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# VIRTUAL REALITY ENHANCED MANUFACTURING SYSTEM DESIGN

**Xiang Yang**
University of Kaiserslautern
yang@cpk.uni-kl.de

**René C. Malak**
University of Kaiserslautern
malak@cpk.uni-kl.de

**Christian Lauer**
University of Kaiserslautern
lauer@cpk.uni-kl.de

**Christian Weidig**
University of Kaiserslautern
weidig@cpk.uni-kl.de

**Hans Hagen**
University of Kaiserslautern
hagen@informatik.uni-kl.de

**Bernd Hamann**
University of California, Davis
hamann@cs.ucdavis.edu

**Jan C. Aurich**
University of Kaiserslautern
aurich@cpk.uni-kl.de

## ABSTRACT

During the analysis and design of manufacturing systems, enterprises 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 mean of such 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 in scientific and 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, a noise simulation and a virtual machining tool have been visualized in a Cave Automatic Virtual Environment (CAVE).

## KEYWORDS

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

## 1. INTRODUCTION

Customers' 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 production of innovative and low-cost products, within an appropriate manufacturing system, became a crucial part in the whole product life cycle. As one of the most important 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 other ones. The total number of new designed factories is declining in developed and developing countries. Therefore, to adapt established manufacturing systems gets more important due to the creasing changed requirements (Kühn, 2006).

Considering this background, a systematic planning of necessary changes in a manufacturing system is essential for two major reasons. On the one hand, the impacts of changes in an established manufacturing system have to be analysed and rated in a holistic manner. Downtime in factories should be prevented. On the other hand, the efficiency of analysing and planning has to be improved to cover the increased change demands. In order to face these challenges, the virtual factory has considerable, still not fully exploited potential. 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. Two of them are visualized in a Cave Automatic Virtual Environment (CAVE). The last section concludes the paper and gives an outlook.

## 2. RELATED WORK

### 2.1 TERM DIFINITION

Based on common understanding, the digital factory is data- and information-centred, but a virtual factory is constructed by using models. In this paper the term virtual factory is used to cover both meanings. A virtual factory is built with geometric models and involved data and information.

Hence the virtual factory comprises modeling and visualization, simulation and evaluation, data management and communication. A holistic view upon manufacturing systems can be provided by the virtual factory. The rebuilding and visualization of a manufacturing system is the base on which further processes are simulated. Machining operations, assembly processes or material flows are examples for the opportunities a consistent database can play out (Weimer et al, 2008).

### 2.2 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).

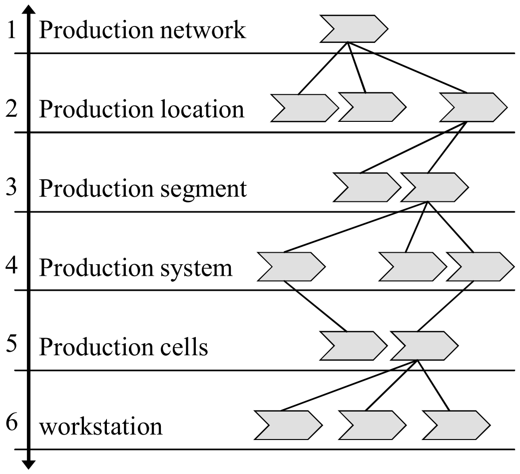


**Figure 1 – Production levels in a manufacturing system**

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 Zahn, 2009). Not all these six levels are considered in this paper, only the levels four through six are taken into account.

### 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 behavior 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 or 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 assembly processes within a workstation (Chryssolouris et al, 2000). Comparing several virtual approaches, according the related problems occurring in a physical assembly situation, 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 illustrated and divided into several phases: modeling, application and adaption (Figure 1). It facilitates the virtual factory tools for manufacturing system design and enables an integrated use of them in a virtual environment.

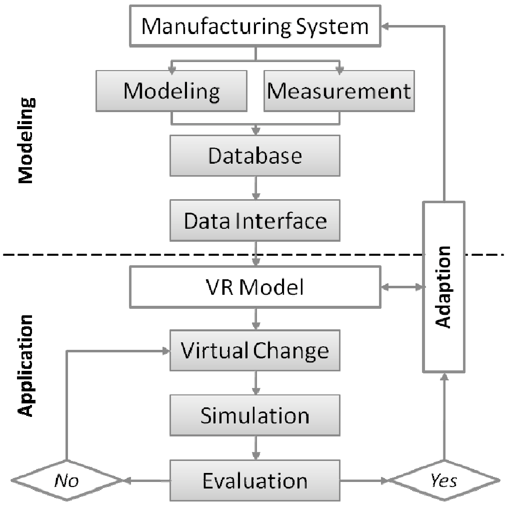


Figure 2 – Workflow of VR framework

### 3.1. MODELING

The modeling phase provides a data basis for further use. Usually it starts with geometric modeling and then generates a VR model. During geometric modeling, different objects in a manufacturing system are involved, such as the machines, people, 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 machine level and the parts, cutting tools or work pieces are not taken into account.

Furthermore, additional information from the manufacturing system are described and integrated to the completed geometric model as a VR model. By using different VR platforms, this VR model is visualized and manipulated. This set-up defines the so-called a virtual environment, in which the applications are implemented.

### 3.2. APPLICATION

In an application phase, two main components are usually included: simulation and visualization. Simulation is the kernel of the whole work flow. Based on the modeled virtual world, it rebuilds the manufacturing processes and provides essential information for visualization and VR. Users are able to get 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, not intuitive and difficult to understand. Visualization makes the viewing and analyzing 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 to help 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).

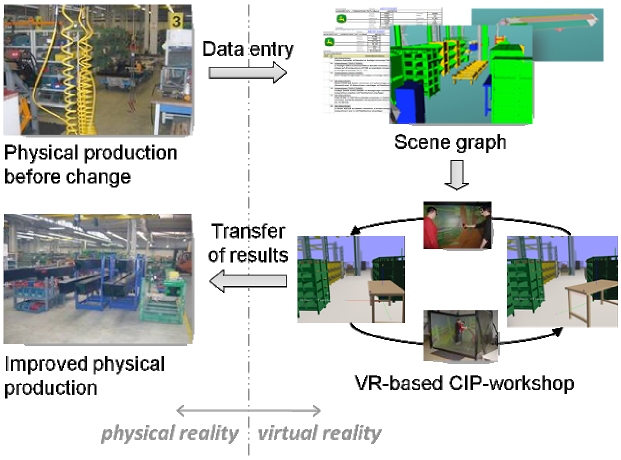


Figure 3 – Procedures of VR-based CIP-workshop

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) analyzing 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 three applications have been implemented by using the introduced framework. The modeling level is generally introduced and shows fewer differences among these three applications. At the application level, different simulations and visualizations have been implemented to achieve different objectives. However, the adaption level is not discussed in this chapter.

## 4.1 MODELLING

The modeling level consists of geometric modeling and modeling of the manufacturing system. The geometric modeling 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. By using modeling 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 modeled 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.

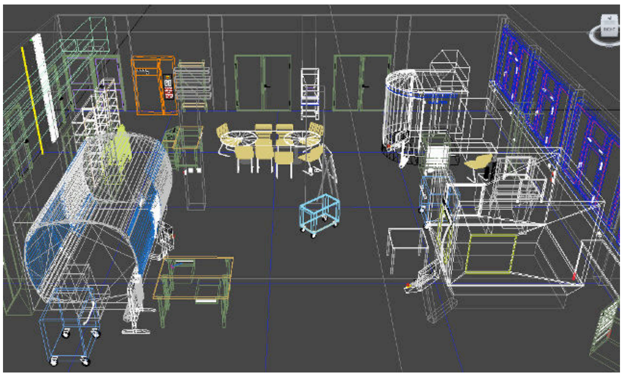


**Figure 4 – Geometric modeling**

The modeling 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. These models are 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.

### 4.2.1 Sound Simulation

Noise from machining processes influences employees' health and it even causes 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.

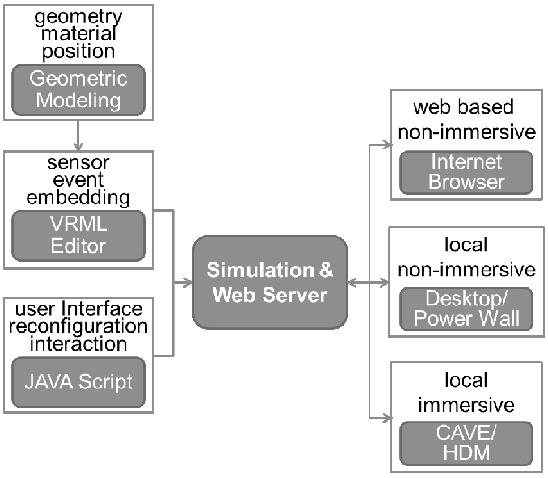


**Figure 5 – Geometric modeling**

In order to determine the influence of noise, acoustic simulations have been implemented. Different numerical simulation methods based on solving wave equations such as Finite Element Methods (FEM) and Finite Difference Time Domain (FDTD) are discussed and compared by Deines (2008). A geometric approach called Phonon

Mapping was developed by Deines, which is implemented for this application.

The simulation kernel acts as 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.

After start, 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 modeled 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 6, 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 7). The playback speed can be adjusted using the '++' and '--' buttons, and the current simulation time step can be selected by a slider (see Figure 6).

The phonon collection method calculates the sound levels at the listener positions and enables users to view the results interactively. Figure 8 shows the sound levels at different operator positions. The virtual workers are shown with corresponding colors according to the sound pressure level: green for low sound pressure levels <80dB, yellow/orange for critical sound pressure levels <84dB 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.

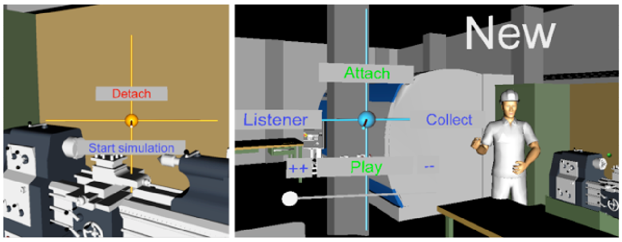


**Figure 6 – Simulation using VRML viewer**

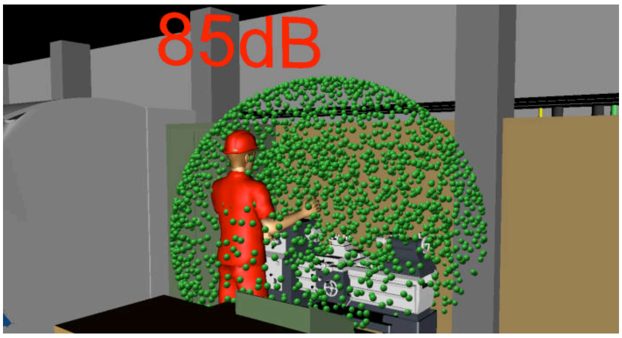


**Figure 7 – Sound propagation**

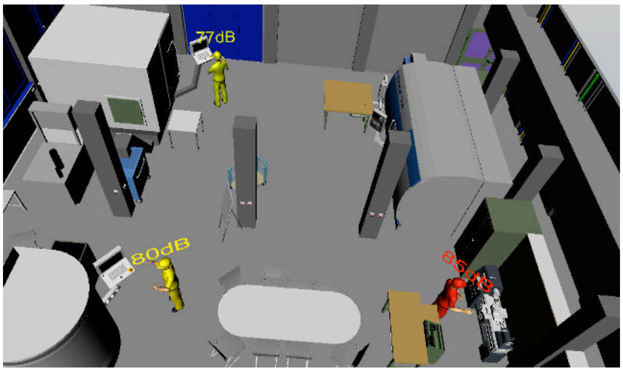


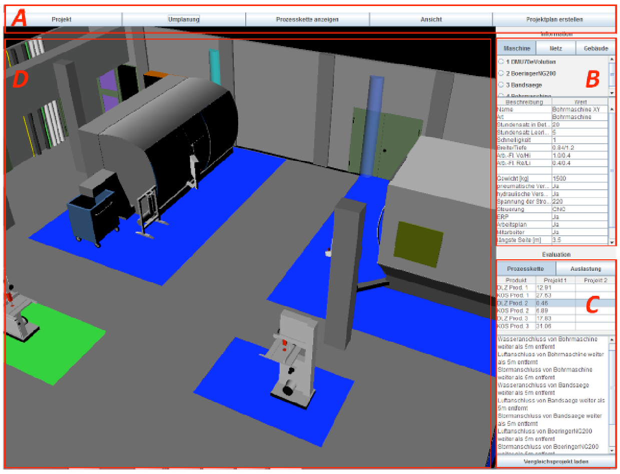
**Figure 8 – Sound levels at different positions**

### 4.2.2 Engineering Change

Enterprises have to change their manufacturing system continuously. The numbers of engineering changes (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 modeling and manufacturing system modeling, showed in chapter 4.1, are used in this application as well. An additional modeled 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 9. 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.



| 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 |
| längste 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
Stromanschluss von Bohrmaschine weiter als 5m entfernt
Wasseranschluss von Bandsaege weiter als 5m entfernt
Luftanschluss von Bandsaege weiter als 5m entfernt
Stromanschluss von Bandsaege weiter als 5m entfernt
Luftanschluss von BoeringerNG200 weiter als 5m entfernt
Stromanschluss von BoeringerNG200

**Figure 9 – Graphic user interface for analyzing and planning of ECs in manufacturing system**

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 gives 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 change, the 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 analyzing 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 provides a transparent decision comparing different options.

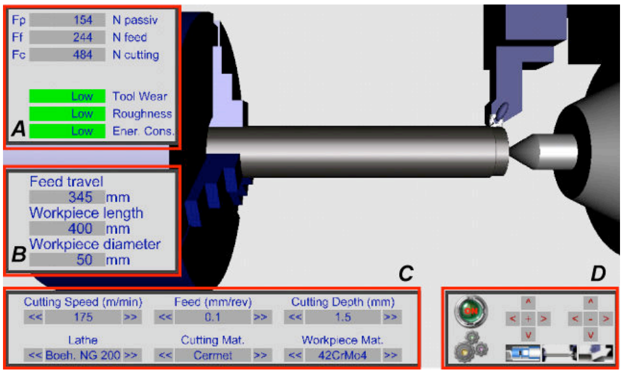
### 4.2.3 Virtual Machining

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 10 shows the graphic user interface performed in the VRML viewer, which consists of four function panels which are labeled from A to D.



Fp 154 N passiv
Ff 244 N feed
Fc 484 N cutting
Low Tool Wear
Low Roughness
Low Ener. Cons.

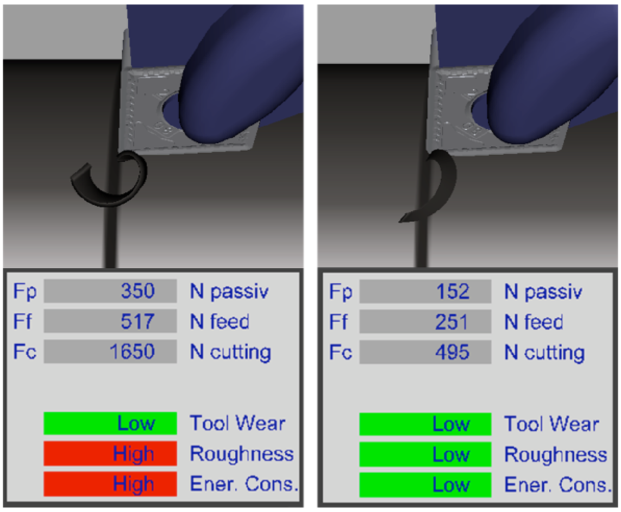
Feed travel 345 mm
Workpiece length 400 mm
Workpiece diameter 50 mm

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 >>

Figure 10 – User interface for virtual machining tool

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 preset cutting conditions. The process forces are displayed numerically, and tool wear, surface roughness as well as energy consumption are evaluated using the colored scales “low,” “ordinary” and “high.” Figure 11 illustrates the process results during the animation of turning using two different cutting conditions: feed $f1 = 0.3$ mm/rev, depth of cut $ap1 = 2$ mm, cutting speed $vc1 = 175$ m/min (Figure 11-a) as well as $f2 = 0.1$ mm/rev, $ap2 = 1.5$ mm and $vc2 = 175$ m/min (Figure 11-b).

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 (Figure 10). Panel D offers a system control. With the system control the user can select different points of view.



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

a)

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

b)

Figure 11 – Process display at different cutting conditions

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 12. The chip formation during turning is recorded by using a high-speed camera.

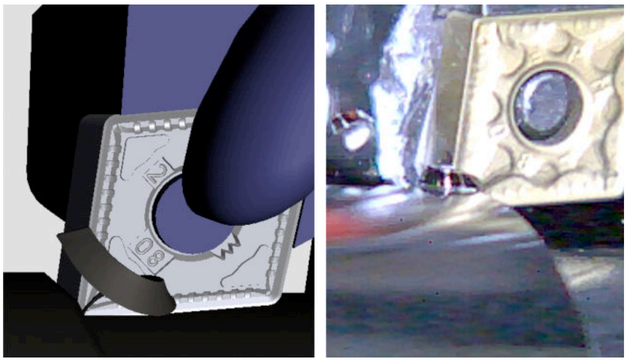


Figure 12 – Chip formation in VR vs. in reality

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. 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.

### 5.1 CAVE SYSTEM DESCRIPTION

The CAVE system located at the FBK institute, University of Kaiserslautern, is a complex system, which is constructed by using different hardware technologies and software solutions. Figure 13 shows a few hardware components of the CAVE set-up. Eight projectors (Figure 13-a), 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 13-c). The user interacts with the virtual environment via different input devices such as a fly stick shown in Figure 13-b.

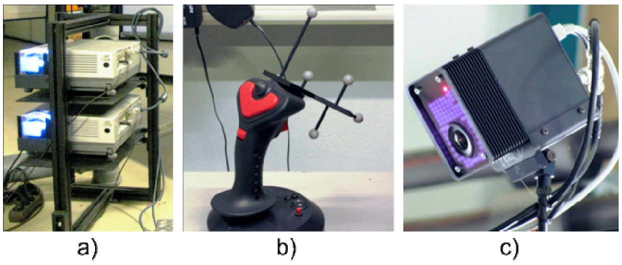


**Figure 13 – Components of CAVE system: a) passive stereo projectors, b) a fly stick with tracking markers, c) an IR camera over the CAVE**

COVISE and 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).

## 5.2 VISUALISATION IN CAVE

The benefit of visualization in CAVE has been discussed in chapter 2.3. The visualization of sound propagation and sound levels in an immersive environment helps to identify possible noise problems in a manufacturing system and determine improvement strategies.

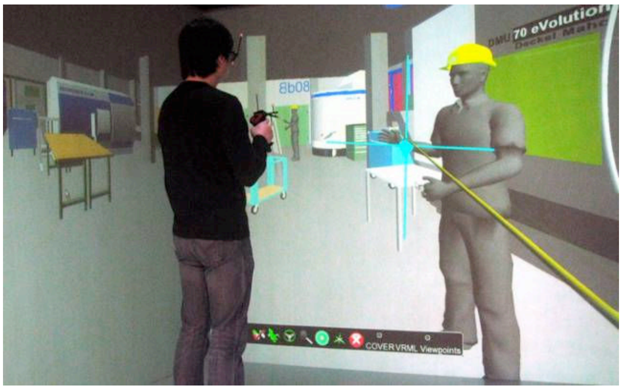


**Figure 14 – Sound simulation in CAVE**

Figure 14 shows, a user exploring the virtual factory in CAVE and simulating the sound to analyze the workstation or layout planning. The scales of the virtual employees are similarly set to a real person, so the user has a strong perception of a real factory environment.

In Figure 15, an animation of a cutting process is visualized in the CAVE. One of the advantages of immersive animation is the free choice of one's viewpoint. Users are allowed to navigate to any interesting and relevant investigation points. Different aspects can be analyzed specifically. Another advantage in this case is the fact that the full immersive environment improves the user's perception and the result of virtual operation training.

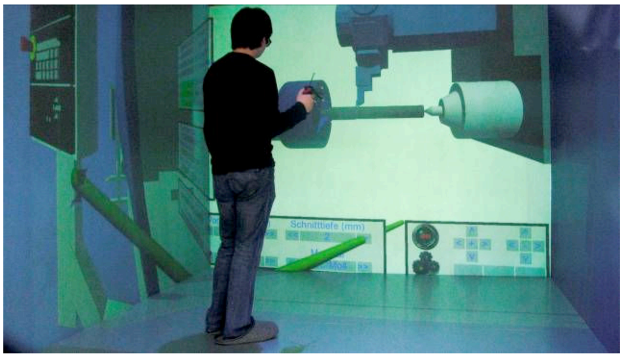


**Figure 15 – Virtual machining implementation in CAVE**

## 6. CONCLUSIONS

This paper 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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