same geometric model and use customized data from simulation, measurement or theory.

Although these three applications are based on the same geometric model, they face different aspects of a manufacturing system. In correspondence to the description of a manufacturing system, each application is directly assigned to a specific production level shown in Figure 5. The exchange of results and parameters between the applications and also between the production levels is granted by that framework.

4.2.1 Sound Simulation

Noise from machining processes influences employees' health and it often can cause serious diseases. It became one of the most frequent occupational hazards in manufacturing. To ensure the health and safety of the employees in a factory, there are existing laws and guidelines. For example, in Germany, the Federal Ministry of Labor and Social Affairs (BMAS) limits noise and vibration levels within Germany's Occupational Safety Law (Arbeitssicherheitsgesetz-ASiG), German ordinance (LärmVibrationsArbSchV) and other additional legal guidelines, see Yang *et al.* (2010).

This application investigates the noise issue in industry and is using a simulation as well as VR-supported method. The visualization of simulation results and enhanced analysis capabilities in VR provide a new point of view to understand this issue and fill the requirements of noise control/reduction during factory planning.

In order to determine the influence of noise, acoustic simulations have been implemented. Different numerical simulation methods based on solving wave equations using a Finite Element Methods (FEM) and a Finite Difference Time Domain (FDTD) approach are discussed and compared by Deines (2008). A geometric approach called Phonon Mapping was developed by Deines, which has been implemented for this application.

Figure 6 shows the structure of this sound simulation tool. The simulation kernel acts as a server, loading the model of the room geometry and generating user interface elements. The resulting VRML code is delivered to the VRML compliant VR platform via HTTP. The server implementation is done by using C++ and Qt®. Qt® supports a simple graphical user interface for starting the server on selected network ports and generating an initial VRML file, which has to be opened by the VRML viewer application. At the same time, Qt® provides a simple interface for managing network sockets which is a basis for an HTTP connection.

Once the system has been started, the server loads a VRML model file and adds additional interactive user interface elements as VRML code. Buttons and sliders have been implemented using VRML and JavaScript. Their visual appearance is modelled using simple VRML geometry and saved as prototype nodes for repeated use. The button geometry is connected to a "TouchSensor" and the sliders to a "PlaneSensor". These sensors release events which are routed to Script nodes containing simple interaction logic written in JavaScript. Commands are sent back to the server by loading a special URL which encodes the action. The simulation is calculated by the server and delivered to the viewer again. This communication is done via HTTP connections. The viewer opens a new connection using an HTTP request asking for a file encoding commands in the filename. The server does its calculation and answers with a new VRML file delivered by this existing HTTP connection.

The simulation and visualization is implemented first using the VRML Viewer “Instant Player” and “Cortona3D Viewer”, which enables the user to navigate and manipulate a VRML-based scene graph in a desktop-based workstation. In Figure 7, two control modules are shown. The left side shows the module for sound source placing and simulation starting/stopping. After loading the geometric model into the VRML viewer, the user can explore the room and place the sound source within the viewer application and start the acoustic simulation. In the right module, one or more listeners (employees) are placed in the explored room according to predefined operation positions. After those settings, the phonon collection step can be performed, which calculates the sound levels at each specified position.

When the simulation step is done, the sound propagation inside the room is visualized by animated phonon paths (see Figure 8). The playback speed can be adjusted using the “++” and “--” buttons, and the current simulation time step can be selected by a slider (see Figure 7).

The phonon collection method calculates the sound levels at the listener positions and enables users to view the results interactively. Figure 9 shows the sound levels at different operator positions. The virtual workers are shown with corresponding colours according to the sound pressure level: green for low sound pressure levels < 80 decibels (dB), yellow/orange for critical sound pressure levels < 84 dB and red when the sound pressure level is too high according to the standard. The simulation and visualization improved the understanding of noise in the environment significantly.

4.2.2 Engineering Change

Companies have to constantly adapt their manufacturing systems. The numbers of ECs which are necessary to manufacture new products and to increase productivity are increasing. A VR-supported method is developed to validate EC analysis and design.

Geometric modelling and manufacturing system modelling, showed in chapter 4.1, are used in this application as well. An additional modelled solution database provides basic algorithms for planners to generate project plans. The solution database is directly linked to the application; by this the access to the knowledge management out of the VR environment is granted.

This application can be performed easily with different hardware platforms and the standard Java library. From Desktop based systems up to an immersive CAVE is the visualization by several output devices possible. A graphic user interface is divided into four fields, which are marked from “A” to “D” in Figure 10. The panel A enables system controls and project configurations. The user can manage files, generate new EC projects or input additional information for changed process chains. Within panel B, users are able to view the static and dynamic information of objects, layouts as well as interrelationships among them. The C panel is an evaluation area for EC results according to different criteria, such as completeness and production bottlenecks. A 3D view of the layout is shown in window D. Besides the basic functions, such as view and navigation, more functions have been implemented by using Java 3D classes. Users are allowed to select, move, add and delete objects.

A 3D visualization of current manufacturing systems provides an understanding and panoramic view for users. Via interaction, the users can access and view objects information directly and change the manufacturing system directly in this 3D virtual environment. After performing changes, the resulting impacts including suggested solutions of ECs are visualized to the user immediately. This application is connected to a manufacturing system database, which contains necessary object attributes such as machine size, facility layouts, and material flows. The database is realized as an object library which contains information out of several areas from the manufacturing system and bundles them. All relevant information is illustrated on the user interface and can be modified directly.

The tasks to realize various ECs are predefined and stored in a solution database. Expert knowledge and lessons learned from previous ECs are accumulated to support planners. From the 3D environment, users can access this database and view recommended solutions. Using a simplified user interface, the experienced planners and experts can supplement and improve the solutions continuously. The process chains are visualized as well. The ECs, processed by users, affect changes of these process chains. Based on the cycle times, estimated by planners, this program calculates the effects on the process chains.

The evaluation panel provides planners direct feedback by estimating the impact of changes related to cycle time and costs of the underlying process chains. As an expeditious measure the application enables the planner to rate the impact of ECs on MS in a qualitative but also comprehensive manner. Additionally, the completeness of ECs is proved and the required operations are illustrated. The visualization of machine capacities helps planners to allocate the resources and gives them a reminder when machine capacities are exceeded. After changes have been made, the new requirements considering the machines and the layout are illustrated to planners as well. Eventually, this application generates project plans for the realization from the solution database automatically.

Using this application can accelerate analysing and planning of ECs in manufacturing systems and increase the quality of the process at the same time. It reduces inconsistent planning of ECs and hence the necessity of reconfiguring ECs.

Finally, it allows one to make an informed and transparent decision comparing different options. For details we refer Malak *et al.* (2011).

4.2.3 Virtual Machining

VR allows an animation of machining operations as well. The machining kinematics and part geometries are allocated prevalently to VR using VRML. In order to animate the machining process closely to a realistic one, the chip formation process needs to be visualized as well. This application presents the animation of external cylindrical turning considering the chip formation and the results of the machining operation, such as process forces.

The chips are described numerically using JavaScript which is embedded into the VRML. The chip form is determined using equations to calculate the chip side-curl radius (Nakayama and Arai 1990), the chip up-curl radius (Li and Rong 1999), and the radius of the spiral chips (Nakayama and Arai 1992). In addition to these specific values, the chip lengths are required. They are determined experimentally. For details about these parameter determinations we refer Yang *et al.* (2011).

Besides the chip form, the animation of chip formation also requires the determination of chip flow, and consequently the chip flow angle. The chip flow angle specifies the angle between the tangent to the chip flow direction and the surface of the machined work piece. According to Colwell (1954), the chip flow angle is influenced by the cutting condition and the corner radius of the indexable insert. The chip flow angles are calculated regarding to these factors of influence.

In order to display the results of the machining operation, such as tool wear, energy consumption and surface roughness, the JavaScript accesses additionally an experimentally generated database. Figure 11 shows the graphic user interface performed in the VRML viewer, which consists of four function panels which are labelled from A to D.

The orthogonal process forces, the roughness of the machined work piece, the energy need of the machine tool during chip removal and tool wear are shown on panel A regarding pre-set cutting conditions. The process forces are displayed numerically, and tool wear, surface roughness as well as energy consumption are evaluated using the coloured scales “low,” “ordinary” and “high.” Figure 12 illustrates the process results during the animation of turning using two different cutting conditions: left feed f1 = 0.3 millimetres per revolution (mm/rev), depth of cut ap1 = 2 mm, cutting speed vc1 = 175 metres per minute (m/min) and right f2 = 0.1 mm/rev, ap2 = 1.5 mm and vc2 = 175 m/min. The length and the diameter of the work piece as well as the feed travel are determined through Panel B. The cutting conditions are defined using Panel C. Panel D offers a system control. With the system control the user can select different points of view.

This application focuses on the animation of chip formation during machining. The real-time-animated and the experimentally observed chip formations as well as chip flow are illustrated in Figure 13. The chip formation during turning is recorded by using a high-speed camera.

Slight differences are observed between the VR animation and the real cutting process, which can be attributed mainly to the various assumptions of the equations used to describe the chip formation process. Nevertheless, the benefit of this application for the virtual training and learning is significant.

5. Use Case

For a better understanding, the applications of sound simulation and the EC software tool are demonstrated by a use case. The functionality and the benefits are discussed in detail in this chapter.

5.1 Initial Situation

For the demonstration of the software tools, the FBK mechanical engineering laboratory, in which gears for the agricultural industry are produced, is rebuilt as a 3D model. It consists of different machine tools, facilities, and other supporting objects as for example an area for CIP workshops. To demonstrate the software tools, the use case focuses the shaft manufacturing process chain. It consists of three processes turning, milling and grinding. The underlying layout with machine tools and the process chain (from 1 to 3) are shown in Figure 14.

The lathes have a low reliability and are not able to cover the increasing production volume. CNC-programming is not supported by these lathes. Therefore the set-up time is very long. In order to solve the identified bottleneck, the lathes should be replaced by a new CNC turning machine. For the machine replacement, the EC software tool is applied. Due to the need of communication in the area of CIP workshops, the noise level has to be considered. Therefore, the sound simulation tool is applied for the different positions of the CNC turning machine.

5.2 Application

For the replacement of the lathes, three positions of the CNC turning machine are considered and planned with the EC software tool. The three alternative positions are illustrated in Figure 15. Due to the CIP workshop area, the predicted noise level of the solution has to be taken into account.

With the EC software tool the lathes are removed from the 3D environment. By using libraries, a new CNC turning machine is loaded into the 3D environment and can be moved by the keyboard to the intended position. The required workspace is linked with the object and can be changed by the planner. Conflicts of workspaces are illustrated automatically as red. The red area switches automatically green if there is no conflict. The functions are illustrated in Figure 16. Distances between machines and required supply systems as electricity, water or pressurized air are illustrated as well in the interface of the system.

When removing the lathes, the EC software tool identifies the manufacturing processes automatically which cannot be executed anymore. It gives the advice which manufacturing processes have to be reconnected. When inserting the new CNC turning machine, manufacturing processes can be connected to the machine. After that, estimated times for the added manufacturing processes can be inserted and the cycle times and manufacturing costs are calculated based on the inserted times. Alternative projects can be loaded in order to compare them with the current solution. The functions are illustrated in Figure 17.

From manufacturing process point of view, there are no essential differences among EC 1, 2 and 3. In order to minimize the sound level in the area of CIP workshops, the sound levels of the three ECs are simulated and visualized by using colour scaling. The results are shown in Figure 18. Person number 2 is located in the area of CIP workshops. According to the simulation results, EC number 2 is the preferred solution, because the Person 2 is exposed to lowest sound level of 72 dB.

Based on EC number 2, the EC software tool generates detailed plans for the implementation automatically (see Figure 19). Those plans consist of detailed information, e.g., task descriptions, required resources, duration, costs, risk, counter measures, etc.

After the EC implementation, the software generated implementation plan can be analysed and evaluated. Based on this evaluation, inaccurate and incomplete task descriptions can be identified. These inaccurately and incompletely described tasks are adapted to the solution database continuously.

5.3 Results

By using prior use case, the essential functionalities and benefits of the developed software tools are demonstrated. The EC process is integrated in the software tool and enables straightforward usage and applications. Through this integration, the model of the digital factory is adapted automatically by applying the EC software tool. Using an interactive user interface, the users are able to navigate, explore, and analyse a virtual manufacturing system.

The ECs can be planned and analysed together with EC and sound simulation software tool. Through the combined method it is possible to compare different alternatives, such as the EC 1, 2 and 3 in the use case. This gives the planner a holistic view of the EC impacts in a manufacturing system. This use case shows the importance of sound level evaluation for areas that require a low sound level.

6. Implementation in CAVE

In this chapter the hardware and software configurations of the CAVE system are briefly introduced. Using this system two of the applications described earlier in chapter 4.2 have been implemented.

6.1 CAVE System Description

The CAVE system located at the FBK institute, University of Kaiserslautern, is a visualization system, which is constructed by using different hardware technologies and software solutions. Figure 20 shows a few hardware components of the CAVE set-up. Eight projectors (Figure 20a), projecting on four walls, offer an immersive virtual environment of more than 17m^3. Passive stereo technology with circular polarization is used for stereoscopic rendering of the 3D scene. The system is operated by a VR cluster, which contains eight clients and one server. Four IR-cameras are part of a user tracking system (Figure 20c). The user interacts with the virtual environment via different input devices such as a fly stick shown in Figure 20b.

The COVISE Collaborative Visualization and Simulation Environment (COVISE) and the Virtual Reality User Interface (VRUI) are used as software platform, due to their wide range of hardware support and the broad spectrum of different functionality modules. Both of them enable an easy integration of different modules as well as visualization functionality. For more details about COVISE and VRUI we refer to Lang and Wössner (2004) as well as Kreylos *et al.* (2006).

6.2 Visualization in CAVE

The visualization in a CAVE system enables the users an improved understanding and a better perception of manufacturing system design. The results of sound propagation simulation and sound levels evaluation are represented in an immersive environment, which enhances identifying possible noise problems in a manufacturing system and facilitates determining improvement methods.

Figure 21 shows a user exploring the virtual factory in CAVE and simulating the sound to analyse the workstation or layout planning. Using fly stick, the users are able to investigate a virtual environment much easier than using mouse and keyboard in front of a desktop display. The scales of the virtual employees are adapted according to real person, so that the users have a strong perception as in a real factory environment.

In Figure 22, an animation of cutting process is visualized in the CAVE. One of the advantages of immersive animation is the free choice of viewpoints. Users are allowed to navigate to any interesting and relevant investigation points. Different aspects can be analysed specifically. Another advantage in this case is the fact, that the full immersive environment with user tracking system improves the result of the virtual operation training.

7. Conclusions

In this paper we have presented an approach to support analysis and design of manufacturing systems at their different levels. The combination of various tools and the integrated use of them enable the study of a holistic application scenario.

Changes to a manufacturing system can be applied to it virtually in order to minimize impacts on the real manufacturing system. It improves the planning quality, accelerates the planning velocity and avoids production shutdowns.

Future research will focus on implementation of more applications in order to improve the design of a whole manufacturing system. Additionally, the interrelationships between different levels will be taken into account. Further research is required to enable a cooperative application of these tools and to consider the interactions between employees and manufacturing systems.

Besides the networking of existing tools, the development of further applications will be pursued. The three introduced tools serve as examples of the framework. More highly adapted applications will be implemented and close the gaps in the digital support of manufacturing system design. The implementation of all those applications in VR as a joint and scalable set of methods will be advanced.

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Figure 1: Production levels in a manufacturing system. Adapted from Westkämper and Hummel (2009).

Figure 2: Workflow of the VR framework.

Figure 3: Procedures of VR-based CIP workshop.

Figure 4: Geometric modelling.

Figure 5: Correlations between applications and between production levels.

Figure 6: Structure of the sound simulation tool.

Figure 7: Simulation control using VRML viewer.

Figure 8: Visualization of the sound propagation.

Figure 9: Evaluation of sound levels at different positions.

Figure 10: Graphic user interface of the EC software tool.

Figure 11: User interface of the virtual machining tool.

Figure 12: Process display at different cutting conditions.

Figure 13: The chip formation in VR vs. the chip formation during real cutting.

Figure 14: The initial situation of use case.

Figure 15: Initial situation and alternative placements of CNC turning machine.

Figure 16: Removing, loading, and moving objects.

Figure 17: The completeness check, comparison of alternative projects, and inserting planned time.

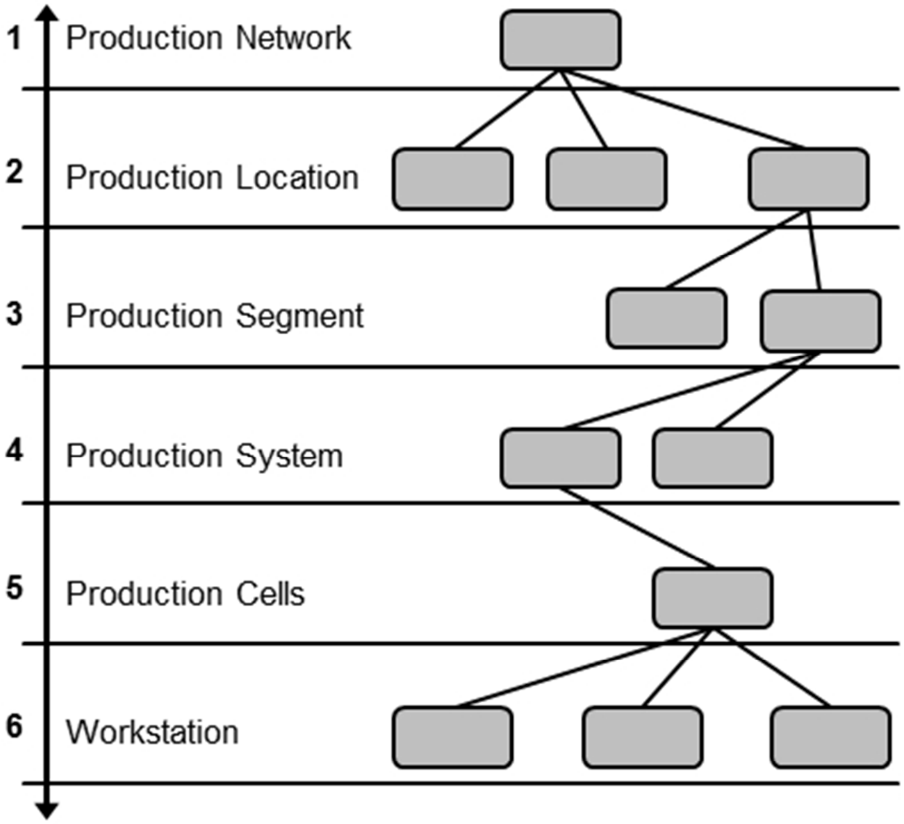
Figure 18: Different results of sound simulation.

Figure 19: Generating implementation plans for ECs.

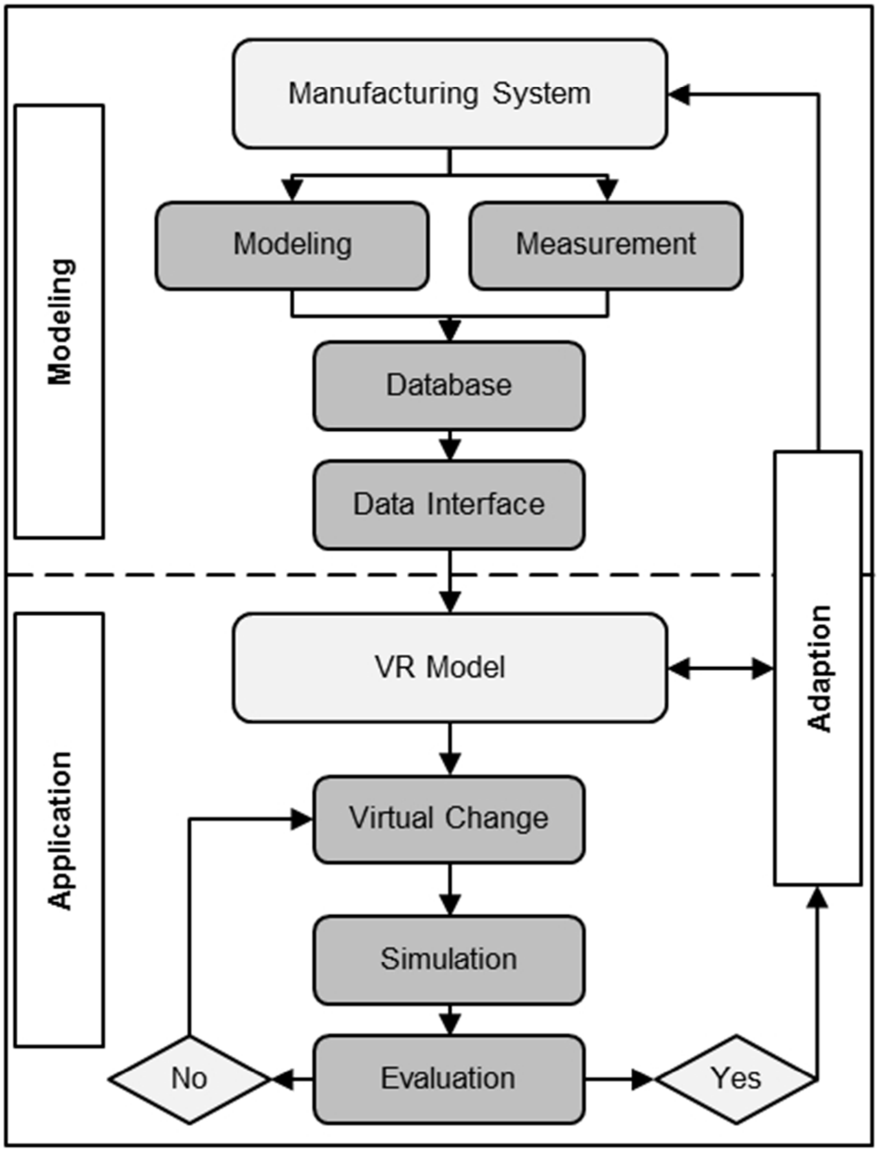
Figure 20: The components of a CAVE system: a) passive stereo projectors, b) a fly stick with tracking markers, c) an IR camera over the CAVE.

Figure 21: Sound simulation and visualization in a CAVE.

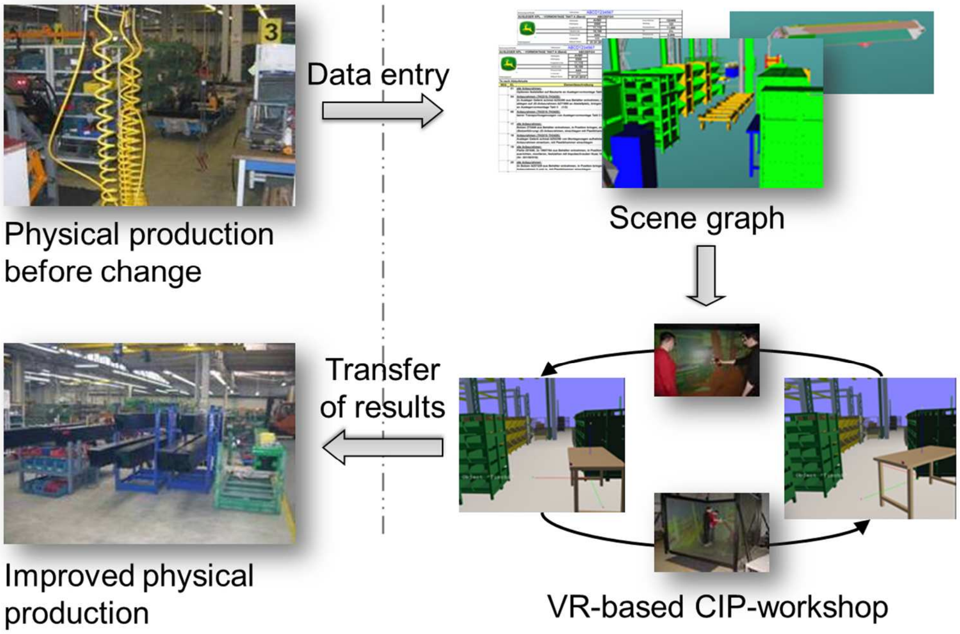
Figure 22: Virtual machining in a CAVE.



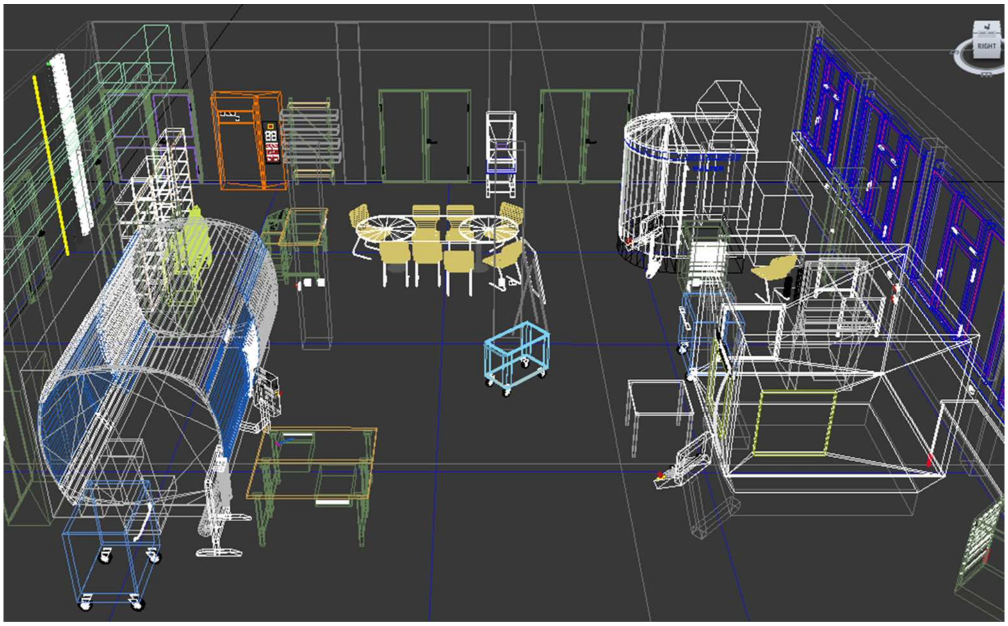
Production levels in a manufacturing system. Adapted from Westkämper and Hummel (2009).
83x76mm (150 x 150 DPI)



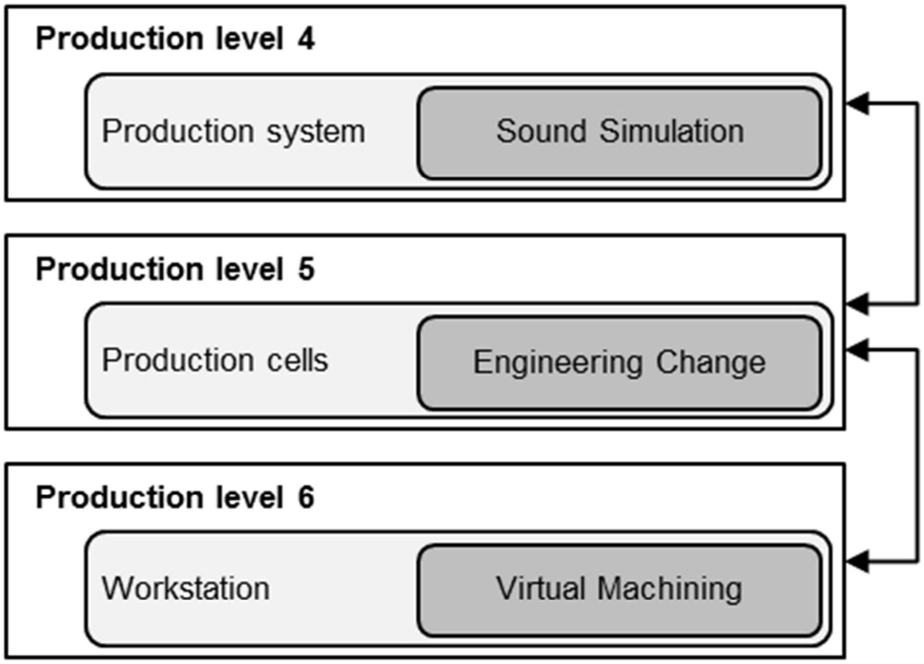
Workflow of the VR framework.
83x110mm (150 x 150 DPI)



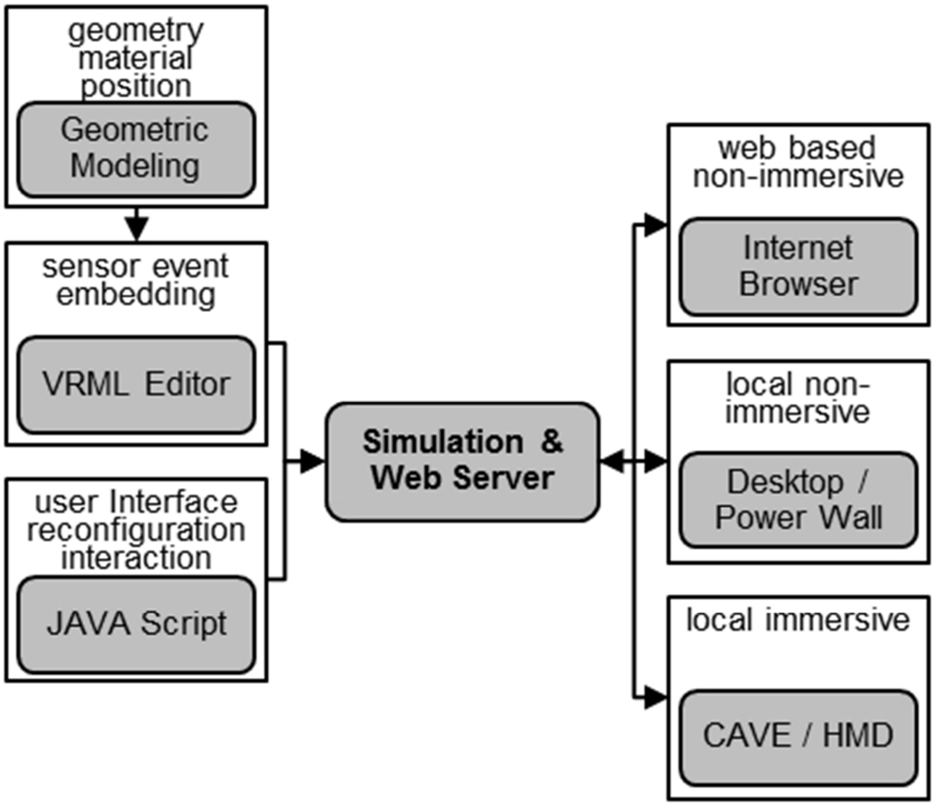
Procedures of VR-based CIP workshop.
226x152mm (150 x 150 DPI)



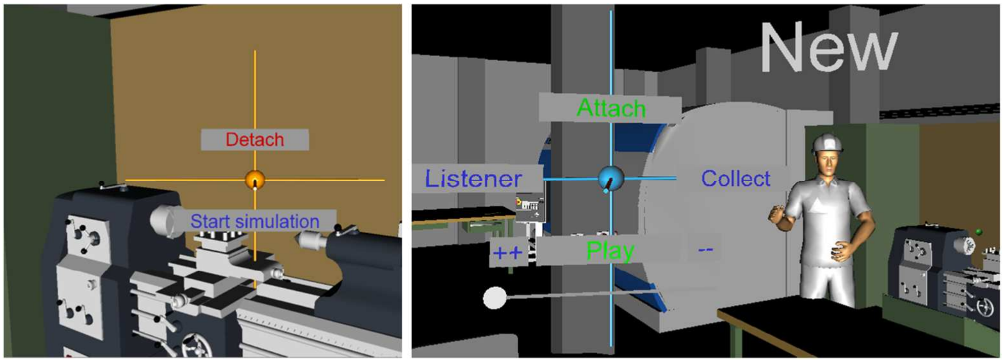
Geometric modelling.
254x150mm (144 x 150 DPI)



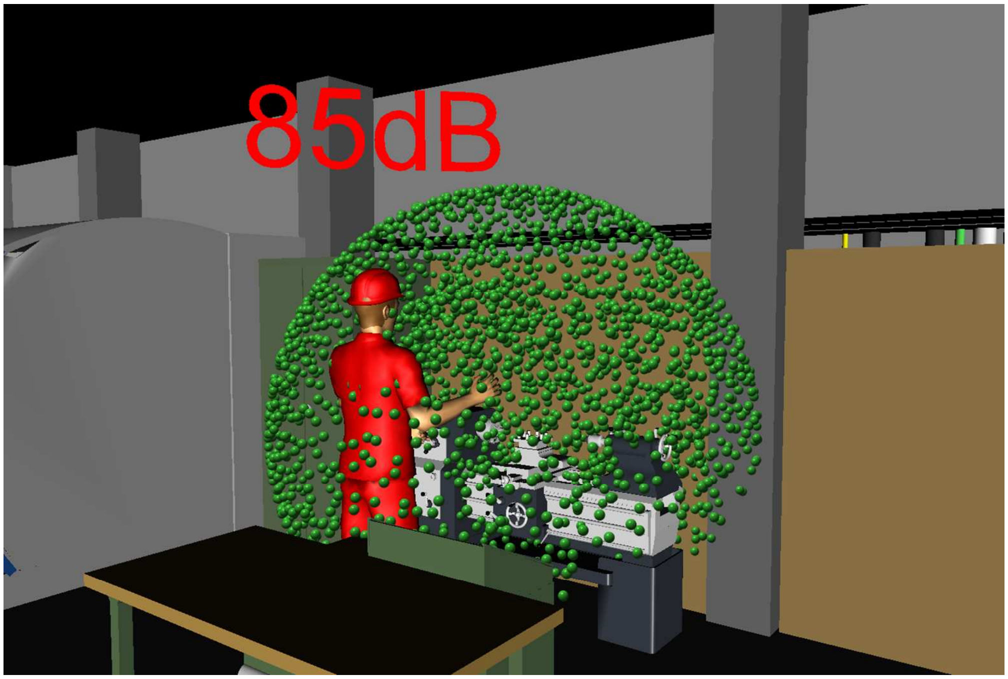
Correlations between applications and between production levels.
87x64mm (150 x 150 DPI)



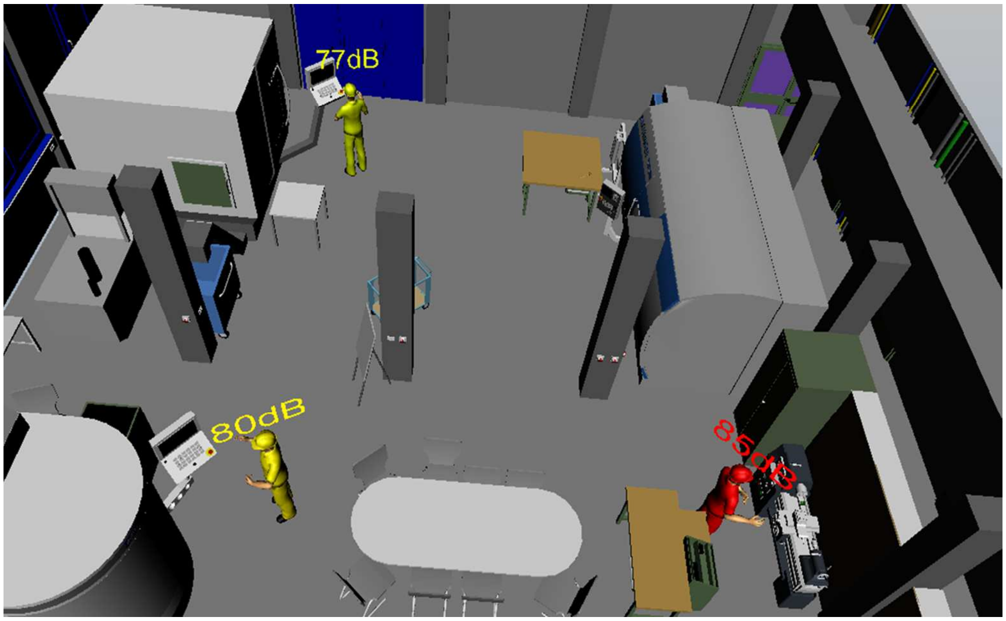
Structure of the sound simulation tool.
83x71mm (150 x 150 DPI)



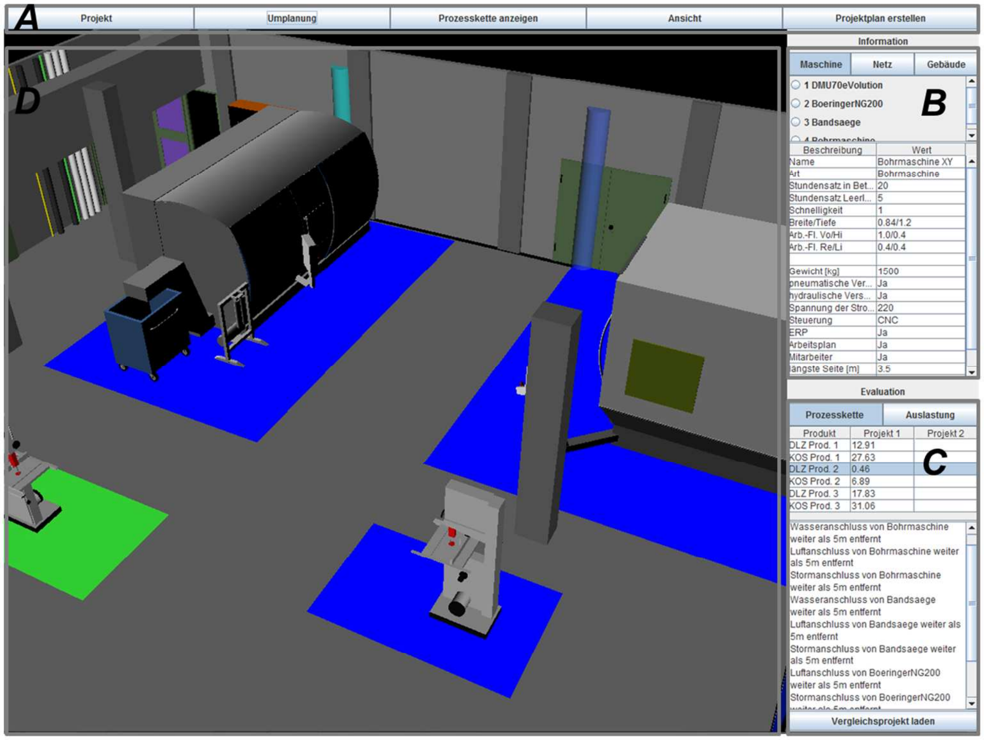
Simulation control using VRML viewer.
243x86mm (150 x 150 DPI)



Visualization of the sound propagation.



Evaluation of sound levels at different positions.
254x149mm (144 x 150 DPI)



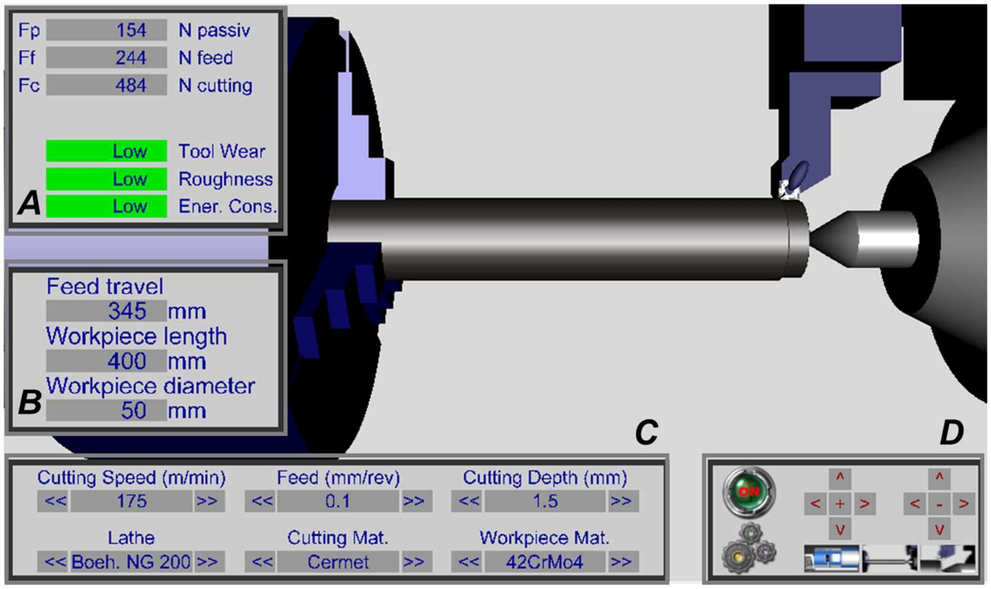
○ 1 DMU70eVolution
○ 2 BoeringerNG200
○ 3 Bandsaege
○ 4 Bohrmaschine

Beschreibung	Wert
Name	Bohrmaschine XY
Art	Bohrmaschine
Stundensatz in Bet...	20
Stundensatz Leerl...	5
Schnelligkeit	1
Breite/Tiefe	0.84/1.2
Arb.-Fl. Vo/Hi	1.0/0.4
Arb.-Fl. Re/Li	0.4/0.4
Gewicht [kg]	1500
pneumatische Ver...	Ja
hydraulische Vers...	Ja
Spannung der Stro...	220
Steuerung	CNC
ERP	Ja
Arbeitsplan	Ja
Mitarbeiter	Ja
ängste Seite [m]	3.5

Produkt	Projekt 1	Projekt 2
DLZ Prod. 1	12.91	
KOS Prod. 1	27.63	
DLZ Prod. 2	0.46	
KOS Prod. 2	6.89	
DLZ Prod. 3	17.83	
KOS Prod. 3	31.06	

Wasseranschluss von Bohrmaschine weiter als 5m entfernt
Luftanschluss von Bohrmaschine weiter als 5m entfernt
Stormanschluss von Bohrmaschine weiter als 5m entfernt
Wasseranschluss von Bandsaege weiter als 5m entfernt
Luftanschluss von Bandsaege weiter als 5m entfernt
Stormanschluss von Bandsaege weiter als 5m entfernt
Luftanschluss von BoeringerNG200 weiter als 5m entfernt
Stormanschluss von BoeringerNG200 weiter als 5m entfernt

Graphic user interface of the EC software tool.
230x176mm (150 x 150 DPI)



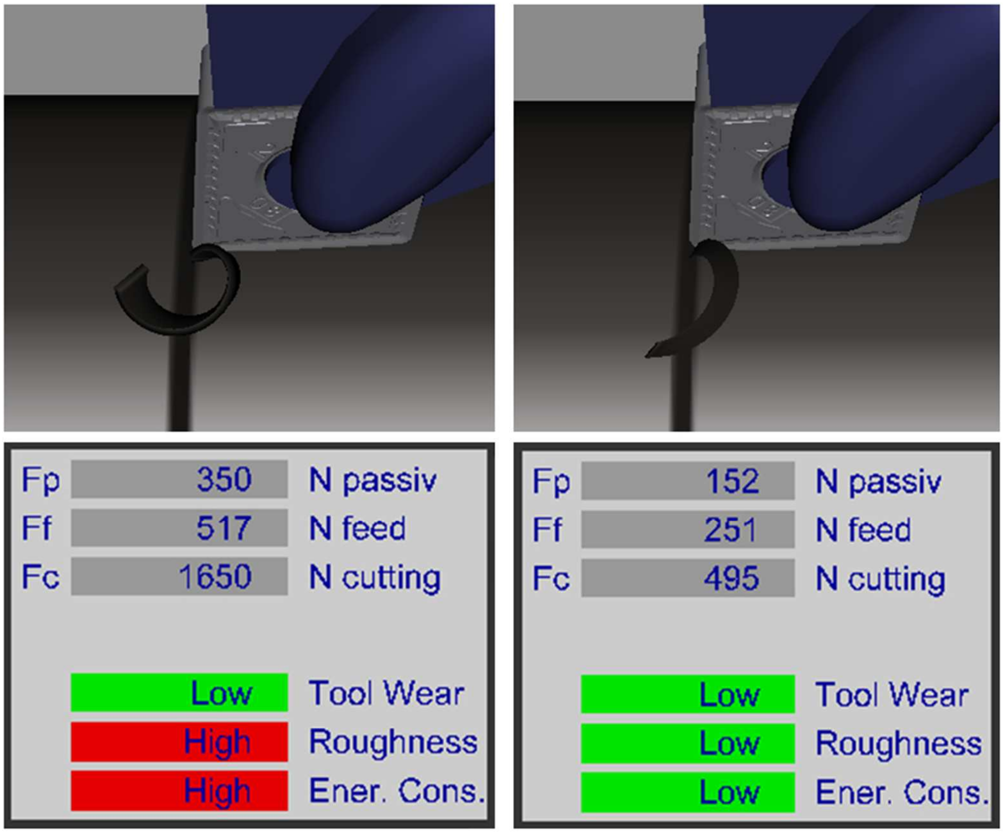
Fp 154 N passiv
Ff 244 N feed
Fc 484 N cutting

Low Tool Wear
Low Roughness
Low Ener. Cons.

Feed travel
345 mm
Workpiece length
400 mm
Workpiece diameter
50 mm

Cutting Speed (m/min) 175
Feed (mm/rev) 0.1
Cutting Depth (mm) 1.5
Lathe Boeh. NG 200
Cutting Mat. Cermet
Workpiece Mat. 42CrMo4

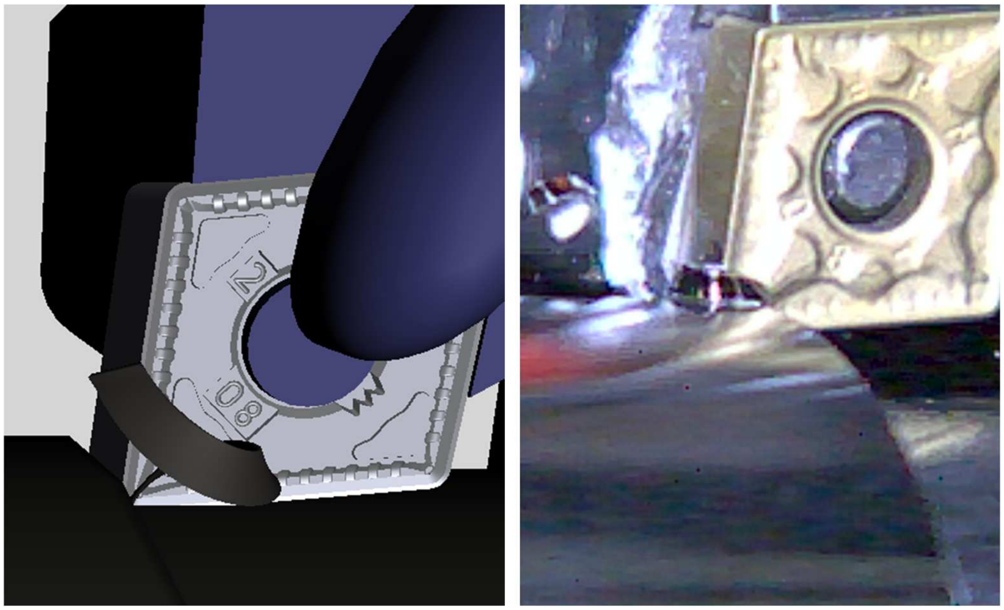
User interface of the virtual machining tool.
243x144mm (150 x 150 DPI)



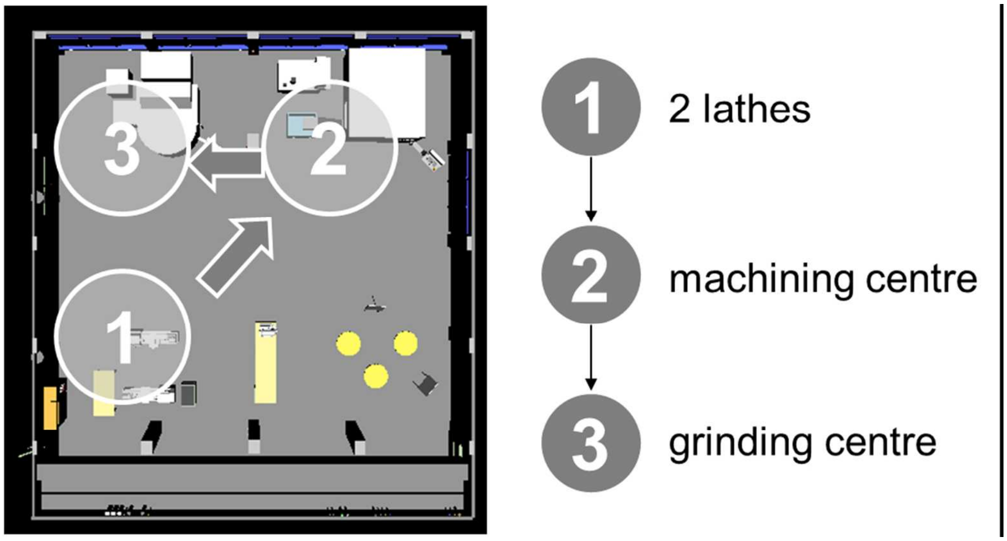
Fp	350	N passiv
Ff	517	N feed
Fc	1650	N cutting
	Low	Tool Wear
	High	Roughness
	High	Ener. Cons.

Fp	152	N passiv
Ff	251	N feed
Fc	495	N cutting
	Low	Tool Wear
	Low	Roughness
	Low	Ener. Cons.

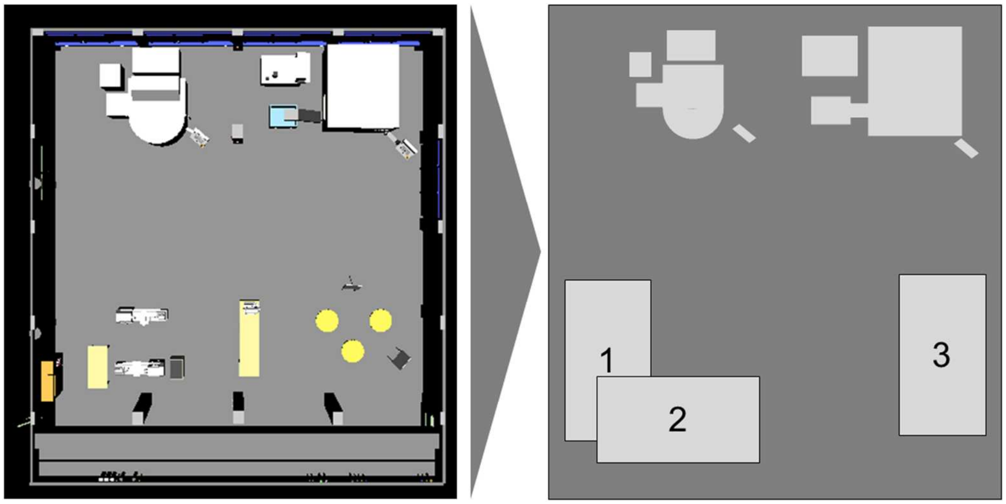
Process display at different cutting conditions.
145x120mm (150 x 150 DPI)



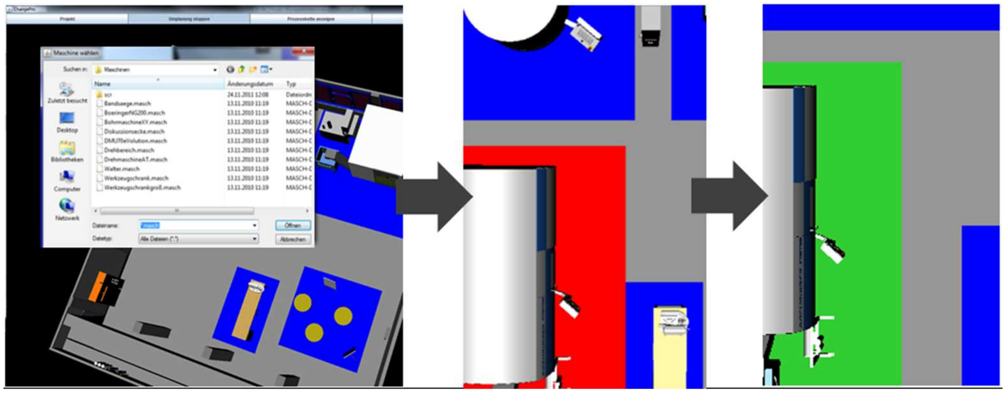
The chip formation in VR vs. the chip formation during real cutting.
332x200mm (150 x 150 DPI)



The initial situation of use case.
174x92mm (150 x 150 DPI)



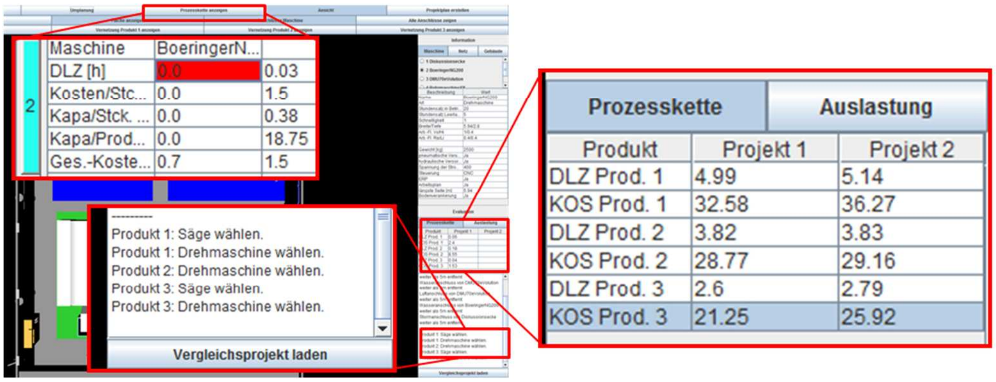
Initial situation and alternative placements of CNC turning machine.
185x92mm (150 x 150 DPI)



Name	Änderungsdatum	Typ
scr	24.11.2011 12:08	Dateiordn
Bandsaege.masch	13.11.2010 11:19	MASCH-
BoeringerNG200.masch	13.11.2010 11:19	MASCH-
BohrmaschineXY.masch	13.11.2010 11:19	MASCH-
Diskussionsecke.masch	13.11.2010 11:19	MASCH-
DMU70eVolution.masch	13.11.2010 11:19	MASCH-
Drehbereich.masch	13.11.2010 11:19	MASCH-
DrehmaschineAT.masch	13.11.2010 11:19	MASCH-
Walter.masch	13.11.2010 11:19	MASCH-
Werkzeugschrank.masch	13.11.2010 11:19	MASCH-
Werkzeugschrankgroß.masch	13.11.2010 11:19	MASCH-

Dateiname: *.masch
Dateityp: Alle Dateien (*.*)

Removing, loading, and moving objects.
168x65mm (150 x 150 DPI)

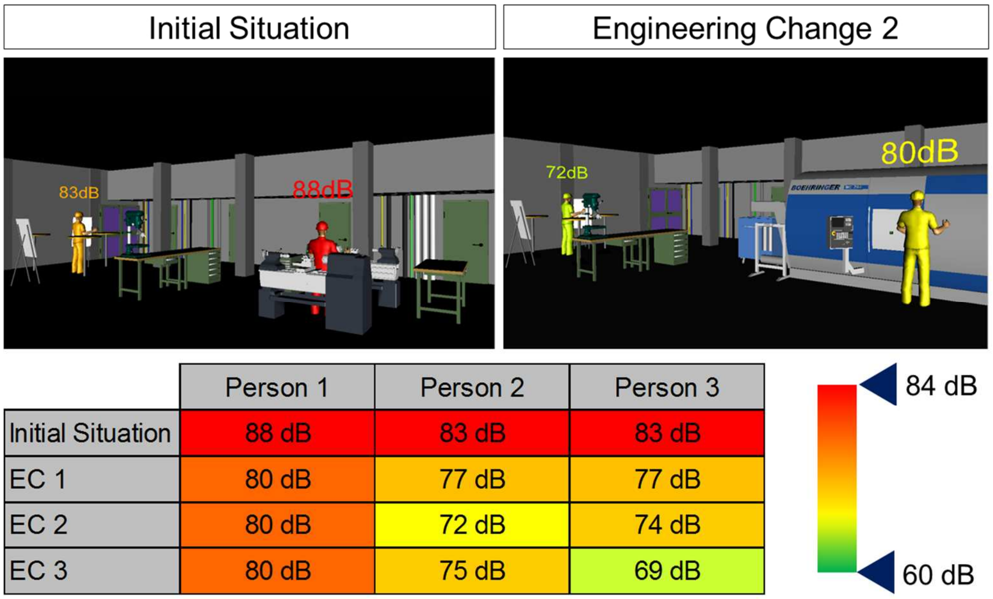


Maschine	BoeringerN...	
DLZ [h]	0.0	0.03
Kosten/Stc...	0.0	1.5
Kapa/Stck. ...	0.0	0.38
Kapa/Prod...	0.0	18.75
Ges.-Koste...	0.7	1.5

Produkt 1: Säge wählen.
Produkt 1: Drehmaschine wählen.
Produkt 2: Drehmaschine wählen.
Produkt 3: Säge wählen.
Produkt 3: Drehmaschine wählen.

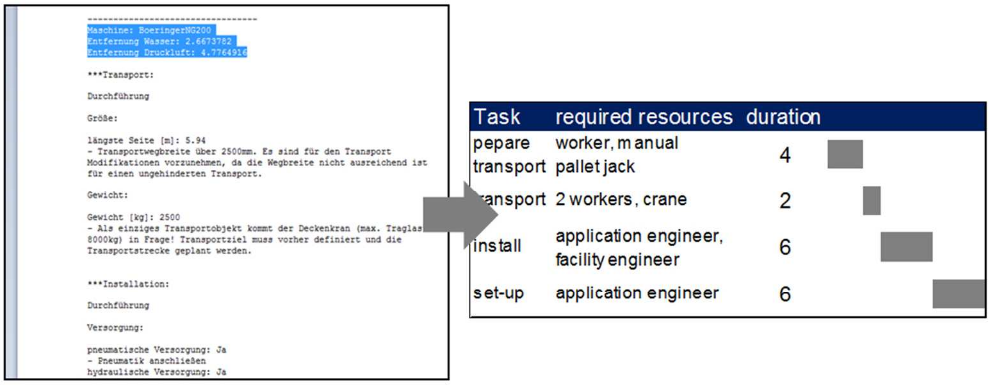
Produkt	Projekt 1	Projekt 2
DLZ Prod. 1	4.99	5.14
KOS Prod. 1	32.58	36.27
DLZ Prod. 2	3.82	3.83
KOS Prod. 2	28.77	29.16
DLZ Prod. 3	2.6	2.79
KOS Prod. 3	21.25	25.92

The completeness check, comparison of alternative projects, and inserting planned time.
172x65mm (150 x 150 DPI)



	Person 1	Person 2	Person 3
Initial Situation	88 dB	83 dB	83 dB
EC 1	80 dB	77 dB	77 dB
EC 2	80 dB	72 dB	74 dB
EC 3	80 dB	75 dB	69 dB

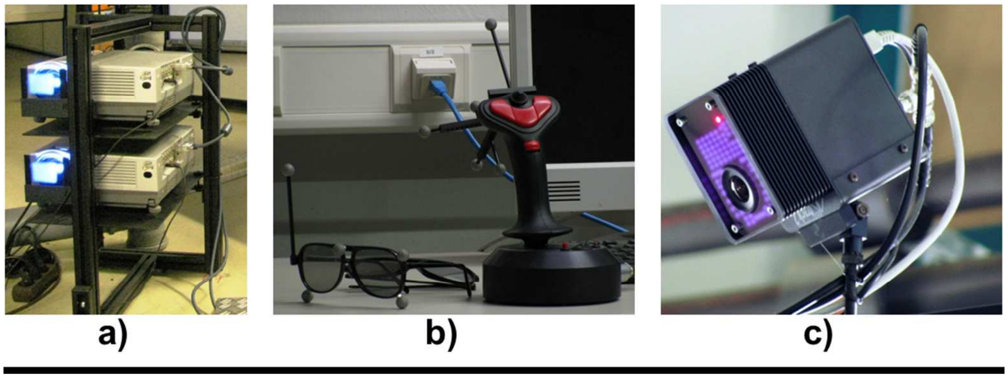
Different results of sound simulation.
228x141mm (150 x 150 DPI)



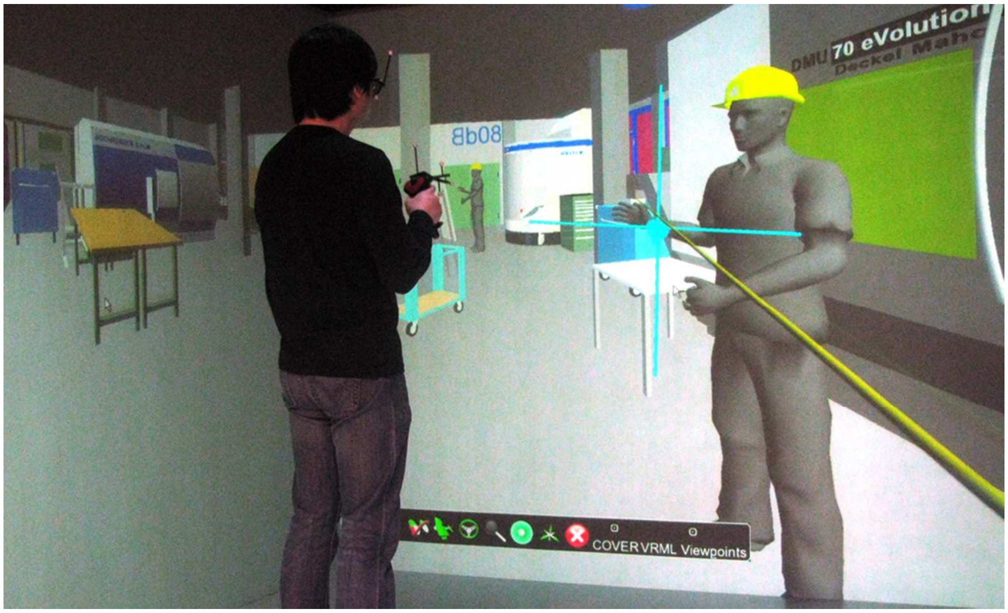
```
--------------------------------
Maschine: BoeringerNG200
Entfernung Wasser: 2.6673782
Entfernung Druckluft: 4.7764916

***Transport:

Durchführung

Größe:

längste Seite [m]: 5.94
- Transportwegbreite über 2500mm. Es sind für den Transport
Modifikationen vorzunehmen, da die Wegbreite nicht ausreichend ist
für einen ungehinderten Transport.

Gewicht:

Gewicht [kg]: 2500
- Als einziges Transportobjekt kommt der Deckenkran (max. Traglas
8000kg) in Frage! Transportziel muss vorher definiert und die
Transportstrecke geplant werden.


***Installation:

Durchführung

Versorgung:

pneumatische Versorgung: Ja
- Pneumatik anschließen
hydraulische Versorgung: Ja
```

Task	required resources	duration	
pepare transport	worker, manual pallet jack	4	■
ransport	2 workers, crane	2	■
install	application engineer, facility engineer	6	■
set-up	application engineer	6	■

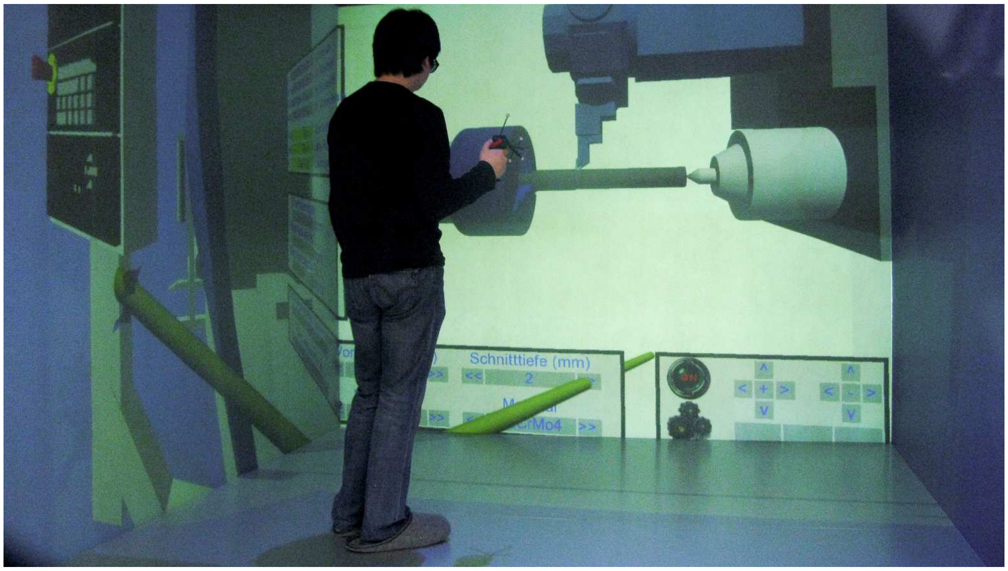
Generating implementation plans for ECs.
172x69mm (150 x 150 DPI)



The components of a CAVE system: a) passive stereo projectors, b) a fly stick with tracking markers, c) an IR camera over the CAVE.
201x74mm (150 x 150 DPI)



Sound simulation and visualization in a CAVE.



Virtual machining in a CAVE.
365x205mm (240 x 240 DPI)