Sound Simulation and Visualization
in virtual Manufacturing Systems

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This work is dedicated to my beloved parents
谨以此书献给我亲爱的父母 杨臻和张小凤

Vorwort des Verfassers

"Zu wissen, was man weiß, und zu wissen, was man tut, das ist Wissen."
/ Konfuzius/

Die vorliegende Dissertation entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Lehrstuhl für Fertigungstechnik und Betriebsorganisation der Technischen Universität Kaiserslautern (FBK).

Sindelfingen, im Oktober 2013   Xiang Yang

Contents

English Summary

The noise issue in manufacturing system is widely discussed from legal and health aspects. Regarding the existing laws and guidelines, various investigation methods are implemented in industry. The sound pressure level can be measured and reduced by using established approaches in reality. However, a straightforward and low cost approach to study noise issue using existing digital factory models is not found.

This thesis attempts to develop a novel concept for sound pressure level investigation in a virtual environment. With this, the factory planners are able to investigate the noise issue during factory design and layout planning phase.

Two computer aided tools are used in this approach: acoustic simulation and virtual reality (VR). The former enables the planner to simulate the sound pressure level by given factory layout and facility sound features. And the latter provides a visualization environment to view and explore the simulation results. The combination of these two powerful tools provides the planners a new possibility to analyze the noise in a factory.

To validate the simulations, the acoustic measurements are implemented in a real factory. Sound pressure level and sound intensity are determined respectively. Furthermore, a software tool is implemented using the introduced concept and approach. With this software, the simulation results are represented in a Cave Automatic Virtual Environment (CAVE).

This thesis describes the development of the approach, the measurement of sound features, the design of visualization framework, and the implementation of VR software. Based on this know-how, the industry users are able to design their own method and software for noise investigation and analysis.

Deutsche Zusammenfassung

Mitarbeiter in produzierenden Unternehmen sind zahlreichen Emissionen ausgesetzt, die ihre Gesundheit und ihr Wohlbefinden negativ beeinflussen. Unter den unterschiedlichen Emissionen verursacht Lärm die meisten gesundheitlichen Schäden. Zudem sind viele Mitarbeiter in der Produktion Lärm ausgesetzt. Daher stellt die Lärmreduzierung eine wichtige Aufgabe dar, da Geräusche aus Bearbeitungsprozessen die Gesundheit der Mitarbeiter schädigen können. Aktuelle Methoden zur Lärmmessung und -analyse sind häufig zeitaufwändig, verursachen hohe Kosten und werden daher in der Regel nicht in den Fabrikplanungsprozess integriert.

Die Virtuelle Realität (VR) bietet im Rahmen der Gestaltung von Produktionssystemen erhebliches Unterstützungspotential. Änderungen können an Modellen von Produktionssystemen virtuell durchgeführt und analysiert werden. Dadurch werden Auswirkungen auf Produktionssysteme bereits im Vorfeld identifiziert und unnötige nachträgliche Änderungen vermieden. Durch die Veränderungen der Daten über eine zentrale Schnittstelle wird der Aufwand, um die Konsistenz der Daten aufrecht zu erhalten und sie zu pflegen, deutlich reduziert.

Ziel der vorliegenden Dissertation ist die Simulation und Visualisierung von Lärmanalysen in die VR zu integrieren. Die Gestaltung von Produktionssystemen wird verbessert, indem Schallquellen und die Schallausbreitung in Produktionssystemen bereits im Vorfeld betrachtet werden. Dadurch erfolgt eine Gestaltung von lärmreduzierten Produktionssystemen, die nicht erst im Nachhinein aufwändig geändert werden müssen.

Zunächst erfolgt eine umfangreiche Literaturrecherche im Bereich Lärmschutz, Gesetze der Arbeitssicherheit, akustische Modellierung und Simulation, VR Theorie und industrielle VR Applikationen. Um die Simulation und Visualisierung von Lärmanalysen in die VR zu integrieren, wird auf bestehende Ansätze aus dem Stand der Technik zurückgegriffen. Darauf aufbauend, werden das Konzept zur Implementierung und die benötigten Methoden entwickelt. Dabei werden digitalen Werkzeuge, wie Modellierungssoftware und VR-Editierungssoftware, nach definierten Kriterien ausgewählt und angewendet.

Drei Hauptdatenquellen werden für die Datenerhebung und -erfassung herangezogen. Zunächst werden geometrische und Objektdaten aus der Fertigung nach einer vorgegebenen Checkliste gesammelt und mit Software modelliert. Dadurch wird die 3D-Umgebung für die spätere Implementierung geschaffen. Informationen, die innerhalb der virtuellen Umgebung erfasst werden, sind beispielsweise die Form, Massen, Material und Oberflächeneigenschaften. Durch akustische Messungen in der realen Fabrik, werden grundlegende Daten aufgenommen, wie Schallquellenenergie und Schalldruckpegel. Die Messungen werden in Abhängigkeit von unterschiedlichen Bedienungspositionen und Arbeitsvorgängen durchgeführt. Zusätzliche Informationen aus der deutschen Gesetzgebung und aus technischen Richtlinien werden in die Visualisierung implementiert. Dadurch werden Überschreitungen von Grenzwerten visualisiert.

Zur Schallsimulation wurde ein Phonon-Tracing-Algorithmus verwendet, der die Ausbreitung und Reflexion der Phononen (Schall- bzw. Soundteilchen) berechnet. Als Inputdaten dienen die Geometriegegebenheiten, die Eigenschaften der Schallquellen und die Schallabsorption

der Oberflächen auf den Produktionsobjekten. Die Simulation wird in zwei separaten Durchgängen durchgeführt. Im ersten Durchgang wird die Energie- oder Druckzersetzung für jedes Phonon aus einer Schallquelle berechnet. Anhand der Ergebnisse des ersten Durchgangs wird die Impulsantwort im zweiten Durchgang für ausgewählte Positionen berechnet und dokumentiert. Anschließend wird das Ergebnis aus beiden Durchgängen visualisiert, wie z. B. die Schallintensität, die Schallausbreitung und die Oberflächen der Hauptreflektionen.

Für die Implementierung der Simulation und der Visualisierung in die VR wird eine Softwarearchitektur aufgebaut, die einen Webserver benutzt. Als Modellierungs- und Visualisierungssprache für die VR wurde die Virtual Reality Modeling Language (VRML) verwendet. Eine 3D-Benutzeroberfläche ermöglicht Anwendern eine intuitive und interaktive Navigation und Modifizierung in einer virtuellen Umgebung. Die Visualisierung von VRML-Modellen und Simulationsergebnissen ist mit Hilfe einer Datenschnittstelle sowohl in desktopbasierten als auch in Cave Automatic Virtual Environment (CAVE) basierten VR-Systemen umgesetzt. Die Schallemissionsniveaus in einer virtuellen Umgebung wurden nach Simulationsergebnissen und Bedienungspositionen bewertet und mit verschiedenen Farben visualisiert. Durch die Visualisierung und die Interaktion wird das Verständnis der Anwender für große Datenmengen deutlich verbessert.

Das Konzept wird in mehreren Anwendungsfällen umgesetzt und evaluiert. Somit kann es effektiv zur Lärmevaluation und Lärmreduzierung eingesetzt werden. Innerhalb der Dissertation wurden wichtige grundlegende Erkenntnisse zur Modellierung und Simulation von Lärmentwicklungen gewonnen. Die entwickelte Daten- und Programmierungsschnittstelle kann auf weitere Applikationen erweitert werden. Die Visualisierung der Schallausbreitung in beiden VR-Systemen – desktopbasiert und CAVE-basiert – ermöglicht es, ausgehend von Schallquellen wie z.B. Maschinen, und der Wirkung verschiedener Materialien und Geometrien, die spektrale Energie- und Druckverteilung im Raum zu beobachten. Die Untersuchungen geben Aufschluss darüber, welche Frequenzbereiche stark absorbiert werden und wie viel Schallenergie in die Umgebung reflektiert wird. Die Schallintensität einzelner Arbeitsplätze wird durch verschiedene Farbindikatoren angezeigt. Diese sind entsprechend den Normen klassifiziert, wie zum Bespiel der Verordnung zum Schutz der Beschäftigten vor Gefährdungen durch Schall und Vibrationen (LärmVibrationsArbSchV). Bei Bedarf können Baumaterialien zunächst in der Digitalen Fabrik ersetzt werden. Nach einer Evaluierung der Änderungen in der VR können diese anschließend in der Realität ausgetauscht werden.

List of Abbreviation

ANC	Active Noise Control	IEC	International Electrotechnical Commission
ANSI	American National Standards Institute	IEEE	Institute of Electrical and Electronics Engineers
AR	Augmented Reality	IIDB	Industrial Injuries Disablement Benefit scheme
ArbStättV	Arbeitsstättenverordnung		
ASiG	Arbeitssicherheitsgesetz	ISO	International Organization for Standardization
BAuA	Bundesanstalt für Arbeitsschutz und Arbeitsmedizin		
		FEM	Finite Element Methods
BEM	Boundary Element Method	FDTD	Finite Difference Time Domain
CAD	Computer-Aided Design	FIR	Finite Response Filters
CAM	Computer-Aided Manufacturing	OSHA	Occupational Safety and Health Administration
CAVE	Cave Automatic Virtual Environment		
		Pa	Pascal
CFD	Computational Fluid Dynamics	PDE	Partial Differential Equations
CIP	Continuous Improvement Process	rpm	Revolutions per minute
		SME	Small and Medium-sized Enterprises
CNC	Computerized Numerical Control		
		SPL	Sound Pressure Level
dB	decibel	SWL	Sound Power Level
DIN	Deutsches Institut für Normung	TA	Technische Anleitung
DGUV	Deutsche Gesetzliche Unfallversicherung	VDI	Verein Deutscher Ingenieure
		VR	Virtual Reality, Virtuelle Realität
e.g.	for example		
etc.	et cetera	VRML	Virtual Reality Modeling Language
ERP	Enterprise Resource Planning		
GUI	Graphic User Interface	UVV	Unfallverhütungsvorschrift
HMD	Head-Mounted Display	X3D	Extensible 3D

1   Introduction

The employee is a key element in manufacturing systems, but they are often stressed out by different influences during their work. Negative factors typically include the noise emitted by the machine processes, pollution from chemical solvent, heat from thermo forming process, or extremely high/low levels of humidity in some industries. The noise - an essential problem and risks for workers in a factory - can be caused by machinery, power tools or other activities. The uncontrolled noise can influence employees' wellbeing potentially causing diseases and other health problems. Not only are the employees exposed to the noise from the factory, the neighbors are as well. Responding to the neighbors' complaints and reducing their acoustic pollution is also a duty of the enterprisers.

Currently, the study of negative noise factor is often ignored during factory design and planning. Therefore, to analyze and reduce the negative noise effects in the working environment of manufacturing systems is an essential and urgent issue. This issue is also related to ergonomics research, human factors, working safety, as well as other topics.

The conventional method is to measure the sound pressure level (SPL) after the factory is built and the manufacturing system is setup. Using the data, the necessary changes are made if the noise level exceeds the limit. This approach is useful, but is usually costly and causes production to stop. Sometimes the necessary changes cannot be made because of the required time and costs. Thus, a new and more efficient approach needs to be developed.

One of the useful tools to support the noise investigation in factory is acoustic simulation, which provides the data of sound wave behavior and SPLs. Inspired by the well-established approaches and algorithms in computer graphics, acoustic simulation has been investigated and further rapidly developed in recent years. Furthermore, the increased computer hardware performance and software technology enables complex calculation of sound propagation and evaluation of its effects to the environment.

In recent years, the Virtual Reality (VR) or virtual environment has become one of the most important research topics, not only in computer science but also in mechanical engineering. Due to its beneficial features –immersion, interaction and imagination– VR has opened a new perspective for researchers in a variety of fields, which enables them to extend current implementations. In industry, VR applications are being developed for experimental and practical research, especially for product design, production and factory planning, information and data visualization, simulation integration, etc. Within a virtual environment, high quality visualization and other types of output, such as audio output and haptic feedback, facilitate participants' perception and understanding. The rich methods of interaction, such as using fly stick and the gesture tracking, allow users to explore the virtual world, analyze the complex data sets, and manipulate the single virtual object.

VR has extended the power of the digital factory concept and become a more and more widely applicable platform to address different issues in manufacturing. Acoustic simulation and visualization in the virtual environment is a sub-topic of virtual workplace design, addressing the issue of noise analysis and control in a manufacturing system. More precisely, sound simulation concerns the influence of sound propagation in workplace design and planning of a factory. Through analysis of the simulated factory layout, absorption material

and used machinery, designers and planners can understand the noise effects before the factory is actually setup. In a virtual environment, changes could be easily made without high costs and potential risks. Different planning choices are able to be viewed and evaluated directly in VR.

Currently, some research projects integrated sound simulation in a digital factory or a VR system. However, there is no existing and well-developed solution for noise investigation in a virtual factory. Some solutions focus on the improvement of simulation algorithms; others only use VR as a visualization tool, ignoring the communication between simulation software and VR systems. To make a better use of acoustic simulation connecting VR systems for industrial applications, it's necessary to connect it to VR systems.

This thesis attempts to contribute to the noise investigation through combining acoustic simulation and VR. The acoustics simulation provides the necessary data and VR is considered to be an ideal implementation platform for simulation and visualization. Although the acoustic measurements are expensive and complex, data from an actual factory provides important input and validation of the simulation, as well as information for further investigation. Hence, the sound pressure and sound energy measurements are taken from a real factory. This factory is then recreated in 3D with geometric details, which provides the basic input data for acoustic simulation and visualization in VR. To facilitate the use of acoustic simulation and enhance the data interface between simulation and VR, a software tool is designed based on the research proposition and application scenario. Several issues are taken into account, such as the converting of file formats, control of simulation processing, and generation of user interfaces.

This thesis is structured as follows. Chapter 2 provides an overview of related research topics and current research. First, the noise issues in manufacturing, general knowledge of noise effects and the established noise investigation methods are introduced. Second, the basic laws of sound waves, acoustic modeling and simulation, and visualization methods are described. The third part provides a brief introduction of VR, including the historic development, term definition, system components, and main features. Then, a review of current VR application from manufacturing system level to the workstation level are presented and summarized. Chapter 3 introduces the main research question in this thesis and defines the key tasks and requirements. Based on research question, chapter 4 describes the development of research approach in five steps. Data acquisition step of the design introduces the required data, the methods to collect the data from an actual factory, acoustic measurements, and a legal regulation study. The modeling step provides a guide to model a virtual manufacturing environment, a sound source, and a human model (avatar). The acoustic simulation step introduces the implementation of "phonon tracing" and "phonon collection" for sound wave simulation and visualization. The last two steps introduce the connection between sound simulation and the VR system, as well as the required hardware and software configurations. Chapter 5 presents the implementation process of the software tool. The software architecture, data basis, user interface design and distributed computing concept are discussed. In chapter 6, several use cases are used to validate the software tools and sound simulation in a virtual factory. The result provides an evaluation of proposed approach and the software tool. Chapter 7 provides a summary of the entire research work and an outlook for further development.

2 State of the Art

In manufacturing systems, noise is an important issue which affects the health and safety of workers, as well as the working efficiency. Therefore, the impact of noise in a factory, selected legal regulations, and some established investigation and control methods are described. To handle such issues, different computer aided methods are implemented, such as the acoustic simulation and visualization. Therefore, brief introduction of these methods is made. Further chapters give an overview of the VR technologies and their recent development. And the implemented applications in manufacturing systems are discussed, which enables a systematic analysis and comparison of current research work in VR field. Based on the information presented here, the main research questions and involved tasks will be defined in later chapter.

2.1 Noise in manufacturing systems

2.1.1 Effects of noise in a factory

The factory workers are exposed to any number of occupational hazards every day, such as chemical solvent, heat, vibration, bad lighting, etc. The noise issue is among these hazards, which is starting point of this thesis. Noise in a factory can be caused by machinery, power tools or other activities, which can influence employees' health and even cause diseases. According to Deutsches Institut für Normung (DIN) standard 1320 and Association of German Engineers (VDI, Verein Deutscher Ingenieure) standard 99, noise is described as unwanted sound causing disorder and health problems. When the noise exceeds specific limits, the risks of hearing loss or other sicknesses increase. Figure 1 shows a brief identification of the noise influences to humans at different SPLs [Fuch10, Mart94, Work02 and Hoes75].

Example sound source	SPL dB(A)	Effect to human
Rocket launching	180	Hearing loss
Jet engine	150	
Rivet hammer	130	
Sheet metal factory	110	Pain threshold
Heavy traffic	90	
Noisy restaurant	70	Productivity loss
Light auto traffic	50	
Soft whisper	30	Sleep disturbance
	0	Hearing threshold
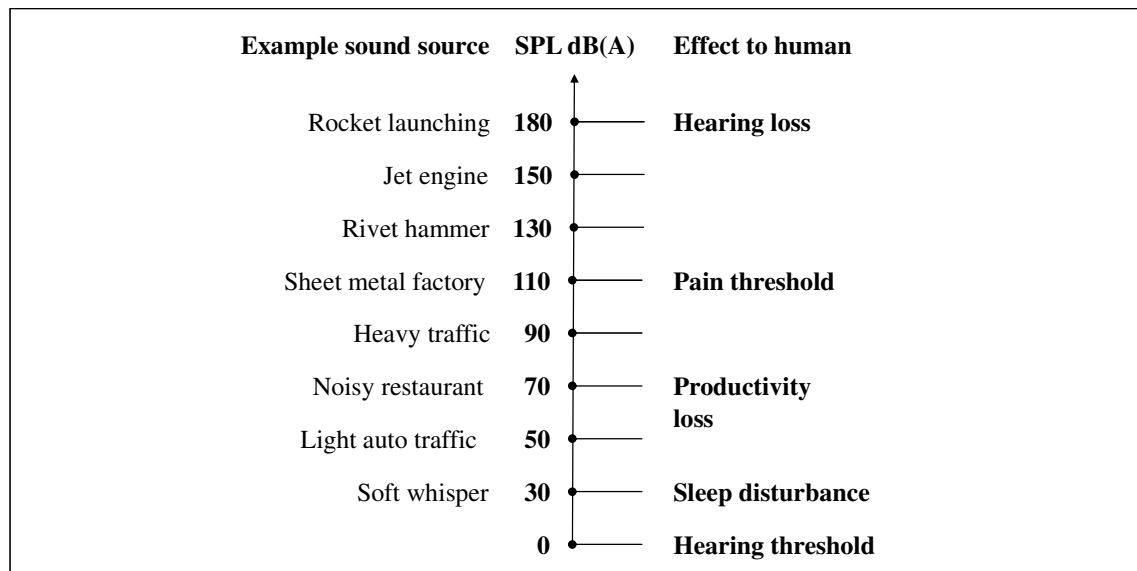
Figure 1: Scale of SPLs in common situations

In acoustics, the SPL is usually used to measure the effective pressure of a sound wave (*P*) relative to a reference value (*P*$_0$). The unit of SPL (*L*$_p$) is decibel (dB), which is converted from sound pressure unit Pascal (Pa).The basic calculation is: $L_p = 20 \lg (P/P_0)$ in dB

Noise is becoming one of the most frequent occupational hazards in manufacturing. A literature study shows that the well-established investigations are made in different countries. The following facts show the importance of this issue.

❑ According to the investigation of the Federal Institute for Occupational Safety and Health (BAuA), about five million employees are exposed to noise in Germany [Schm09 and BAuA11]. Figure 2 shows the recognized occupational diseases and patient rates in 2009, which is based on German Statutory Accident Insurance (DGUV) data. About 34% occupational diseases belong to noise-induced hearing loss and the accident insurances pay about 170 million Euros every year for those cases. Especially in metal manufacturing enterprises, the proportion of noise related diseases is 41% of all recognized occupational diseases cases [Schm09].
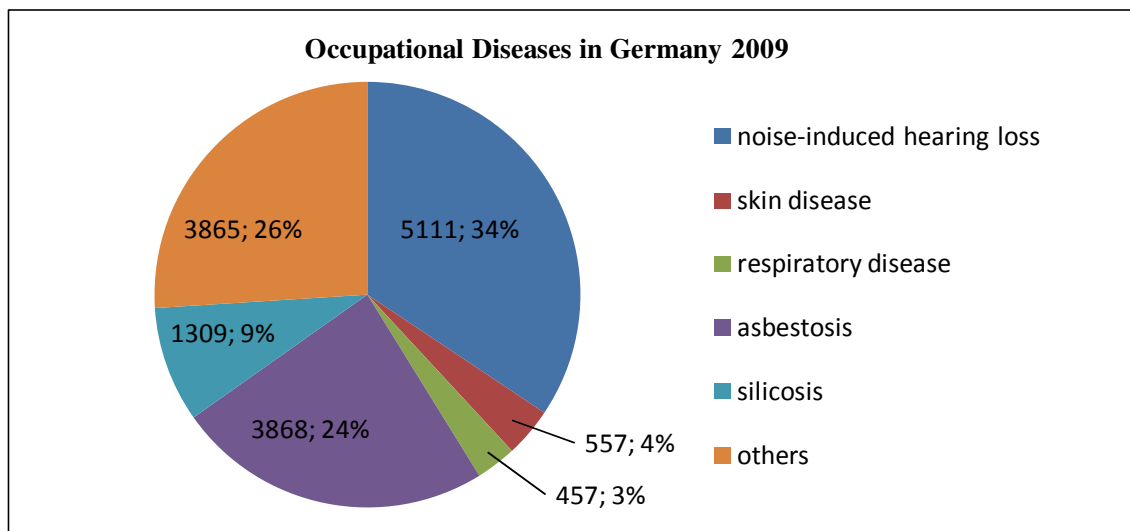
Figure 2: Recognized occupational diseases in Germany 2009, based on DGUV data

❑ In Singapore, an investigation was made in small and medium-sized enterprises (SME). Over 38,000 workers are examined by designated factory doctors annually. Among them, about 88% are due to noise exposure [Phoo90].

❑ CLARK stated in 1991 that over six million workers in the USA are exposed to hazardous noise [Clar91]. According to the evaluation by Centers for Disease Control and Prevention in 2011, approximately 22 million workers in the United States are exposed to hazardous noise levels at work. An estimated 242 million dollars are spent annually on workers' compensation for hearing loss disability [CDC11].

❑ There is no national standard in Kuwait. Therefore, the researchers investigated the industrial noise pollution in Kuwait according to the UK standard (British Noise at Work Regulation of 1989). The research results show that the workers at all five investigated manufacturing facilities, such as cutting, canning or packing, are exposed to noise louder than allowed minimum values [Khur00].

❑ A study of the Health and Safety Executive estimated that as many as 170,000 people in England suffer from deafness, tinnitus, and other hearing difficulties resulting from

exposure to noise at work. And over one million employees are estimated to be exposed to potentially harmful levels of noise [Brit10]. From 1991 to 1995, members of UK Association of British Insurers handled about 230,000 noise related claims for deafness [ABI96]. Furthermore, in the period from 2008 to 2009, 210 people in England qualified as new cases of noise caused deafness (permanent hearing loss) based on the statistical data from the Industrial Injuries Disablement Benefit (IIDB) scheme (see appendix 11.1).

❑ In the study made by CHEW and LIN in Hong Kong at 1988, more than a thousand workers were examined. 37.5% were found to be working in locations with the noise level in excess of the limit and 18.6% were found to have industrial hearing loss [Wong90].

The impacts of noise to the workers in manufacturing systems are classified into three main categories: occupational safety, negative health impact and preservation of work performance. They are described as follows:

❑ The occupational safety: according to International Organization for Standardization (ISO) 7731 [ISO03a], for workers' safety the loudness of warning signal in industries must be 15 dB louder than the ambient noise. The high noise level could cause the waning signal to be ignored which may cause accidents. Another case is the communication requirement among workers. The quality of lingual communication is deteriorated with excess noise in a working environment, another potential unsafe factor. More details about communication problems caused by noise refer to [ISO03b].

❑ The negative health impacts: health damages results from exposure to repeated or very loud noise at work. The health damage could be stress and tiredness, dizziness, hearing damage, temporary/permanent hearing loss, heart diseases, among others. However, the effects of noise caused hearing loss are irreversible, which means there is no cure if an employee's hearing has been lost [Brit10]. For other noise related health risks, such as physiological effects, loss of eye clarity, or loss of color perception and night vision refer to [VDI88, Kryt94 and VDI99].

❑ The preservation of work performance: Much research work discusses about the impact of noise to workers' performance. The results of studies point to the same conclusion. Different authors stated a significantly poorer performance when employees are exposed to noise [Sher90, Sund94 and Ljun07].

The costs paid for the negative effects of noise to employees are huge. "Such costs include not only the financial compensation or damages that must be paid, and the reduced enjoyment of everyday life for those with a hearing loss, but also less quantifiable factors such as reduced productivity, increased stress, disturbed speech communication and risk of accidents for a large number of workers." [Embl97] Therefore, a comprehensive approach to investigate the noise issue in earlier planning is necessary. The costs and time to take this issue into account in design and planning is considerably less than the costs for factory re-planning or the costs for employee compensations.

2.1.2 Legal regulations in Germany

The laws and guidelines for noise control differ among countries. Some examples are the British Noise at Work Regulation of 1989 in England, the US Occupational Safety and Health Administration (OSHA) standards of 1996 in USA, and the Law of the People's Republic of China on the Prevention and Control of Environmental Noise Pollution of 1996. These legislations show differences, such as the upper limits on noise over an eight hour period and

the limits of peak SPL. For example, the limitation of an eight hour average A-weighted SPL is 85 dB in Austria, Brazil, Finland and Germany, but 90 dB in Argentina, India, Japan, and some states in Canada. An overview of the main features of legislation in various countries can be found in 11.2 [Embl97]. The investigation in this thesis uses the legislations of Germany. Based on this study of the essential laws and guidelines, the noise limits to ensure employee health and safety in German industries are well-defined and used in this thesis's approach.

ASiG

The Germany's Occupational Safety Adviser Act "Gesetz über Betriebsärzte, Sicherheitsingenieure und andere Fachkräfte für Arbeitssicherheit (Arbeitssicherheitsgesetz - ASiG)" was legislated in 1973 and the last change was made in 2006. This Act defines the basic organizational structure of occupational safety and the employers' duties at operational level including their tasks, responsibilities and established collaboration. It can be used in combination with other occupational safety laws as guidelines for employers.

LärmVibrationsArbSchV

Commonly in the European Union, the minimum requirements to protect the workers from noise are determined by European Parliament and the Council with directive 2003/10/EC [EC03]. In 2007, the Federal Ministry of Labour and Social Affairs of Germany (BMAS) published the "Verordnung zum Schutz der Beschäftigten vor Gefährdungen durch Lärm und Vibrationen (Lärm- und Vibrations-Arbeitsschutzverordnung - LärmVibrationsArbSchV)" as guidelines for employers [BMAS07]. It is the German transposition of the European directive 2003/10/EC. This ordinance closed a gap in the German law for occupational safety and health. Since then, the 2003/10/EC directive has been adapted by using national legislation LärmVibrationsArbSchV. The most recent changes were made in 2010 (BGBl. I S. 964).

The main features of the both ordinances are identical. For example, based on §6 of LärmVibrationsArbschV, correspondingly §6 of 2003/10/EC, the upper and lower action values are provided to guide the noise control duties. The upper and lower action value of a eight hour average A-weighted ($L_{ex,\ 8h}$) are 85 dB(A) and 80 dB(A), respectively. Furthermore, the upper and lower action values of peak SPL (LC_{pk}) are 137 dB(C) and 135 dB(C), respectively.

With the new ordinance, employers have legal information about the limits of dangerous noise and risk assessment methods for the noise hazard. The employers are also responsible for informing the workers about the noise hazard and for providing the safety training and the appropriate health surveillance. In addition, the employees need to know the technical and organizational methods that can be used to eliminate or to reduce the risk of over-limited noise. It is an essential duty for the employers to train their workers about safe working practices to minimize the exposure to industrial noise.

UVV - Lärm

In 1989, the European directive 86/188/EWG was implemented in Germany by using the guideline "Unfallverhütungsvorschrift (UVV) - Lärm" (number BGV B3), which aims to reduce the risks of hearing damage and hearing loss resulting from working conditions. In

2007, the use in this guideline was replaced by LärmVibrationsArbSchV. The corresponding accident prevention measures were passed on the new directive.

ArbStättV

The workplace ordinance "Verordnung über Arbeitsstätten (Arbeitsstättenverordnung - ArbStättV)" was released in 2004 and the last change was made in 2010 (BGBl. I S. 2179). In this ordinance, the setup and operation of the workplace with respect to the safety and health of employees are established. Chapter §2 defines the term *noise* and *noise hazard* in industry and further defines an area of noise over 85dB as noise endangered area. Chapter §15 establishes the upper limits of noise in different work areas, namely the labor, office, industry and social room. This ordinance also suggests that the noise should be kept as low as possible given the nature of the undertaking. The action values of A-weighted SPL and peak SPL are identical to the defined action values in LärmVibrationsArbSchV.

TA Lärm

Based on §48 chapter of the national law BlmSchG, the guideline "Technische Anleitung zum Schutz gegen Lärm mit Erläuterungen (TA Lärm)" was made (GMBl Nr. 26/1998 S. 503). It aims to protect the neighborhood and the general public from the harmful effects of noise and prevent negative environmental effects caused by noise. It provides many realistic based methods and tools to measure, analyze, and evaluate the effects caused by noise emitted from industry. Different limitations for day and night time are provided, with the area types, such as the pure residential area, the mixed residential area, and the pure industry area taken into consideration.

VDI 2058

This German directive, which was established by VDI, aims to provide guidelines for assessment of industrial noise and prevent its negative effects in the neighborhood. This directive is not a law, but as a collection of expert options, it is still essential reference for noise control. Therefore, it is now often implemented together with "TA Lärm" and is as generally the accepted principle for manufacturers in Germany.

	Indoor Area			
Legislations	LärmVibrationsArbSchV and ArbStättV			
Situation	lower action value	upper action value	exposure threshold	exceptional situation
Limitation of SPL (A) $L_{ex, 8h}$	80 dB(A)	85 dB(A)	87 dB(A)	90 dB(A)
Limitation of Peak SPL LC_{pk}	135 dB(C)	137 dB(C)	140 dB(C)	
	Outdoor Area			
Legislations	TA Lärm and VDI 2058			
Situation	day, industry area	night, industry area	day, mixed area	night, mixed area
Limitation of SPL (A) $L_{ex, 8h}$	65 dB(A)	50 dB(A)	60 dB(A)	45 dB(A)

Table 2-1: A brief summary of various legal limitations in Germany

According to the study of these laws, directives and guidelines, the limitations of A-weighted SPL and peak SPL that are implemented in German industry are listed in Table 2-1. For an

indoor area, the lower action value, upper action value and the exposure threshold of SPL are 80dB, 85dB and 87dB, respectively. They are the most essential limitations for noise control in a factory. The actions to be implemented as the limits are exceeded are shown in next section. For outdoor limitation for the two typical areas in day and night are also shown in Table 2-1. However, this thesis focuses on the indoor acoustic simulation and evaluation. In addition, the simulation algorithms and approach for indoor and outdoor areas are fundamentally different. Therefore, the investigation of outdoor area limitations is not further considered.

Duties of employers

The laws and guidelines require employers to act on the noise risks, namely to eliminate or reduce the risks from exposure to noise. Specific duties are also placed on employers when the noise exposure to average SPL and peak SPL reach certain limits. Then, the corresponding methods should be implemented in the factory. Table 2-2 provides an overview of these methods at different limitations, which are based on the investigation of LärmVibrationsArbSchV and ArbStättV [Schm09].

Duties of employer at different action values and limitations								
	Information Provided for Staffs							
	information, introduction on the risks posed by noise and and training on protection methods							
		general information and instruction of occupational health						
	Hearing Protection							
		provided suitable and sufficient hearing protection						
							required hearing protection	
	Preventive Medical Examinations							
		provided health surveillance				required medical examination		
	Additional Measures							
						identified noise areas		
							noise reduction programs	
L$_{ex, 8h}$ dB(A)	80	81	82	83	84	85	86	≥ 87
LC$_{pk}$ dB(C)	135	136				137	138	≥ 140

Table 2-2: Employer duties as this noise arrived specific limits [Schm09]

At the lower action value (average SPL of 80dB or peak SPL of 135dB) employers have a duty to provide their employees information on the risks posed by noise and about how to protect themselves. Hearing protection methods and wearable equipment, as well as the health surveillance, should also be provided by employers at the lower action value.

Additional measures are required as the noise level reaches the upper action value (average SPL of 85dB or peak SPL of 137dB). The employers have a legal duty to identify/mark the noise area and make sure the workers are protected by wearing ear protections. The blue sign to identify the noise threatened area is shown in Figure 3a. If the noise evaluation shows that the workers are often exposed at or above upper action value, the employers have to implement suitable noise reduction measures. More investigation about noise control and employer duties can be found in [Hoes75 and Brit10].

Figure 3: The sign of a noise-identified area (a) and various hearing protection tools (b)

2.1.3 Noise investigation and reduction

To evaluate the noise risks and to select suitable noise control measures in a factory, a few methods are commonly implemented. These methods include the identifications of noise types, noise sources, noise related effects, hearing protection methods, and the noise assessments. They are listed as follows [Brit10]:

❑ Identify the different types of noise in the workplace. Usually all sound sources are taken into account, from speech between employees to the sound from machinery.

❑ Identify people who might be exposed to noise. The exposure time and area are recorded as well.

❑ Estimate the employees' noise exposures and compare them with legal limits.

❑ Identify the types of noise measurements that are needed.

❑ Identify the types of hearing protection that are needed. Determine protection method which is best for each employee based on their noise exposure.

❑ The results of health surveillance are taken into account.

❑ Record all results of noise assessment in factories.

❑ Update the assessment regularly, etc.

These measures ensure a step by step noise investigation in a factory. However, most of these measures are based on the measurements and surveys once a factory is running. An early check during factory planning is not possible. Due to the high costs and time, subsequent adaptions and modifications in a manufacturing system are preferred to be avoided. Therefore, an approach to enable the noise assessment during the factory and workplace design phase, with respect to the manufacturing processes and facilities, is required.

According to the noise analysis and evaluation, the methods to reduce noise in a factory are required in case of exceeded action values. SCHMISCHKE summarized the different methods and classified them into five main categories [Schm09]. These methods, shown in Figure 6, rang from technical solutions to organizational measures and personal protections. The primary methods are more efficient and more cost-effective than the secondary methods. The objective for implementing such methods is to create a better working environment, improve communication in the workplace, reduce stress, and reduce the risk of hearing damage.

The methods in the first category achieve to eliminate the noise sources directly. For example, selecting and using low-noise machines and manufacturing processes. Commonly, a duty of facility manufacturers is to provide the emission information of their products [VDI96 and EC06], so that the factory designer and production planner are able to compare and evaluate different facility choices in the design phase. In other words, the noise related risks should be reduced before the manufacturing system is established, if possible. It helps the employers to meet their legal obligations and reduces the need for additional sound reduction measures at a later stage, which mostly result in high costs. In [Fach07 and Brit10], the author provides a set of guidelines to help employers purchase quieter machineries.
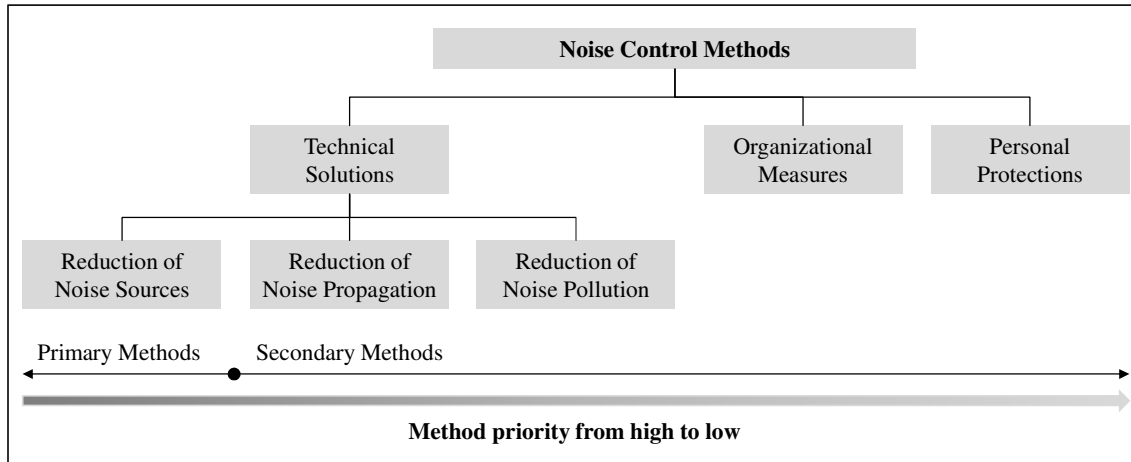
Figure 4: Noise reduction method classification

The methods in the second category focus on reducing the sound propagation through air and objects. Typical methods are encapsulation and shielding of noisy machinery, use of noise absorption materials to isolate the noise sources, or vibration isolation etc. [DIN10d and Möse10b]. The third category provides the noise reduction methods for noise polluted areas. Methods include building a cabin or using absorption shields. Figure 5 shows the cabin and shield products from the company J.I.M. GmbH. More suggestions and guidelines to implement cabins and shields in a manufacturing system can be found in [VDI83a and VDI83b]
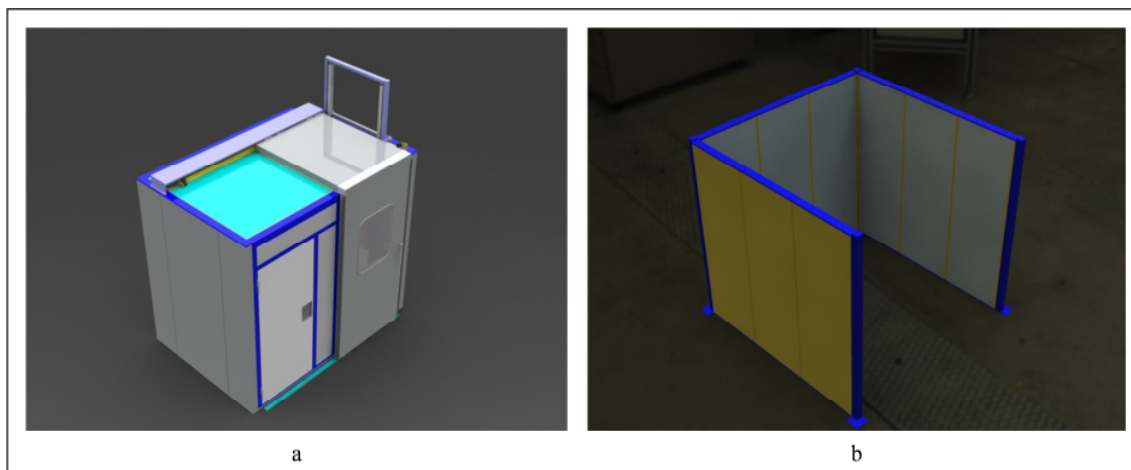
Figure 5: The noise isolation cabin (a) and noise absorption shield (b) [JIM12]

The organizational methods include factory layout planning and work scheduling related approaches. For example, the redesigning of the workplace and more breaks for the workers in a quiet social room. Such measures cannot reduce the noise and its propagation in a factory, but can reduce the negative effects of noise to the workers. The personal hearing protections would also be required. It is important for the employees to have a range of protectors to choose from, so that they can have the best suitable ones. Therefore, it is important for the employers to provide a wide range of hearing protection solutions and encourage their employees to use them. Some of the protectors, such as foam earplugs, pre-molded earplugs, earmuffs, and custom ear molds are shown in Figure 3b.

In addition to the typical noise control methods, Active Noise Control (ANC) approaches have rapidly developed in recent years. Limited by the high costs of hardware configuration, these methods are not widely implemented despite their efficient noise reduction effects. Several successful implementations can be found in military and aerospace use. Hansen provides a review of current and future ANC industrial application. Different essential components, such as sensor, controller and filter, are described. He also discusses the necessary further developments to overcome the technical limitations of ANC applications in industry [Hans05]. As an important supplement to currently widely used methods, ANC offers new potentials to improve the noise control systems in industrial applications.

2.2   Sound simulation and visualization

Nowadays, there are many established methods for sound simulation and sound visualization, which are widely implemented for computer games, multi-sensory user interface, or acoustic prototyping. These methods are mostly wave-based or geometric methods. This chapter provides an overview of the basic laws of sound propagation, as well as existing acoustic modeling and simulation approaches.

2.2.1   Basic laws of sound propagation

Both the wave-based method and geometric method of sound simulation are based on the fundamental physical laws of sound wave propagation. Phenomena such as reflection, refraction and absorption are used in the methods and are briefly introduced in this section.

A sound wavefront is commonly understood as a surface consisting of all points on a sound wave at the same position in a wave cycle. That means all of the points located on the crests or troughs of the same wave form a sound wavefront. Based on Huygens's principle, a basic physical law which interprets the propagation of waves, the sound envelope of sound waves can be understood well. The Dutch physicist CHRISTIAN HUYGENS states that: every point of a wavefront may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the waves [Grim91]. Figure 6a and Figure 6b show the propagation of plane and spherical sound wavefronts respectively. HUYGENS's principle shows that both the plane and spherical wavefronts resemble plane wavefronts as they travel. Each of the spherical wavelets for all of the points on each wavefront has the same radius and travels to another plane wave (the sound speed is considered as constant). And as shown in the figure with the arrow, the direction in which the spherical wavelets travel is locally perpendicular to the wavefronts.
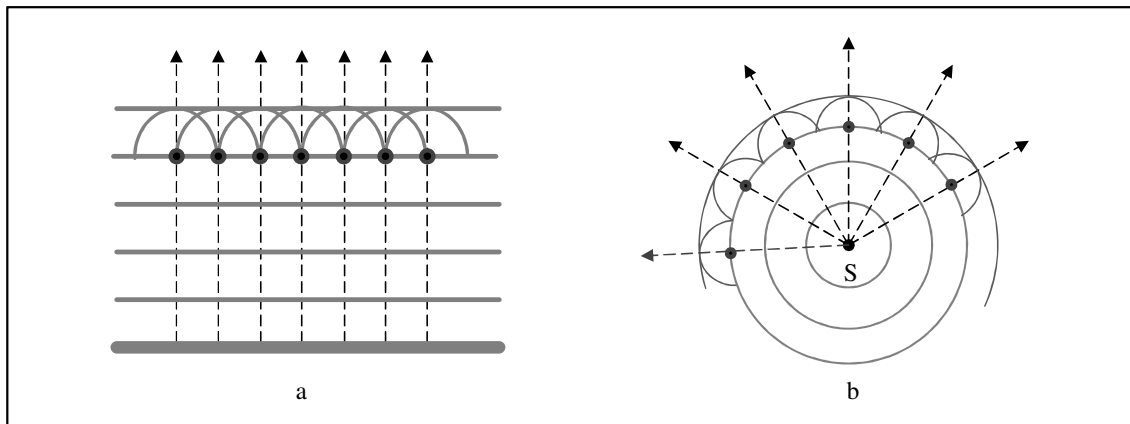
Figure 6: The illustration of plane wavefronts and spherical wavefronts [Dein08]

When the sound wave leaves one medium and enters another one, a portion of the sound wave will be absorbed by the medium (absorption), while the rest reflects off of the medium surface (reflection). Secondary effects such as refraction, dissipation and diffraction are also involved. Using HUYGENS's principle, such phenomena during sound wave propagations can be explained well.

Reflection

The effect of reflection changes the direction of the waves that are emitted by the sound sources. A refection occurs when the sound wave bounces off a surface, such as a surface on a wall or a machine. The reflection of the sound wave follows the law "angle of incoming (incidence) equals angle of outgoing (reflection)", also known as the "law of reflection." The same phenomena are observed with light and other waves as well. Therefore, performing calculations using Huygens's law obtains identical results as NEWTON's geometric optics, which focuses on the particle principle of light.
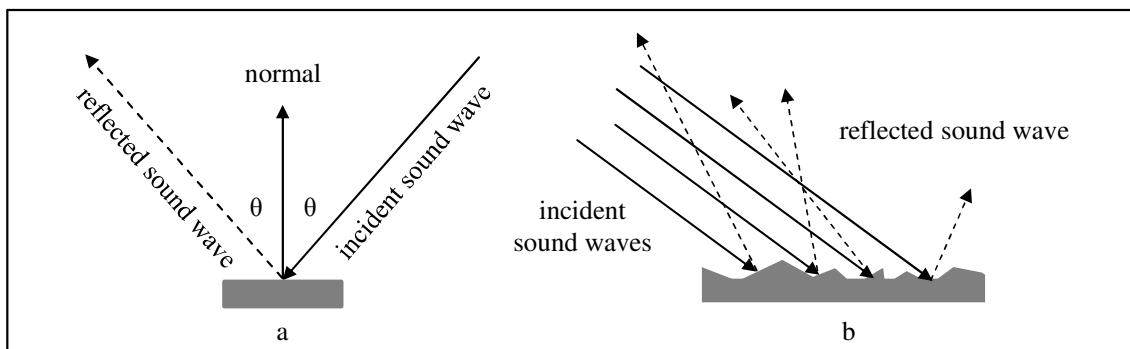
Figure 7: The illustration of sound wave reflection at surfaces (specular and diffuse)

According to the surface features, the reflections are divided into two types, specular reflection and diffuse reflection. Figure 7, illustrates both cases. If the reflecting surface is "smooth", for example a flat mirror, the sound wave reflexes specularly. The incident sound wave and the reflected sound wave are on the opposite sides of the normal with the same angle (Figure 7a). If the surface is not smooth, the sound waves are reflected unevenly in different directions, referred to as diffuse reflection (Figure 7b). For more discussion about diffusion effect, refer [Cowa94 and Embr01].The smoothness of surface is measured by using wave-length. If the dimensions of surface unevenness are considerably smaller than the wave-length then the sound wave is specularly reflected. Many common materials show a mixture

of specular and diffuse reflections. Due to their longer wave-lengths, for the sound waves at low frequencies it is easier to find a perfect reflector compared to the sound waves at high frequencies.

Absorption and refraction

When the incident sound wave strikes a surface, only a part of the energy is reflected back, the rest is absorbed by the material. The energy loss of a sound wave during absorption can be considered as two parts: refraction and dissipation. As a result of dissipation, the fibers or particles the absorbing material vibrate and cause heat due to the friction. In other words, the sound absorption is accomplished by way of energy to heat conversion. This also explains why a fibrous material is more absorptive than a denser material.

The velocity of a sound wave is dependent upon the properties of the medium through which the wave propagates. If the medium property changes, the wave velocity changes. Therefore, refraction occurs as the sound waves pass through from one medium to another in a changed direction due to changed wave velocity. Huygens's principle also explains the refraction phenomenon and is used to derive SNELL's law, also known as law of refraction. The refraction coefficient is able to be calculated through the ratio between the transmitted sound intensity and the incident sound intensity.

To describe the absorption property of a material surface, one factor and four coefficients are used. The reflection factor R expresses the amplitude and phase changes of a sound wave, which strikes a material surface and reflects back. The absolute value of R varies according to the frequency and to the direction of the incident sound wave. Then the reflection coefficient ρ is equal to $|R|^2$. Derived from the reflection coefficient, the absorption efficient is $\alpha = 1 - \rho$. For more details about the derivations, refer to [Kutt00].The absorption coefficient can be further divided into two parts: refraction coefficient τ and dissipation coefficient δ. The energy balance of a sound wave can be described using following formal: $\alpha + \tau + \delta = 1$ [Faso84].
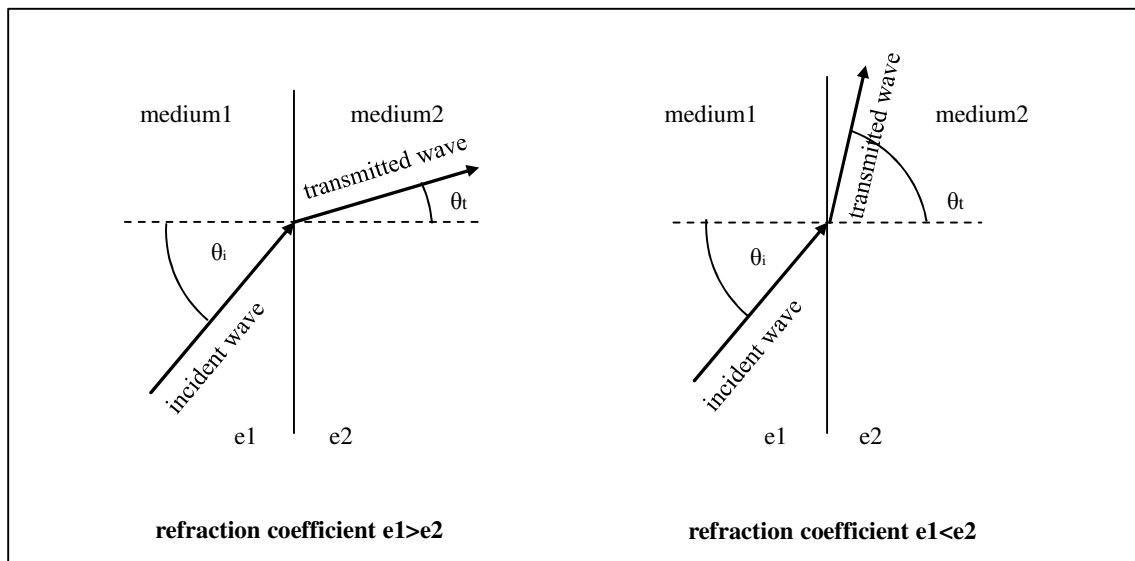

Figure 8: The refraction of sound waves

The absorption coefficient value at different frequencies can be determined by experimental approaches. A commonly used method is the KUNDT's tube measuring method, which is normed according to DIN EN ISO 10534-1 [DIN10a] and DIN EN ISO 10534-2 [DIN10b]. Two different measurement settings are respectively based on voltage standing wave ratio [DIN10a] and transfer function [DIN10b]. DIN EN ISO 354 shows another measuring method for estimating the absorption coefficient in a reverberation room [DIN03b]. Two reverberation times are measured, with or without a specimen placed in a reverberation room. The sound absorption coefficient of the acoustic material for various angles of sound incidences is then averaged. This method is widely implemented as an evaluation index for acoustic design of a concert hall, interior materials for automobiles, or construction materials. Both of these two methods are limited to laboratory measuring conditions, while the ADRIENN-method is more application-related. Using this method, the absorption coefficient is calculated by determining the difference between the impulse responses in empty space and in front of the measuring surface.

Air which absorbs sound is a medium in most working space. The amount of the absorption is dependent upon the frequency, the relative air humidity, the air temperature and the environmental pressure. The sound intensity after absorption can be calculated through the original sound intensity at the source, the distance the wave travelled, and the attenuation coefficient [Kutt00]. Some of the attenuation coefficients at 20 ^{o}C and normal environment pressure are shown in Table 2-3. For the calculation, refer to [Bass90].

Relative Humidity in %	Frequency in kHz						
	0.5	**1.0**	**2.0**	**3.0**	**4.0**	**6**	**8**
40	0.60	1.07	2.58	5.03	8.40	17.71	30.00
50	0.63	1.08	2.28	4.20	6.84	14.26	24.29
60	0.64	1.11	2.14	3.72	5.91	12.08	20.52
70	0.64	1.15	2.08	3.45	5.32	10.62	17.91

Table 2-3: Example air attenuation coefficients at 20 ^{o}C with normal pressure [Kutt00]

Diffraction

Diffractions occur when a sound wave goes through an opening within a barrier. According to the HUYGENS's principle, every point of the sound wave within the opening can be considered as a newly created circular wave which propagates outward from the opening (see Figure 9).
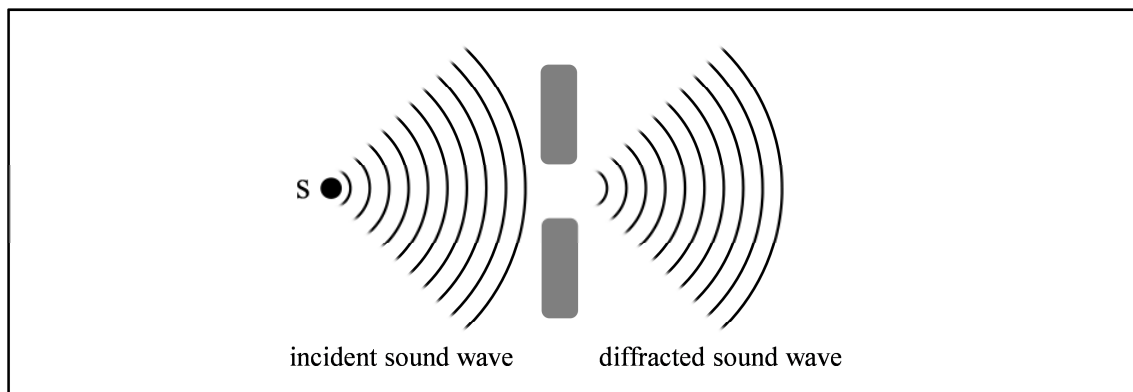

incident sound wave   diffracted sound wave

Figure 9: The diffractions of sound waves

In other words, the sound bends around a change of medium [Berg95], which is why sound can be heard around corners or behind a barrier between the sound source and the listener [Crem78]. The diffractions occur often around bigger objects, such as tables and lathes, while small objects, such as bottles and cups, have little effect on the sound wave propagation.

2.2.2   Acoustic modeling and simulation

In order to determine the influences of noise in a factory, the acoustic simulations rebuild the sound propagation processes, enhancing the understanding of noise behavior. Based on the literature review, an overview of the different simulation methods is provided in this chapter. The methods are commonly divided into numerical and geometric methods. A survey of those methods is also given in [Rabe97, Sche98, Sven02, Dein08 and Silt10b].

The numerical methods, such as Finite Difference Time Domain (FDTD), Boundary Element Methods (BEM), and Finite Element Methods (FEM), rely on the first principles of physics. Discrete simulations are developed by discretization of Partial Differential Equations (PDE). They enable the exact physical modeling and simulation since the spatial and temporal step sizes are defined small enough. To ensure the accuracy, the step size has to be smaller than the wave length, but this causes the computational load to exceed today's desktop capabilities.

The geometric methods, such as the image source method, ray tracing and beam tracing methods, use a simplification of the sound propagation processes. The sound waves are considered as acoustic rays, which travel in the mediums and reflects at the boundaries of mediums according to the geometric laws. Compared to the numerical methods, the geometric methods improve the computational performance of sound simulation significantly, but at the cost of simplifying assumptions.

2.2.2.1   Numerical methods

The numerical methods, also known as wave-based methods, are based on Huygens's Principle and commonly use the KIRCHHOFF-HELMHOLTZ integral [Helm60, Kirc83, Born99 and Rile02]. They provide accurate solution of sound propagation and are independent of model complexity. However the computing performance is limited at low and middle frequencies.

The FDTD method is one of the grid-based differential time-domain numerical modeling methods, which uses a Cartesian grid for discretization [Yee66]. A FDTD formulation without a Cartesian grid is also implemented in [Bott95]. In traditional FDTD methods for sound propagation simulation, the sound pressure and volume velocity are needed and determined for each grid point. However, using only one variable is also possible [Savi10]. The corresponding PDE are estimated using finite difference functions simplifying the solution of the system. The implementation of the FDTD methods is straightforward and all the calculations are done in the time domain. More discussions of FDTD methods can be found in [Bott95, Savi02, Wils04 and Savi10].

In FEM, the computational domain is subdivided into small volumes called elements. Each element is assigned to a size and a constitutive behavior that describes the acoustic material properties to which the element belongs [Ihle98 and Brae03]. For a closed space, the wave equations could preferably be solved using FEM, which approximates the wave equations by a large system of ordinary differential equations (ODEs). However, the FEM simulation is not

able to simulate the sound waves at high frequencies because it approximates the oscillating pressure field by smoothly. To resolve a wave, at least three or four elements per wave are needed, leading to a huge number of degrees of freedom. For more implementations of FEM simulation in acoustic investigation, refer to [Kopu95 and Kaga98]

The BEMs are numerical computational methods to solve linear PDEs that are formulated as integral equations (such as KIRCHHOFF-HELMHOLTZ equation). This method is widely applied in science and engineering areas [Bane94], including the acoustic investigations [Kopu95 and Wu00]. The BEMs only subdivide the boundaries of the considered environment, not the entire surface or volume. In the FEM or FDTD simulations, the whole domain of the PDEs is discretized. The basic idea is to describe the propagation of sound waves in the interior of the domain by means of the static variables at the boundary. And the estimation of the sound pressure or velocity is a linear combination of a finite number of basic functions on the elements. Hence, the BEM is often applied because it is easier to use and more computationally efficient than the FEM and FDTD methods [Kaga92 and Kopu95].

Such numerical methods for sound simulation are mainly used at low frequencies and for simple geometric models, because the computing time and storage space increase dramatically at higher frequencies. Therefore, due the time and memory consuming, FEM and BEM methods are not often used for interactive virtual environment applications.

2.2.2.2 *Geometric methods*

Sound, like light, is also a wave. Therefore, many geometric methods for sound propagation modeling and simulation are inspired by methods in computer graphics, such as the ray tracing related, beam tracing related, and radiosity related methods. Some essential differences between light and sound were considered and taken into account during the method development for this thesis. For example, the sound wave has a much longer wave length than light, so diffractions around small objects are not remarkable. As a result, the geometry for sound simulation is usually large scaled and with a low level of detail. For more different considerations between the methods from computer graphic and sound wave simulation, refer to [Sche98, Dein08 and Silt10b].

Image source methods

The image source method is the simplest solution of the geometric simulation methods which treats boundary problems. Figure 10 shows the basic idea of image source method: new sound sources model the specular reflections. The sound effect caused by the reflected sound source S at the surface 1 is simplified to the sound effect caused by a new sound source S_1, which is reduced by absorption. For simple geometries, construction of image sources up to certain number of reflection times is easy. Based on the image source simulation, the SPL at the listener position can be calculated by using all the new generated sound sources (virtual sound sources).

However, the number of virtual sound sources increases remarkably with geometry complexity and exponentially with the number of times the reflection occurred. Therefore, this method is usually implemented for simple geometry and a low number of reflection order cases. More details about image source method can be found in [Alle79, Bori84, Kris93 and Rabe97].
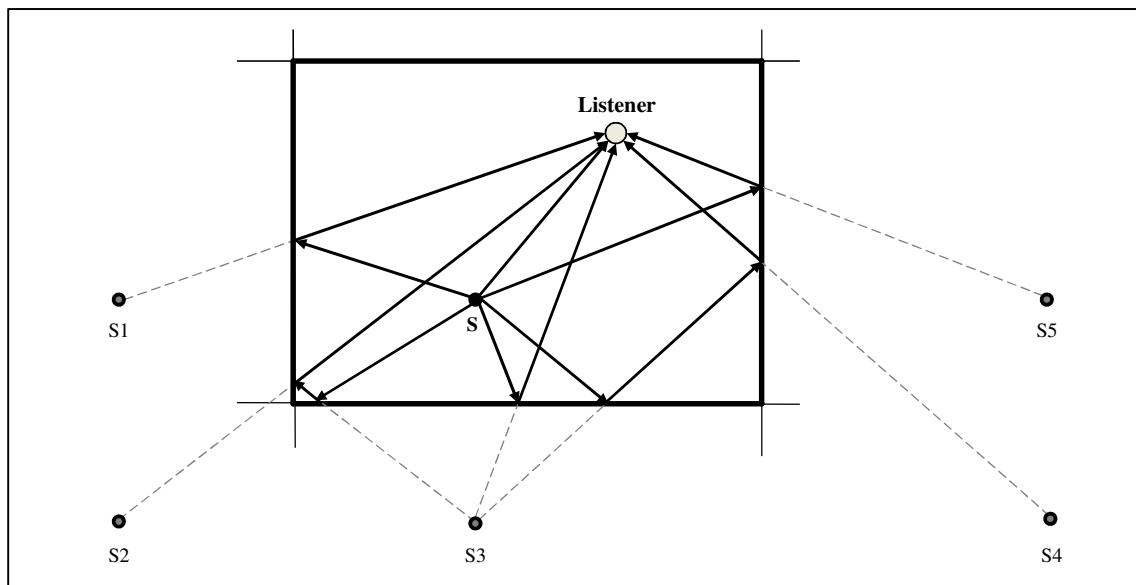
Figure 10: Illustrated principle of image source [Rabe97]

Ray tracing related methods

Specular reflection is well simulated in the image source method, but diffuse reflection needs other methods. In the ray tracing method, reverberation paths between a source and listener are determined by emitting rays from the sound source position and following them through the room until an appropriate set of rays reach a representation of the listener position [Kroc68 and Kulo84]. Monte Carlo path tracing methods are used to generate paths from the source to the receiver randomly.

The ray tracing method depends on the calculation of the intersections between rays and surfaces and the energy loss in the paths. Therefore, the computing complexity increases sub linearly with the number of surfaces. When each intersection is found, the paths of specular reflections, diffuse reflections, diffractions, and refractions can be sampled [Cook84]. However, the discretely sampled set of paths leads to aliasing and errors in predicted room responses. Moreover, the results are dependent on listener position dependent, so that a recalculation is required if the listener moves in the room. More discussion of advantages and disadvantages of the ray tracing method can be found in [Kaji86 and Lehn93].

Figure 11: Illustrated basic principle of ray tracing method [Funk98]

Beam tracing related method

Beam Tracing can be considered an improvement of the ray tracing method [Funk98]. The ray line, whose thickness is zero, is replaced with pyramidal beam. In beam tracing, the intersection between beams and surfaces (polygons) are detected. The original bea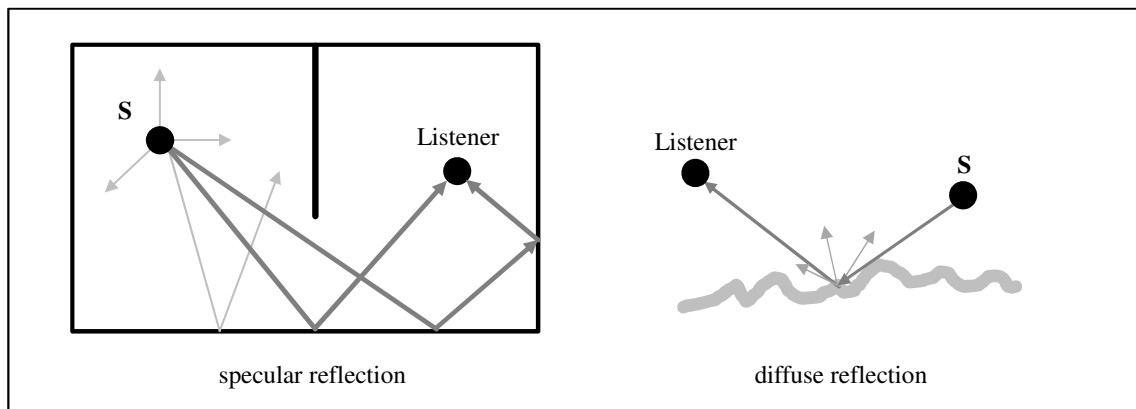ms are split into transmission beams and reflection beams. The transmission beams are used to determine the shadow region and the reflection beams are constructed by mirroring the transmission beam over the polygon's plane. This basic idea is shown in Figure 12. This method has been widely used in acoustic modeling [Dado85, Funk98 and Funk99] and radio wave propagation [Fort99].
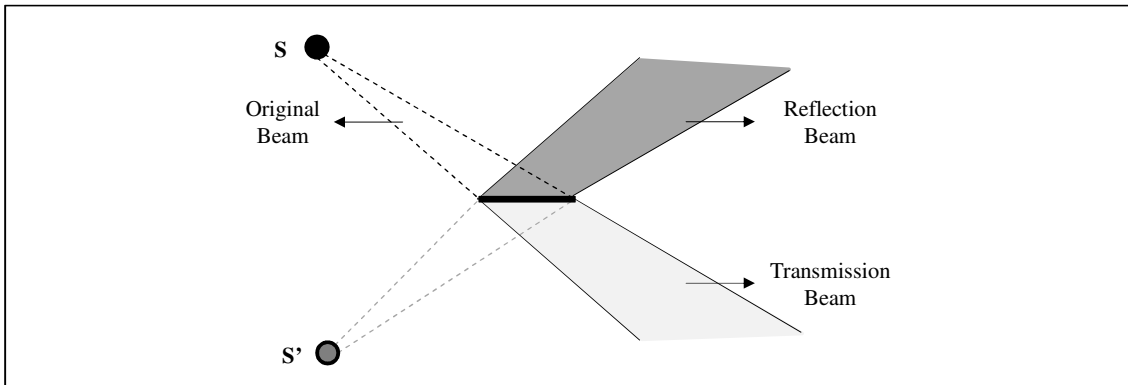
Figure 12: Illustrated basic principle of beam tracing method [Funk98]

When compared to the image source method, the beam tracing method needs less virtual sources for simulation. The beam tracing method has also the advantage of spatial coherence when compared to the ray tracing method. For interactive application, such as the VR applications, beam tracing results can be pre-computed to enhance the usability of the applications. However, similar the image source method, beam tracing cannot handle complex geometry, especially curved surfaces, and depends on listener position.

Radiosity related methods

Another type of geometric method is the radiosity method, which was originally used in thermodynamics [Sieg81] and further implemented in computer graphics [Cohe85]. Unlike the image source and ray tracing methods, the radiosity method is a listener position independent algorithm. Based on the input of geometry and sound source features, the sound field within the geometry can be constructed without recalculation when the listener moves.
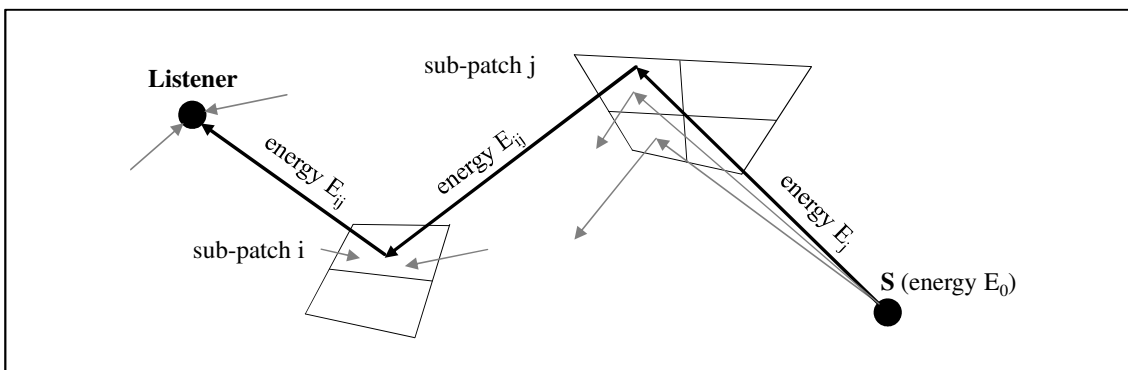
Figure 13: Illustration of the radiosity method [Cohe85]

The basic idea of radiosity is to calculate the wave energy within the given environment. The space is split into more finite sub-patches and the energy transfers among them are determined (Figure 13). As compared to the FEM simulation, the size of each patch does not have to be smaller than the wave length, so this method is more efficient than FEM.

However, the energy exchange between two patches is commonly defined through the so-called form factor, whose calculation is time consuming. In [Shi93], an algorithm is introduced to use the radiosity method for sound wave simulation. The air absorption and time delay of arriving sound are considered in this algorithm. More introduction and improved computation approaches can be found in [Nosa04].

**More acoustic simulation methods**

In addition to the previously discussed methods, there are also computer aided approaches, which are implemented for sound wave propagation modeling and simulation. Some of them are inspired by the computer graphic methods and others combine two or more basic methods to overcome the disadvantages of a single method.

❑ The radiance method is closely related to radiosity method. The main difference is that the radiosity methods uses Lambertian diffuse reflection algorithms, while the radiance method allows for any directions of reflection. SILTANEN et al. introduced an adapted radiance method for sound wave implementation. The hybrid modeling brings benefits by combining the advantages of the beam tracing and radiance methods [Silt07b and Silt10a].

❑ Inspired by photon mapping, another geometric method called sonel mapping is introduced in [Kapr04 and Kapr06]. The sonel mapping is a particle based Monte Carlo method and can be implemented for acoustic calculations for complex geometries. Sonel mapping is a two stage method which enables the modeling and simulation of sound specular reflection, diffuse reflection and diffraction. In the first stage, sound particles called sonels are traced through the virtual scene in order to populate the sonel map. This map is then used in the second stage called the rendering stage. In combination with distribution ray tracing, the rendering stage calculates the echogram at a given listener position.

❑ The simulation software "ODEON" provides a hybrid method, which uses rays to discover the location of image sources. The ray cones are used to find valid image sources that could possibly be missed [Nayl93].

❑ In [Vorl88], the ray tracing method is used for visibility detection. Moreover, the ray tracing method is combined with image source method for calculation of direct sound and early reflection [Hein93].

❑ LEWERS represented another hybrid simulation method combining beam tracing with radiosity [Lewe93] in a two stage approach. Firstly, the triangular beams are traced in the space for calculation of early specular reflection. The diffuse energy is stored at the surfaces for each reflection. Secondly, the stored energy is used to determine the diffuse reverberant.

❑ To combine the advantages of image source method, tray/beam tracing methods and radiosity method, the quantized pyramidal beam tracing approach is introduced by STEPHENSON. The sound wave energy is carried with polygonal beams and split into reflection and diffraction. This method improves the computation time but used more memory [Step04].

❑ SCHIETTECATTE and NACKAERTS introduced a so called "mesh tracing" approach, which combines both the mesh-based numerical method and ray tracing method. Three computing steps are included: preprocess to create a randomized waveguide mesh, impulse response calculation for each pair of sound source and listener, and real-time reverberation using a fast convolution algorithm. This approach enables an acoustic simulation in real-rime [Schi03].

❑ To overcome the high computing expense of geometric methods in the case of complex geometry, TSINGOS et al. developed an improved method using programmable graphics hardware. This method can accelerate the simulation calculations and provide more realistic modeling scattering [Tsin07a and Tsin07b].

Phonon tracing method

Due to the computation complexity, the wave-based and geometric methods are not practical or efficient for large geometric models. An improved geometric approach called "phonon tracing" was developed by DEINES et al. to simulate sound propagation [Bert05, Dein06a, Dein08 and Dein10] and is introduced and implemented in this thesis. This method is inspired by the photon tracing method which uses the light particles called photons and simulates photo realistic images [Chri00 and Jens96]. Analogous to photon tracing, the phonon tracing method uses particles called "phonons" to model the sound source with defined acoustic energy. The simulation result is further used for visualization of wavefronts and evaluation of the sound energy, as well as sound pressure levels at different positions inside a virtual environment.

This phonon tracing method involves phonon emitting/tracing and phonon collecting/filtering processes. Using an unchanged sound source, only one tracing step is needed. The tracing only needs to be executed again if the sound source is changed. Based on the traced phonon map, more collections can be made for different listener positions. In the phonon emission step, the phonons emitted from the sound source carry defined information: energy, initial position, outgoing direction, and the distance traversed from the source. The emission is based on the given energy distribution, which is estimated as a sphere shape. The speed of phonons in the air is set as a constant. With each reflection, the phonon's sound pressure is decreased according to the material's absorption coefficient. At each reflection position (intersection point), the current sound pressure of the phonon is stored. The simulation can be terminated according to a pre-defined minimum number of phonons distributed to the phonon map or minimum number of reflections. These two conditions will be explained in chapter 4.

After the emission and tracing step, the phonon collection step calculates the influence of all phonons to a particular listener position. The information of all reflection positions is collected and weighted according to their distance to the listener. To trace the energy and the pressure for different frequency bands, the finite response filters (FIR) are used for each listener position. More details about filter design can be found in [Bert05].

In phonon tracing, all reflections are considered as specular reflection and the diffuse reflections are not taken into account. This simplification does not significantly affect the accuracy of the simulation, because sound wave lengths are long, therefore the diffuse reflection is usually not as considerable as light. However, the assumption is not true if the surface structure is not significantly smaller than the wave length. In order to model the diffusion, a scattering coefficient could be implemented to differentiate the reflection type

between specular and diffuse. If the implementation is done, the phonon emission step would be improved [Mich08].

Using phonon tracing, refraction and dissipation are both considered as absorption and are not separately computed, since only the reflected sound waves are essential in room acoustics. Compared to the wave-based methods, the phonon tracing method and other geometric methods fail in the low frequency range. There are two main reasons for this:

❑ Because the wave lengths of sound are long and of the order of typical dimensions of the room, the diffraction and interference are necessary to consider. However, they are however not taken into account in geometric methods.

❑ The air damping is commonly lower at lower frequencies so the reverberation time becomes much longer. Representing such a long reverberation time using reasonable length for a convolution kernel is difficult.

Due to the limitation of geometric methods, a combined approach could provide more ideal and accurate simulation. For example, DEINES suggested an additional wave-based method implementation to simulate the sound wave propagation at low and middle frequencies [Dein06b]. In this thesis, the simulation algorithm is not extended. However, based on the application scenario, a new software tool is made to facilitate the use of it.

2.2.2.3   Summary of sound modeling and simulation methods

A short summary and comparison of wave-based and geometric methods can be seen in Table 2-4. These methods are shown with a short description of the features, such as the input/out data, advantages and disadvantages, and the essential references used in this thesis. To compare the methods, several features, such as the computing performance, listener dependence, geometric applicability, frequency accuracy, are taken into account.

The selection between wave-based and geometric methods for a given frequency depends on the complexity and size of the model. For example, for small rooms the wave-based methods can be used in the mid-frequency range. But for large space such as factory halls, geometric models are needed. More discussion about the strengths and weaknesses of sound simulation methods can be found in [Rabe97, Sven02 and Silt10b].

In room acoustic investigation and especially in VR applications, most implemented methods are based on geometrical acoustics methods, due to the higher computing speed. Because the accuracy and performance fulfill the implementation requirements of current research work, the original phonon tracing is used in this thesis without any improvement.

		Data Input	Pros and Cons	References
Wave-based Methods	**Finite Difference Time Domain (FDTD)**	• sound position and time discreted pressure • grid discreted geometry	+ straightforward + ideal computing for low frequencies + operating in the time domain + accurate and robust − middle computational expense − restricted to low frequencies	Bott95 Savi02 Wils04 Savi10
	Boundary Element Method (BEM)	• position of sound source and sound energy • mesh discreted geometry • set of boundary conditions	+ very accurate + relative high computing speed + less discreted mesh +/− mesh size dependent computing speed − restricted to low frequencies − middle computational expense - only solves linear problems	Kaga92 Kopu95 Wu00 Sven02
	Finite Element Method (FEM)	• position of sound source and sound energy • mesh discreted geometry	+ very accurate + also solves nonlinear problems + many commercial software +/− mesh size dependent computing speed − restricted to low frequencies − high computational expense	Kopu95 Kaga98 Ihle98 Brae03
Geometric Methods	**Image source related method**	• position of sound source • position of listener • geometry with material acoustic properties	+ simple and robust + accurate for low ordered specular reflection + fast computing in box shaped geometry − not physical modeling − diffuse reflection is not considered − only for simple geometries, not for curved surfaces − only for low order of reflections	Alle79 Bori84 Kris93 Rabe97 Sven02
	Ray tracing related method	• position of spherical sound source • spherical listener position • geometry with material acoustic properties	+ easy to implement + efficient computing for complex geometry + generality for reflection, diffraction etc. − aliasing and errors in predicted room responses − to avoid possibly missed reverberation paths, a large number of samples are requried for computation − recalculation is needed for new listener postion	Kroc68 Kulo84 Cook84 Kaji86 Lehn93 Rabe97
	Radiosity related method	• sound source description • geometry with material acoustic properties	+ listner postion independent + efficient computing for complex geometry + ideal difuse reections − high computing expense	Shi93 Nosa04
	Beam tracing related method	• position of sound source • position of listener • geometry with material acoustic properties	+ less virtual sources + spatial coherence with less sample error + possible pre-computing for interactive applications − too complex for 3D geometry − only for simple geometries, not for curved surfaces	Dado85 Funk98 Funk99 Rabe97 Fort99
	Phonon tracing method	• position of spherical sound source with energy distribution • geometry with acoustic properties • position of listener	+ listner postion independent + efficient computing for complex geometry + pre-computing for finite response filter + reusable phonon map − diffuse reflection is not considered − restricted to high frequencies	Bert05 Dein06a Dein08 Dein10

Table 2-4: A comparison of main sound simulation methods

2.2.3 Visualization of sound propagation

Sound propagation can be described as data sets, which are complex, not intuitive, and difficult to understand. Visualization serves as a key method to improve verification of models, understanding of simulation results, design, and communication among a non-technical audience [Rohr00 and Kühn06]. According to the survey made by LOKKI and NENONEN [Lokk06], simulation, when compared to measurement data, enables several essential features of sound visualization, such as the ray/phonon paths, beam paths, particle clouds and diffractions. Therefore, high quality visualization enhances the understanding of data significantly.

The main acoustic visualization methods are divided into two groups. The first group of methods focuses on the propagation of the sound waves inside a room. Based on simulated results using the FDTD approach, YOKOTA et al. visualized sound propagation in 2D room sound fields [Yoko02]. PETRAUSCH and RABENSTEIN introduced an OpenGL based visualization of 2D sound wave propagation in real-time [Petr05]. BERTRAM et al. introduced their approach to visualize the frequency-dependent sound fronts in a room which enables the viewing of sound propagation in air and sound reflection at selected material and selected frequencies [Bert05]. This approach was further extended by DEINES et al. through more functions, such as the visualization of SPLs [Dein08]. In [Toki05], the authors represented the particle displacements in a cube-shaped room, which is pre-computed using wave-based simulation. Additionally, an implementation using VRML, enabling a time step dependent presentation, was shown.

The second group of methods focuses on the room impulse response for individual listener positions based on measured or simulated data. LOKKI and NENONEN provided a review of acoustic visualization and further implemented the visualization using the CAVE System, in which the trace paths and particle paths are shown. [Lokk06]. Based on the beam tracing approach, FUNKHOUSER et al. visualized source point, pyramidal beams, and reverberation paths, which enhance the understanding and evaluation of their modeling method [Funk98]. KHOURY et al. represented the visualized SPLs using color maps and the first wavefront using isosurfaces. The color maps provide not only sound propagation information but also an overview of sound pressure in a room [Khou98]. After optimization of acoustic systems, MONKS et al. introduced the visualization using different acoustic metrics. For example, the sound strength was visualized at room surfaces, which indicated the SPL at different time using colors. This approach enables the users to optimize their room design and compare the acoustic values between two designs [Monk00].

In this thesis, the visualization of acoustic simulation is basically an adaption and further development of the approach introduced by DEINES et al. [Bert05, Dein06a, Dein08 and Mich08]. Several visualization methods are implemented, which enables the viewing of the source point, phonon path, 3D sound front and SPLs at specific positions in a virtual environment. The simulation algorithm is not further developed, but the implementation of a software tool helps the user to use phonon tracing method to analyze noise issues in a manufacturing system.

2.3 Virtual Reality (VR) theory

2.3.1 A brief history and definitions

The human perception of the outside world is controlled by five senses: sight, hearing, touch, smell, and taste. If the sensory inputs are produced intentionally and artificially, commonly by computer technology, the reality could be called "Virtual Reality (VR)." The term "Virtual Reality" was introduced by JARON LANIER in 1986 in a conversation regarding the work of SCOTT FISHER, who used the term "Virtual Environment" in 1986 [Fish86].

MORTON L. HEILIG invented the first multi-sensory simulator named "Sensorama" (see Figure 14a) in 1957 and patented it in 1962. This mechanical device provided the users with an illusion using a 3D motion picture with smell, stereo sound, vibrations of the seat, and wind in the hair. This system was not interactive; the view was fixed and pre-recorded [Rhei91]. In fact, this invention is much older than the computer graphic field itself.

As a pioneer of computer graphics, SUTHERLAND wrote about "the ultimate display" in 1965, which is described as a device providing interactive graphics, tactile feedback, and mentioned audio, smell, and even taste [Suth65]. He invented a "Head-Mounted Display" (HMD) in 1968. This system had two displays which enabled the viewer to have a computer generated graphic overlaid on the real world [Suth68]. Together with his colleagues and students at the University of Utah, SUTHERLAND also developed fast algorithms for removing hidden surfaces from 3D graphics images. This contribution is essential to generate high quality visual image for a VR environment.
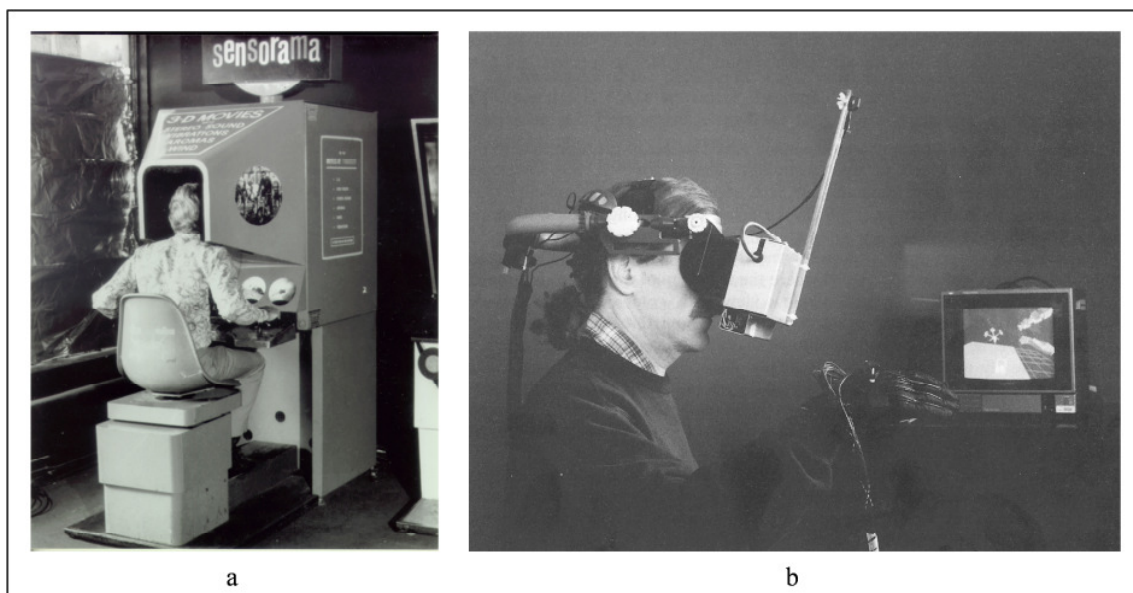
Figure 14: The Sensorama system (a) [Rhei91] and the VIVED system (b) [Fish86]

An implementation of a virtual environment named "VIVED" (VIrtual Visual Environment Display) at NASA Ames Research Center was made in 1984 [Fish86]. This system was a head-mounted, wide angle, stereoscopic display controlled by the user's position, voice and gestures (see Figure 14b). The VIVED is considered to be the first low-costs HMD with high immersive degree. Later, based on VIVED, an extension named VIEW (Virtual Interactive Environment Workstation) was implemented with the focus of human-computer interaction.

This project was under the direction of SCOTT FISHER. At the same time, Furness designed a virtual cockpit, which enabled a very wide field of vision, for fighter-airplane pilots [Furn86].

At the University of Wisconsin, KRUEGER worked on the development of his "Videoplace" system. In the graphic scene, the relation between the user's image and the virtual image could be controlled by the computer. Moreover, the movement of a virtual object could be coordinated with the actions of the user [Krue83].

DEFANTI and SANDIN developed the first functional gloves, "Sayre Glove," in 1977, which provided an effective method for multidimensional control. After that, GRIMES developed and patented a digital data entry glove in 1983. This glove integrated finger flex sensors, tactile sensors, orientation sensors, and wrist-positioning sensors. More details about gloves and gesture interface devices can be found in [Stur94 and Bier08].

The first virtual environment, with the concept of a graphic projected room, was invented at the Electronic Visualization Lab at the University of Illinois Chicago Circle in 1992. This system has been called "CAVE" (CAVE Automatic Virtual Environment) [Cruz92 and Cruz93] and significantly improved immersion in a virtual environment.

The rapid development of computer power and software development made it possible to create real-time images and visualize large-scale sets of data. More novel in/output devices were developed to enhance the human-computer-interaction. Each of these earlier efforts and attempts enabled the foundation and development of the VR concept. More investigation about the historic development of VR can be found in [Kala93a, Mazu96, Burd03, Bril08, and Zhou09].

Nowadays, VR is a comprehensively developed technology and widely implemented for scientific visualization, education and training, operation in hazardous environment, space exploration, entertainment etc. [Giga93 and McLe04]. VR became a highly multidisciplinary field drawing from computer graphics, human-computer-interaction, software engineering, and even social and psychological issues. However, there is not unambiguous definition of term "VR".

Under broad definition, VR is often referred to as "Cyberspace," "Artificial Reality," and "Virtual Environments." MYRON KRUEGER discussed "Artificial Reality" in 1983 [Krue83], and a year later, WILLIAM GIBSON used the term "Cyberspace" in his book "Neuromancer" [Gibs84]. The term "Artificial Reality" is described as a video-based, computer-mediated interactive media and the term "Cyberspace" has the meaning of a global information and entertainment network. However, these two definitions do not correctly describe VR. The term "Virtual Environment" is considered by many authors as synonym for VR [Furn86, Kala93a], because it involves the most essential features as VR. Based on a review of current research in field of VR and its applications, various definitions can be found in the literature. Some are selected and listed as follows:

❑ The definition made by SUTHERLAND was: "a system that can display information to all senses of the user with an equal or bigger resolution than the one that can be achieved in a natural way so that the user cannot say that the artificial world is not real." [Suth65]

❑ GIGANTE provided a definition of VR: "The illusion of participation in a synthetic environment rather than external observation of such an environment. VR relies on three

dimensional (3D), stereoscopic, head-tracked display, hand/body tracking and binaural sound. VR is an immersive, multisensory experience." [Giga93]

❑ BRIGGS defined VR in 1996: "Virtual reality can be defined as a three-dimensional, computer-generated simulation in which one can navigate around, interact with, and be immersed in another environment." [Brig96]

❑ According to BURDEA, "Virtual Reality is a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, and taste." [Burd03]

❑ MANETTA and BLADE defined VR in their book as "a computer system used to create an artificial world in which the user has the impression of being in that world and with the ability to navigate through the world and manipulate objects in the world." [Mane95]

❑ MCLELLAN defined VR "as a class of computer-controlled multisensory communication technologies that allow more intuitive interactions with data and involve human senses in new ways." [McLe04]

More attempts to define VR term can be found in [Steu92, Kala93a, Bane94, Bril08, VDI09, Zhao09, Zhou09 and Brac11]. Based on above definitions, two main perspectives can be found. The first perspective considers VR as a computer-based technology or an integration of more technologies. Another perspective focuses on the application of VR and sees VR as an artificial environment or a human-computer user interface. These two perspectives identify VR with respect to technical issues and application experience, but also cohere with each other. Therefore, some essential commonalities can be found in these various definitions:

❑ VR is a computer generated environment.

❑ The user can interact with virtual objects inside.

❑ Real human perceptions are created by artificial world.

In this thesis, the term VR, considering the further implementation in manufacturing systems, can be described as following: a virtual environment generated by combined communication and information technologies, in which the user can navigate, interact and manipulate the environment and its involved objects. Human perceptions, which exist in real world, will be enabled in the VR. The usability of the human-computer-system and the understanding to the objects, which are rebuilt in a virtual world, can be enhanced.

2.3.2 Main features of VR

In addition to term definition, the main features are important in order to distinguish one technology from the others. "Immersion", "Interaction" and "Imagination" are commonly understood as three main features of VR. BURDEA represented these three features in a three I's illustration [Burd93 and Burd03], which is shown in Figure 15a. Figure 15b extends these three features with their essential elements. Similar understanding of these features can also be found in [Kuhl99, Bier08, Bril08 and Brac11]. According to some authors, the "real-time simulation" is considered as the third essential features of VR, instead of "Imagination." The immersion experience can be improved significantly when the real-time simulation is integrated into the VR system. These features distinguish VR systems from other computer systems and illustrate the unique advantages of VR systems.
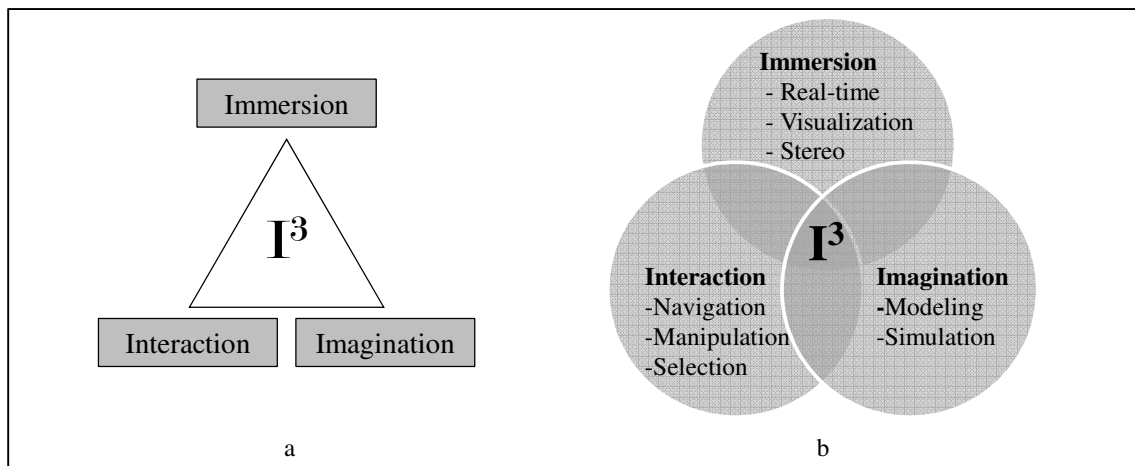
Figure 15: The three I's of VR systems [Burd93 and Burd03]

Interaction

Interaction is the possibility for the user to move within a virtual world or to interact with the objects in a virtual world. LUNENFELD defines interaction in two categories: extractive interaction and immersive interaction [Lune93]. When the user accesses information via hyperlinks, then it is an extractive interaction. When the user is immersed in a 3D world, then it is an immersive interaction. Each interaction approach can be implemented in a wide variety of ways. The objective is to establish a natural and intuitive mapping between a user action in the reality and the resulting action in the virtual world. VR interactions involve four basic components [Mine95]:

❑ Navigation: the simplest and the most essential interaction for users in a VR is to move through the virtual environment. To do that, the mapping of physical motion of users to virtual motion is needed. The correspondence between physical motion and virtual motion is an issue that needs to be considered. Navigation be one-to-one or a highly exaggerated correspondence. Some alternative methods to move through a virtual world which are independent of physical motion are also possible (e.g. flying by using a joystick).

❑ Selection: interaction with virtual objects requires different ways of object selection, such as the touching on grabbing of an object. There are two primary selection techniques: local and at-a-distance. The local technique means that the desired object is within reach and the user can interact with it directly (e.g. a touchscreen). If the user is not able to reach the objects, then the action-at-a-distance selection is required.

❑ Manipulation: it is one of the most important interactions in VR, which enables the user to change the specifications of an object's position, orientation or scale in a virtual world. Only if the virtual world is changeable, the interaction between virtual objects and participants can be considered as "real". The manipulation function is usually combined with selection and movement.

❑ Menu interaction: the menus and toolboxes in a virtual environment enable the user to change additional functions. For example, the user can set filters for complex data to show the useful information only. The menu interactions are distinguished by using different visual design (e.g. list menu or sphere menu) and selection mechanism (e.g. touching or clicking).

An interaction is also possible to be made between two people in two different virtual worlds or between one immersed person and another person in real world. More interaction possibilities are discussed in [Sher02, Bril08 and Zhao09]. The interaction techniques also rely on suitable hardware devices and VR systems. Some of the input devices are introduced in next section. Generally, no single interaction technique can fulfill all the needs of all tasks. Therefore, several different interaction techniques are usually required at the same time. A comprehensive review of different interaction methods is provided in [Bier08].

Immersion

The term "immersion" has been investigated by psychologists for long time and can be easily understood as "being there". CSIKSZENTMIHALYI defined immersion as "the state of being completely involved in an activity for its own sake and losing other unrelated perceptions is called as immersion" [Csik75]. In other words, the virtual environment created by VR allows the users to be in an artificial surrounding and to isolate themselves from the real world. This immersion perception is attributed to the high quality visualization with wide field of view as well as interactive user interfaces. Because of the missing perception from real world, the users can sometimes feel uncomfortable or even sick [Bril08]. LAVIOLA JR. provided a comprehensive investigation and discussion of the sickness phenomenon in virtual environment and called it "cybersickness" [LaVi00].

Immersion is directly related to real-time visualization and interaction issues. The quality of visual perception determines degree of immersion. SHERIDAN discussed the relation between immersion and interactivity. In order to obtain the feeling of immersion, the user must be able to move through the virtual world and to observe it under any point of view [Sher91]. THANH also investigated the increasing immersion degree by using more interaction functions with higher interaction degrees [Than10]. To enhance immersion, different input devices are needed, which simplify the creating and modifying of 3D models in a virtual environment. Some examples are 3D-Maus, data glove, and fly stick. Additionally, acoustic and tactile perception effects the immersion [Brac11]. The speed of image rendering and interaction is a key issue for immersion, so that real-time interactive graphic is required. BRILL also mentioned that, the interaction speed commonly depends on the hardware and software configurations [Bril08].

Imagination

ALBERT EINSTEIN said, "Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world." [Vier29] But in reality, imagination cannot be created without perception of knowledge. In VR, different data are visualized and enable the participants to have a comprehensive presentation of the artificially created world. To generate this "replacement" of the real world, modeling and simulation are key elements. Modeling tools enable a static description of existing and non-existing environments and objects in 3D, with realistic color, texture and lighting. Some VR systems allow direct modeling tools in a virtual environment, and others provide data interface for external modeling software. The simulation presents the dynamic process data for VR, such as the object moving, shape changing or time dependent processing. This enables the use of realistic exploring, training, and designing. The virtual world extends the human knowledge and encourages the people to image, overcoming the limits of existing knowledge.

2.3.3 Various VR systems

VR concept involves various computer technologies, such as real-time 3D graphic rendering, stereoscopic displays, viewer position tracking, gesture tracking/controlling, binaural sound, haptic in/output, etc. Based on the need of the application, users can design a suitable system with different system configurations. For example, KALAWSKY represented a simple and a comprehensive VR system in 1993. This full immersive enables the participants to interact with computer generated objects and artificial persons (avatars) [Kala93b].

2.3.3.1 Main components of a VR system

Nowadays, a typical VR system involves computer, VR software, input devices and output devices. The computer is used to install an operating system, to execute a simulation, to manage the data, and to compute different software tools. To enhance the computing performance, powerful computer servers and modern multimode computer systems for distributed computing are implemented [Pach06 and Jin07]. The proportion of computer costs for the whole VR system costs is continually decreasing.

The VR software provides the user with different functions, such as the data input, filter setting, data presentation, connection with different hardware devices, etc. Due to the graphic's role in a VR system, the VR software is a central element in the whole system. The requirements of VR software are application and cost dependent. Issues, such as the data interface, rendering performance, editor functions, network connection security, and programming interfaces are usually taken into account. Currently, numerous types of VR software are being developed, some for specific users and others for more general applications. Some examples of commercial software tools are: VIZARD, EON, 3DVIA, Avizo, Amira, IC:IDO, DeltaGen, and COVISE. A few open source software/library providers are as VTK, VRJuggler, Vrui, VISTA, and VDT.

VR Software	Provider	Last Release	Open Source	API	3D Visualization	Modular	CAVE Support	User Tracking
Vizard	WorldViz	V4.0 (02/2012)	No	Yes	Yes	Yes	Yes	Yes
EON	EON Reality	V7.6 (08/2011)	No	Yes	Yes	Yes	Yes	Yes
3DVIA	Dassault Systemes	V6 (12/2011)	No	Yes	Yes	Yes	Yes	Yes
Avizo	VSP	V7.0 (09/2011)	No	Yes	Yes	Yes	Yes	Yes
Amira	Visage Imaging	V5.4.2 (03.2012)	No	Yes	Yes	Yes	Yes	Yes
IC:IDO	ICIDO	VDP9.0 (03/2012)	No	No	Yes	Yes	Yes	Yes
DeltaGen	RTT AG	V11.0 (06/2012)	No	-	Yes	Yes	Yes	Yes
COVISE	HLRS	V6.5 (2011)	No	Yes	Yes	Yes	Yes	Yes
CAVELib	Mechdyne	V3.2 (2008)	No	Yes	Yes	-	Yes	Yes
K2Vi	AAM	V3 (2011)	No	-	Yes	-	No	No
VR4MAX	Tree C Technology	R7 (2011)	No	-	Yes	-	Yes	Yes
VTK	Kitware	V5.10.0 (2011)	Yes	Yes	Yes	Yes	Yes	Yes
VRJuggler	Iowa State University	V3.0 (06/2010)	Yes	Yes	Yes	Yes	Yes	Yes
Vrui	UC Davis	V2.3 (03/2012)	Yes	Yes	Yes	Yes	Yes	Yes
VISTA	RWTH Aachen	V1.13.0 (07/2012)	Yes	Yes	Yes	Yes	Yes	Yes
WorldToolKit	Sense8	V0.8.6 (07/2009)	No	Yes	Yes	Yes	-	Yes
VDT	Fraunhofer IFF	- (not specified)	No	No	Yes	-	Yes	Yes

Table 2-5: An overview and comparison of commonly used VR software

Generally, these programs provide an interface to import/export 3D files, connections to VR hardware and interaction devices, and extendable libraries. According to users and applications, the usability and implementation are various. A brief summary and comparison

of 15 software tools is provided in Table 2-5. All of these software tools support 3D visualization and most of them support the CAVE system, user tracking, API and modular extension.

For a better immersion experience, the interaction quality is an essential element. The interaction combines input and output together as user-computer interfaces, using perception canals of humans.

Output devices usually contain graphic, audio and haptic output technologies. Visual perception provides the main input and dominants the immersion degree. Graphic output technologies are for example the conventional LCD/LED displays and modern active/passive 3D projections. For desktop-based VR solution, LCD/LED displays are often used as the graphic output solution. 3D display is rapidly popularized in recent years. The greatest weakness of the displays is a small field of view. To realize a large sized display for Powerwall or CAVE, projection technology is preferable. Therefore, 3D projection, both active and passive, has been rapidly popularized in recent years.

In addition to graphic output, the sound and haptic output supply the human perception for hearing and feeling. A study by HENDRIX showed that the spatial sound is associated with higher presence than either no sound or non-spatial sound [Hend96]. In [Bril08], a 5.1 surround sound system for VR was introduced. Haptic perception provides non-visual information about shape, texture or force from objects and further improves the co-presence of the user in a virtual world [Basd00]. AZIZ provides a review of current haptic output devices used in VR and defined different terms, such as the "Haptic", "Proprioceptive", "Kinesthetic", "Tactile", etc. [Aziz09].

Input devices can be classified into conventional input devices, tracking devices, navigation devices, and audio interfaces. The conventional input devices include the mouse, keyboard, and draw pad. These devices are commonly used for a desktop system, but are not suitable for immersive systems. To manage a complex file system, the wireless keyboard is sometimes used in an immersive VR system.

Various tracking systems enable the interaction between the user and virtual world. From a technical perspective, the systems are divided into mechanical tracking, magnetic tracking, ultrasound tracking, optical tracking, and hybrid tracking. A review of these technologies can be found in [Burd03 and Bier08]. The tracking systems are developed for position tracking, motion tracking, gesture tracking, and eye tracking. Position tracking provides and maps the user position in a virtual world, so that the viewpoint can be continuously adapted. Motion tracking enables the interaction between real and virtual actions in a virtual environment (e.g. the implementation of fly stick). The gesture tracking technology enables a gesture-interface in VR or a device free interaction. A gesture-interface is implemented by using devices, such as a data glove [Burd03]. Open source software platforms enable a customized implementation, for example the SDK from CyberGlove. A device free gesture-based interaction relies on gesture recognition systems, such as the popular product "Kinect" from Microsoft. Eye tracing technology captures the gaze point and eye motion of user, which can be used for user interface or product design investigation in a virtual environment. Since it is an important technology, eye tracking has already been implemented in several research projects [Duch02 and Haff09]. As an example, Figure 16 shows the fly stick, finger gesture

tracker, the head position tracker using markers from company A.R.T., the gesture/motion tracker Kinect from Microsoft, and the eye motion tracker Tobi Glasses from the company Tobi.

Figure 16: Fly stick (a), finger tracker (b) and 3D glasses with markers from A.R:T., gesture tracker (d) from Microsoft and eye tracker (e) from Tobi

Navigation devices enable participant to move and explore the virtual world. They are essential interact devices, which relate directly to tracking technology. The fly stick and track ball, for example, are dependent on the optical or magnetic tracker. New navigation methods, such as the eye tracking or gesture tracking based navigation systems are also found in [Tanr00, Kim04, Pfei08 and Ding09]. The audio input interface, such as a microphone used for voice recognition, can also be implemented to enhance the human-computer interaction. McGLASHAN described the benefits of voice interface in VR and discussed the requirements of voice recognition and language understanding in a virtual environment [McGl95].

In [Mine95, Mazu96, Talb97 and Ni06], more information about VR technologies can be found. TALBERT discussed the human factor in a VR environment and said that a VR system should be a human-centered system. Different visualization and interaction technologies enhance the human perception in a virtual world and further improve the system's usability and practical applications [Talb97]. SANCHEZ-VIVES investigated the relation between virtual presence and different interaction methods. Several case studies show that the presence experience in VR is also worth study on its own [Sanc05].

2.3.3.2 *VR system classification*

According to the user immersion levels, the VR systems are classified into non-immersive, semi-immersive, and full immersive. A non-immersive VR system is, according to some VR definitions, not a real VR system. In this thesis, this type of VR systems is considered as a desktop-based workstation with conventional graphics using monitors, keyboards, and a

mouse. This system allows users to view 3D models with different perspectives, manipulate the models, interact with the virtual objects, and implement different applications [Robe93].
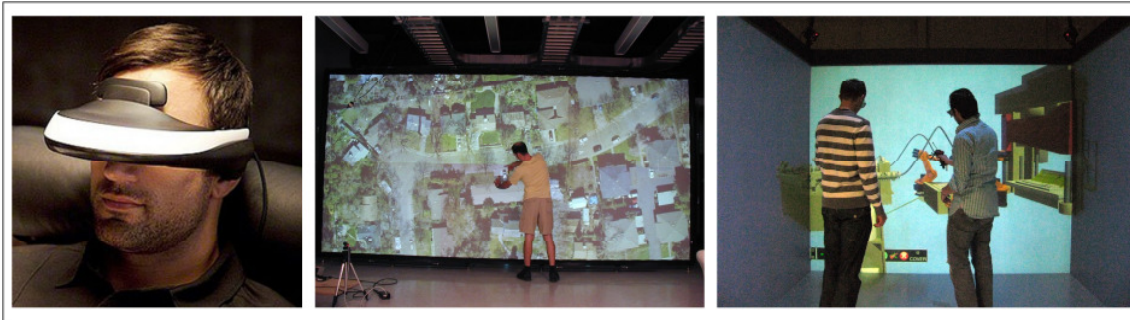

Figure 17: Various VR systems. From left to right: HMD from SONY, Powerwall at the University of California, Davis and CAVE system at the FBK institute

The full-immersive VR systems, such as CAVE, provide the most costly and complex solution, but with unique benefits. Compared to a non-immersive system, an immersive VR system has a higher sense of situational awareness, a wider field of view, a higher scale perception and a sense of immersion. However, a non-immersive VR has the advantages of lower costs, shorter development time, and better implementation conditions.

VR System	Classification	Advantages	Disadvantages
Display	Non-immersive	❏ high resolution ❏ viewed by one or more person at same time	❏ small field of view ❏ very low immersion ❏ only active 3D visualization available ❏ only for simply analysis and evaluation
HMD	Semi-immersive	❏ 1:1 visualization available ❏ relative high immersion ❏ simple implementation	❏ small field of view ❏ only for one person ❏ low resolution ❏ limited movement by connection cables
Powerwall	Semi-immersive	❏ viewed by one or more person at same time ❏ active and passive 3D visualization available ❏ front and rear projection available	❏ relative low immersion ❏ the field of view and virtual space are dependent on the size of projection surface
CAVE	Full-immersive	❏ 1:1 visualization ❏ viewed by one or more person at same time ❏ wide field of view ❏ active and passive 3D visualization available ❏ very high degree of immersion	❏ expensive and complex solution (equipment, space, people etc.) ❏ limited movement inside CAVE ❏ only rear projection available

Table 2-6: Comparison of four typical VR systems

Semi-immersive VR systems have an immersion level between the non-immersive and full immersive ones. Powerwall systems and the head mounted displays (HDMs, und also called "goggles") are a few examples. The costs and system complexity fall in between as well. In Table 2-6, the detailed advantages and disadvantages of different systems are listed [Nube01 and Mujb04].

Due to the considerable advantages, the CAVE system has become a popular visualization environment for scientists and industry users. In 1992, the first CAVE system was invented at the University of Illinois Chicago Circle [Cruz92 and Cruz93]. Based on this method, a virtual environment is built in a room with stereo graphics projected from behind the walls. The first implementation by CRUZ-NEIRA et al. was a back-projection method, which is strongly followed today by many further developers. In CAVE, the users are surrounded by the projected images and are free to move inside the room. Compared to other ordinary VR systems, the CAVE system has the advantage of users having wider field of vision.

A CAVE is not only a surround screen VR system, but also a surround sound system, and a head and hand tracking system, along with some additional parts. Based on the user position tracked by tracking system, the correct perspective is produced. A sound system enables the participants to have audio feedback. Visual and auditory sensorial channels are the main methods to improve the user's perception in a virtual environment. Multiple participants are allowed to share experiences and discuss while inside the CAVE, enabling researchers to exchange their ideas. Usually, one user is the active viewer who is controlling the 3D input device, while the other users are passive viewers.

2.4   Industrial VR applications

As a promising technology, VR is widely used in every field for manufacturing systems. PHILIPPSEN gave a comprehensive review of the VR applications in different fields, such as the telecommunication, entertainment, training, medicine, design and prototyping, and automobile industry [Kala93a and Phil99]. At the annual IEEE Virtual Reality Conference, VR topics related to various application fields are covered. On the one hand, rapidly developed VR technology including simulation, modeling tools furthers implementation; on the other hand, the application needs further research and development to be successful.

VR enables a direct link of simulations to an immersive, virtual environment and allows users to interact and model during processes simulation and visualization. This offers high potential for exploring complex interactions between users, objects and operations [Doro10]. Therefore, VR is a reliable platform for virtual design/planning tools and suitable to support a wide range of manufacturing applications. These applications include production planning, product design or the technical qualification of employees [Benn05, Oliv07 and Rund07].

To set the boundaries for facilitating a literature review of current VR applications, a model of a manufacturing system with hierarchical levels is used. Figure 18 shows the levels including manufacturing network, manufacturing location, manufacturing segment, manufacturing system, manufacturing cell, and workstation/machine [West09]. Due to the proposed development, the focus is on the last there levels and the other three levels are not involved in literature review.
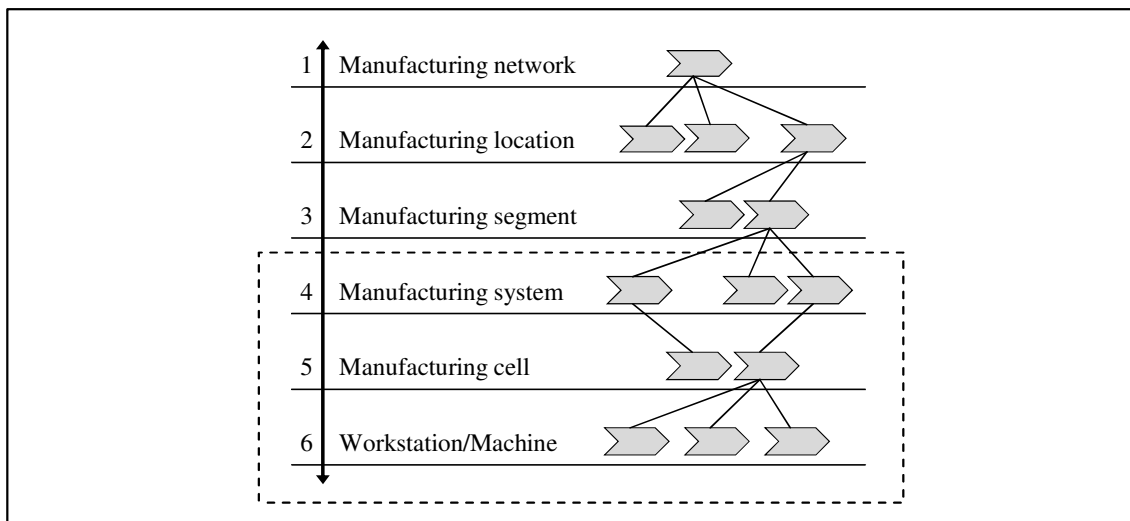
Figure 18: Hierarchical manufacturing levels of an enterprise [West09]

2.4.1 Manufacturing system level

At manufacturing system level, VR is implemented to support analyzing, modifying and simulating existing shop floors to improve the design of new layouts. Some fields such as the layout design, manufacturing environment analysis, CIP (Continuous Improvement Process), and system monitoring are widely investigated by researchers.

Factory layout design and planning

Layout design is a rich area of industrial research and practice, which involves many essential issues, such as the throughput time, production volumes, product quality, and employee morale. A well-designed factory layout provides the investigation basis, on which idle time and bottlenecks in a manufacturing system can possibly be prevented. VR has the potential to help the facility designers and engineers to view and compare various design choices with significantly reduced costs and time.

SMITH and HEIM described a design environment that was constructed to evaluate the use of VR for layout design of manufacturing facilities [Smit99]. Firstly, they reviewed the layout design methods and various virtual environment designs. Then, they summarized the need of layout design and the benefits of VR implementation. Two major benefits could be found in this paper. One is "to improve the decision-making processes from both qualitative and quantitative perspectives". Some needs are the visualization of workplace, assessment of layouts, and rearrangement of workplaces. The corresponding VR solutions were also shown. Another benefit is to enable designer access to use and modify the rich information in VR so that they could do their tasks much more efficiently. This benefit relies on a well-designed virtual environment with rich interaction possibilities, such as haptic feedback or eye tracking input. Furthermore, the authors implemented a design environment for aircraft manufacturing. Because of extra-long materials and work pieces, movement of the objects is a problem. Considering the limitations, the production areas, machine tools and material flows are redesigned. To do so, a non-immersive VR system was used and the interactions, such as the grabbing, moving, coloring, were enabled. Data import and export between CAD system and VR system was also introduced. Of course, the network structure is not comparable with

current technology. However, this paper provided a relatively comprehensive view of the VR implementation addressing the layout planning issue.

WESTKÄMPER and RUNDE presented VR applications relating to the "digital factory" concept in industry, especially in factory design and planning fields [West06]. Various research issues were involved: factory planning, assembly planning, manufacturing process planning, workplace design, and training and learning. Different VR systems and their applications were represented in this paper. For example, the application based on Holobench was shown, which enables user to evaluate the assembly workplace considering the issues such as the light, air and noise [Mers02]. Another application showed the visualization of the relationships among objects in a factory, which represented their complex logistical connections in a CAVE system. Not only was each single application field discussed, but also the work technique, such as the distanced and collaborative use of VR.

ABEL and FRANKE provided a practical case study of VR application for factory and facility planning. Based on the needs of a middle-size foundry, they showed solutions based on Powerwall, planning table and CAVE systems [Abel07]. Their solution enabled the integration of the data from modeling, simulation and designing and the use of data from product design to layout planning and even employee training.

Based on their study, BRACHT and REICHERT introduced the use of 3D factory planning and provided fundamental methods as well as the implementation requirements [Brac10]. Considering the needs and limitations of small and middle size enterprises, they demonstrated their concept including the analyzing step, check list generation, modeling method selection, adaption of technique infrastructure, and project execution. Several essential check questions were listed to evaluate the implementation conditions. For example: "If the hardware performance fulfills the application requirements?", "What kinds of data should be shared/not shared/partly shared/highly protected?", or "Which ERP interface is needed?" The authors showed a comprehensive project information system and considered VR as an essential component of it. Additionally, they introduced the potential use of a VR mobile platform in factory planning, especially the potential improvement of data input, output and visualization.

Manufacturing environment

There are numerous factors within a factory environment, such as noise, light, air pollution and radiation. These effects are difficult to measure, analyze and control. Based on an existing factory, the adaptions to reduce these factors that cause damage to employees are costly. However, employee as a human factor is the most essential element in manufacturing systems. In other words, the working safety and health are top priority for the manufacturing designer and employers. To avoid remedies and huge compensation costs, these factors are considered during design. For example, AHREND and FLOSS investigated the noise control issue in manufacturing design. Comprehensive study of limitations and control methods are included in [Ahre00]. However, a VR-related discuss is not provided. Due to the immersion feature of VR, some other researchers have already attempted to integrate visualization and simulation in VR in order to investigate these manufacturing environment issues.

In [Viga09], Viganò et al. introduced the "GIOVE" toolkit, which enables planning with respect to the human factor. They conclude that there are major advantages of the human-oriented factory planning, such as the increased efficiency of collaboration, reduced

complexity of communication, reduced factory design time, and better working conditions. However, concrete methods to describe the light, air quality or noise in a factory were not mentioned. In the computer science field, RAGHUVANSHI et al. represented a real-time simulation approach for sound wave propagation, especially for game engine [Ragh10]. This approach was further tested using different scenarios, such as in a living room and outdoor walkway. The potential implementation in manufacturing system is considerable.

"SoundPLAN" is a commercial software tool, which provides an indoor noise model based on VDI 3760 [Soun12]. Using this model, a simulation and evaluation of noise level in manufacturing is facilitated. Different assessment and visualization methods are included in this tool. At the same time, the extended module "AirPLANs" enables the designer to simulate the indoor and outdoor environment air pollution levels. However, the application of this tool is limited by simplified conditions and environments. Furthermore, an interface connecting the simulation and extended visualization tools and VR systems has not been found.

CIP (Continuous Improvement Process)

To support the improvement of processes in a manufacturing system, a well-established method is applied, namely the CIP-workshop. The research focus of AURICH and OSTERMAYER is investigated continuously in a virtual environment [Auri06, Oste08 and Auri09]. This extended VR-based CIP-workshop overcomes the disadvantages of a traditional one. In a virtual manufacturing environment, the workers, designers and decision makers are involved together on a shared platform. The immersive environment provides the participants rich perception and better understanding of the manufacturing systems. Within this virtual environment the CIP-workshop is implemented in five steps: i) detecting problems, ii) analyzing selected problems, iii) developing improvement measures, iv) realizing the measures with workers and v) evaluating the results. Following the successful implementation of the workshop the results are immediately transferred to enable the realization in the real production environment.

System simulation and monitoring

As a promising approach, VR enables users to have a clear overview of complex systems. Customized interfaces connect simulation and the VR system, so that the information in the virtual environment is much richer. Static and dynamic data are visualized and allows interactive modeling and analyzing.

DANGELMAIER described a system architecture using VR and AR to support the planning process of complex manufacturing systems [Dang05]. The integration of discrete simulation into the virtual factory was shown. The proposed system assisted users during modeling, simulating, validating and the optimization of a manufacturing system. To visualize the 3D-data within VR and AR environments, a graphic rendering library was used. As an example, the visualization of an assembly line in automotive industry using Powerwall was demonstrated. According to their approach, the dynamic process simulation is directly connected to this visualization.

In his dissertation, RUNDE investigated VR implementation possibilities, methods and benefits in industrial enterprises systematically [Rund07]. Four methods were developed to describe the four steps: the requirements in digital factory identification, job description, VR

system/solution selection, and the implementation of VR in industry. This work provided concrete implementation steps with detailed information, such as the hardware device model, rendering library, and software tool.

ZHOU et al. combined process simulation and system monitoring into one VR application [Zhou11]. Established simulation architecture with a closed loop of virtual factory integrated platform was introduced, which includes the 3D data, dynamic and static simulation data and integrated database system. A chemical industry was taken as an example to validate this concept. Functions included the visualization of static and dynamic simulated fluid and gas flows or the visualization of process information (temperature, pressure, flow volume, etc.). The most interesting use of this concept was to visualize the process faults, for example the spilled oil from the tower top. Important process information was well visualized and monitored using a 3D environment, which brings significant benefits for complex manufacturing systems.

To summarize, a few selected research works were studied, considering their application fields at the manufacturing system level. The most investigated field is the layout design and planning, due to the large scale visualization feature of VR. Manufacturing environmental studies and the CIP-workshop can be seen as small but necessary supplements to mainstream research work. More studies and discussions of VR applications including the research issues can be found in [Flai98, Wien02, Brac06 and Brac11].

2.4.2 Manufacturing cell level

At the level of the manufacturing cell, VR is often used to design and analyze a single work cell or assembly process within a system. Comparing several approaches and related problems occurring in physical situations, different methods using VR lead to suitable benchmarks. Through identifying constraints and oblique problems in early design stages, various choices can be compared and improved. To improve the parts flow through a shop floor or factory is another key issue, which can be solved by using different simulation measures in VR.

Work cell design

Combining the uses of different software tools, such as "Delmia-Quest", "eM-Workplace" and "Factory CAD", CAPUTO et al. introduced their concept to simulate layout and robotics in work cells. They recommended that the using real size of the factory plant in VR facilitates the layout evaluation for the work cell. Their research also involved the ergonomic issues in a work cell. The workers were modeled as avatars (e.g. "JACK" model) and integrated to the virtual environment. The process of train manufacturing was studied as an example for both work cell layout planning and ergonomic evaluation [Capu06].

Considering the special needs of engineering changes and the impacts to factory layout planning and rearrangement, MALAK et al. presented their concept to enhance the planning processes [Mala11]. This concept was further implemented using Java3D based software tools, which enabled users to access, view and modify the object information directly. A 3D-visualisation of the manufacturing system and its objects, such as the machine tools, transporters and energy slots, provided users a clear and panoramic overview. The needs of factory planning, which are discussed in [Smit99], were realized in this paper. Users are

allowed to change the layout directly in a non-immersive VR system and compare the different planning choices.

Material flow simulation

BRACHT and MASURAT integrated material flow simulation and process simulation in Virtual Reality for digital process prototyping in logistics and production [Brac03]. They studied a high-frequency welding process and built 3D models in a digital factory. Based on the digital data, the movement sequence of robots, band conveyers, cutting machines, and feeders were programed according to the well-designed manufacturing processes. The material flow was further simulated using both geometric and process data. The process information of each facility, such as the manufacturing time, pending time and set-up time, could be monitored in real-time. The movement and material flow was then visualized in a non-immersive VR.

Combining the virtual manufacturing environment and simulation, AURICH et al. introduced their concept to integrate material flow simulation and FEM simulation in VR [Auri07]. Software tools VD2 and eM-Plant were used to operate the CAVE system and simulation respectively. Concrete implementation steps were well described and an implementation guideline was provided.

JIMENO and PUERTA made a state of the art study involving current research works in the VR field for product design and manufacturing processes [Jime07]. According to their survey, using VR use for process simulation minimalizes material waste and material flow bottlenecks. In addition to presenting essential VR benefits, several disadvantages, such as complicated implementation in some cases, were also noted by them.

SCHENK et al. implemented both production simulation and worker qualification in VR [Sche09]. This application could be used firstly as simulation tool for foundry planning. The eM-Plant runs as a material flow simulator and the VR software VDT (also see in Table 2-5) provides a VR environment. Furthermore, this application enables the simulation and training of a power generator assembly.

Assembly simulation and visualization

Assembly is an interaction-intensive and physically based process. To simulate these processes in a virtual environment, the algorithms, framework, and suitable devices are all necessary. The VR provides significant benefits to improve the user experience, filling the perception gap between the real and virtual world. So, complex and high-risk assembly jobs can be simulated and visualized in advance and even be practiced by workers.

SHARMA et al. introduced their assembly evaluation tool [Shar97] and two implementations were presented. The first one showed an AR-based assembly support system. Useful information could be shown and mapped to the real objects. The second implementation enabled image capture and identification during assembly and interrelationships were verified. Since the technology was not as advanced as today, there was no high quality 3D graphic implementation. However, this method opened a new prospective.

CHRYSSOLOURIS et al. investigated the VR-based method to simulate and verify manual assembly processes [Chry00]. In an immersive and interactive virtual environment, the processes are realistically generated. Additionally, an ergonomic model was integrated in this application, which enabled ergonomically acceptable conditions. To validate this method, a

semi-experimental time model was developed for an assembly test case. In this application, a number of process parameters and their interrelations were considered as well.

BEIER described several web-based VR applications for the manufacturing system [Beie00], such as the simulation of ship production or the robotics simulation in a manufacturing cell. VRML was the basic VR language and the modeling was implemented by CAD/CAM. However, these applications were limited at the low complex level without Java supported algorithms. The geometric modeling and human-computer interaction was relatively simple. Thus, the user perception was relatively poor.

Using haptic devices, KRAUSE et al. [Krau00] implemented VR as test platform for simulation and evaluation of complex assembly and disassembly processes. The parts were modeled graphically and the user hand motion could be transferred to the virtual assembly scene through haptic hardware. The manipulation of virtual objects and the force feedbacks were simulated in real-time. Even though it is not an immersive environment, the user perception is in this case significantly improved through the haptic interaction.

ZACHMANN provided a comprehensive review of VR techniques, focusing on collision detection, interaction and simulation algorithms. He also introduced an implementation concept for assembly simulation in VR and developed a framework and several native functions, such as the nature grasping and collision detection [Zach00]. Based on this framework, he implemented the assembly simulation using the VD2 platform.

REINHART et al. introduced the integrated use of AR and VR in the area of manual assembly. The extended use of digital models was not only implemented for assembly planning in a virtual environment, but also supported the assembly workers using AR. A case study in the automotive industry showed the steps and benefits for the user. [Rein02]

Using IC:IDO software, an application to simulate and validate the complex cable bundle was developed [Wien08]. A real-time simulation and visualization of the physical behavior of flexible objects (cables) was realized. The algorithms were adapted according to the cable types and showed high accuracy. Based on their validation, 90% of the solutions would be adequate, if the environment is typical.

At the manufacturing cell level, the most intensive investigated issue is the assembly process. This issue directly or indirectly influences the design of the work cell and material flow. More applications about virtual assembly can be found in [Brac11 and Seth11].

2.4.3   Workstation and machine level

As essential element in a factory, the human factor is more of a focus at the workstation and machine level, because the interaction between human and machines influences directly the processes in manufacturing system. In addition, human factor involves more research issues in virtual environment [Stan98]. A lot of research has been done with respect to the human performance, health and safety. Next, the research work in fields of workstation design, training and manufacturing process simulation are described.

Workstation design

The issue of workstation design relates with rich research topics, such as the CIP, training, and assembly simulation. In addition to these topics, ergonomics is another close related

research focus. ZÜLCH classified ergonomics into micro- and macro-ergonomics [Zülc05]. Micro-ergonomics analyzes human posture and body motion during tasks execution, whereas macro-ergonomics analyzes the stress and strain of the tasks accomplished by the workers. Some of the following research work showed the application in this field.

HEGER introduced a VR-supported method to analyze and evaluate the manual assembly workstation. Using the virtual product prototypes and the algorithms of grapping, moving and joining, the virtual manufacturing processes were simulated and visualized in VR. An interaction between the participant, virtual objects, and avatars were possible. The assembly time, steps and schedules could be analyzed and optimized in a virtual world in advance, which provided a significant advantage to reduce the planning time and costs [Hege98].

BENNIS et al. gave a review of the VR technology and applications in industry and considered VR as a human-centered tool. Therefore, more human-centered applications, such as training, ergonomics, maintenance were discussed [Benn05].

Within the research project "DiFac" (Digital Factory for Human Oriented Production System), LAWSON et al. described ergonomics, presence, and collaboration in virtual environment. They extended the conventional method of an ergonomics study using VR. The benefits were analyzed by using a few established applications and software tools [Laws06].

YANG et al. investigated an engine assembly line and implemented VR for workplace planning and ergonomics evaluation [Yang07a]. For the use of "JACK" model in this application, refer to [Capu06].

HOFFMANN and DANGELMAIER used their applications to facilitate the optimization of industrial manual workplaces [Hoff08]. Numerical human models and user motion tracking systems were integrated. The user motion from the real world could be mapped to the avatar in the virtual world. Through 1:1 large size visualization, analysis of workplace layout design and assembly processes was significantly improved. In addition to this application, they provided an evaluation tool "iTeach" to reduce the assessment process.

SCHIRRA described an innovative concept to enable a complete planning workflow with one VR application [Schi08]. To do so, user requirements and technical requirements were studied. A data server for CAD data was built to control the parametric and VR converter and the data model was made by using information from entire product, process and resources. Changes of the system components could be made directly through the server in an immersive environment. The 3D GUI made the interaction more straightforward and intuitive. Furthermore, six persons were involved in the evaluation which showed positive results.

Process simulation and visualization

Simulation and visualization enable an essential feature of VR: imagination. In the lower levels of manufacturing process, simulations and software tools like CAD/CAM are widely used in the industry today. However, just a few of them can be implemented directly in a virtual environment [Ceci07].

RANGA and GRAMOLL [Rang00] introduced and implemented Java programming into VRML and improved the performance in 3D FEM analysis. This web-based virtual environment includes customized GUI as well. The useful implementations of Java and JavaScript enable a mobile 3D FE analysis and visualization without high performance software and hardware. A

similar application made by YANG et al. also showed significantly improved simulation by implementation do to the JavaScript coding. Chip formation and material removal were simulated and visualized in real-time in a VRML based scene graph [Yang11c].

HUHN and SIEGERT attempted to improve machinery development. The features and advantages of VR, such as immersion and interaction, were found to enhance the process analysis and optimization [Huhn02]. USTARROZ et al. introduced their application "VIRTOOL", which enabled users to perform a 3D cutting process analysis [Usta04]. At the same time, this application provided a learning environment for machine tool use.

By using VTK and VISTA (also see in Table 2-5), SCHÖNING and HAMEYER implemented both non-immersive and immersive VR systems for FEM simulation [Scho08]. Huge data could be managed, filtered and visualized according to the engineering needs.

JIN et al. introduced an X3D based method to support 3D visualization and animation of cutting processes. The method also enabled a collaborative use through the web for people with the same models [Jin07].

VRABIC presented a grinding animation in the immersive VR [Vrab09]. The kinematic of the grinding process was visualized using a parametric description of the object surfaces. The purpose of this animation was to enhance the understanding of the process and to assist the machine tool operator. However, the simulation software was not connected to the VR system with real-time communication.

For operation for geometrically determined cutting edge, HE and WU [He09] illustrated their architecture for web-based simulations with VRML for milling operations. The positioning of the work piece element, the tool and their interaction by tool movement was realized by Java. The visualization of the work piece and the tool can be used for checking collisions or optimization of tool paths. The combination of Java and VRML upgrades increases the possibilities in VR-visualization.

Training and learning

In addition to various VR applications in their training center, BLÜMEL et al. found value for in-factory training of the manufacturing system [Blüm03]. Through the combination of more sub-systems (authoring system, training scenario, run time system and VR), different training modes were enabled for employees with different qualification degrees. For example, the guided mode was made for new learners and a free training mode was provided for experienced employees. In the application, VRML-sequences, CAD-drawings and video presentations are used to support the different learning modes.

WANG et al. introduced a VR training system for CNC machining [Wang04]. Based on the WTK platform, they implemented a 3D environment with interactive controls. The creation and editing of numerical control codes, as well as the modification of the cutter, was enabled. OLIVEIRA et al. implemented a CAD integrated VR system to enable industrial training [Oliv07]. This application allows the use of the proprietary file format or the VRML/X3D format. The most significant advantage is that the training data and software can be distributed together in a unique device.

Using VR, the company VRSim developed the "SimSpray" software tool for spray painting and coating training and "VRTEX360" for arc welding training [VRSi12]. The costs of spray

painting are caused by high materials usage (e.g. paint, thinners, work pieces, and air filters), facilities, and time. The realistic experience of training in a virtual environment accelerates the learning of fundamental spray painting skills and minimizes costs at the same time. Because the learning and training are operated in the VR, the potential for accidents is also minimized and the solution is environmentally friendly.

2.4.4   Other VR applications

VR applications facilitate the data visualization, analysis, and modification in extensive industrial fields and can involve all essential research issues. A complete review of all industrial VR applications is not made in this thesis. In this section, more than 50 research and practice related papers were reviewed and represented and close to one hundred applications were involved in these papers.

In addition to the applications already mentioned, a few important research works were also studied, without being classified into the pre-defined manufacturing levels. They show comprehensive use of VR in various fields like the logistics system, change management, data visualization and product design.

❑ In [Baro09 and Jime07] and [Bues07], product design and product prototyping using virtual environment are discussed respectively. The essential VR features for designers, such as the realistic texture rendering and shape verification, were shown. NEUGEBAUER et al. described VR tools used to visualize and analyze the energy flow and consumption of machinery during machining processes. This method improved both energy consumption optimization and product design [Neug11].

❑ In the virtual development and training center in Magdeburg, the VR researchers focused not only on the manufacturing system but also the logistics field [Sche10]. Through the study of VR supported product life cycle investigation, the logistics chain was analyzed and the time/costs saving were considerable.

❑ Some authors show the benefits of data visualization in VR [Lang04 and Stra04]. The huge and complex data such as FEM and CFD simulation could be filtered and manipulated in an immersive environment, which makes understanding easier. BARBIERI et al. also showed the integration of CAD/CAE use in VR as well [Barb08].

❑ SCHENK et al. extended VR application to the service field [Sche04]. They provided a few practical case studies and the implemented applications to the use of VR for product presentation, product use introduction, and product maintenance.

❑ Based on established object library and simulation algorithms, KOCAR and AKGUNDUZ introduced their implementation of VR for engineering change management [Koca10]. The merging of graphical and parametric data of the processes into a virtual platform improved the comprehension of users and hence decreased the required time.

The described applications, addressed on three selected manufacturing levels of enterprises, provide a well-established research basis in theory and practice. Some applications are implemented at the low immersive level and provide relative poor user experience. There are two reasons for this. First, many applications are limited by the technologies of the day. Second, some applications serve a customized problem in which the immersion is not the only issue. Thus, these applications provide basic concepts and ideas for the proposal, which will be implemented in this thesis.

3   Research Question

Noise is a prevalent issue in manufacturing systems. The estimation of noise level in a factory and technical solutions to address this issue are usually costly and time consuming. Digital Factory tools enable the analysis and simulation of noise related problems during factory design and planning process. VR systems, one type of Digital Factory tools, provide significant advantages such as the information visualization and user-computer interaction, which enhance the understanding of complex issues. The main objective in this thesis is to develop an innovative VR-supported method which improves the analysis and evaluation of noise level in workplace design. Figure 19 illustrates the research question with the main elements involved. A new method could enhance the assessment quality and efficiency of sound problems in a factory. The simulation method, which serves as central element of this approach, is much more cost-effective compared to acoustic measurement approaches. Furthermore, the virtual environment allows planners to try different solution options without stopping the manufacturing process. The visualization from the simulation results helps the planner to improve their understanding of noise propagation and support the solution finding process in a factory.
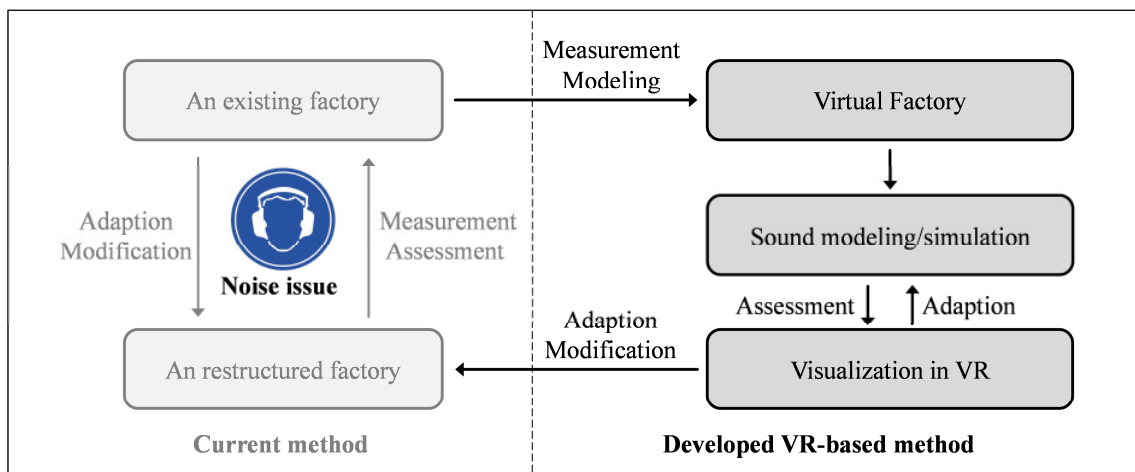

Figure 19: The research issue in this thesis

To achieve the aforementioned objective, several tasks (subdivided objectives) are involved and will be implemented in this thesis. They are organized in Figure 20 and listed in below:

❏ Development of the sound investigation approach in VR

❏ A survey of noise-related legal regulations

❏ Design and implementation of acoustic measurements in a manufacturing environment

❏ Summary and evaluation of measurement data

❏ 3D modeling of a manufacturing environment

❏ Description of a sound source

❏ Parameter setting of acoustic simulation

❏ Comparison and validation between simulation results and measurement data

❏ Development of a data interface between VR and simulation

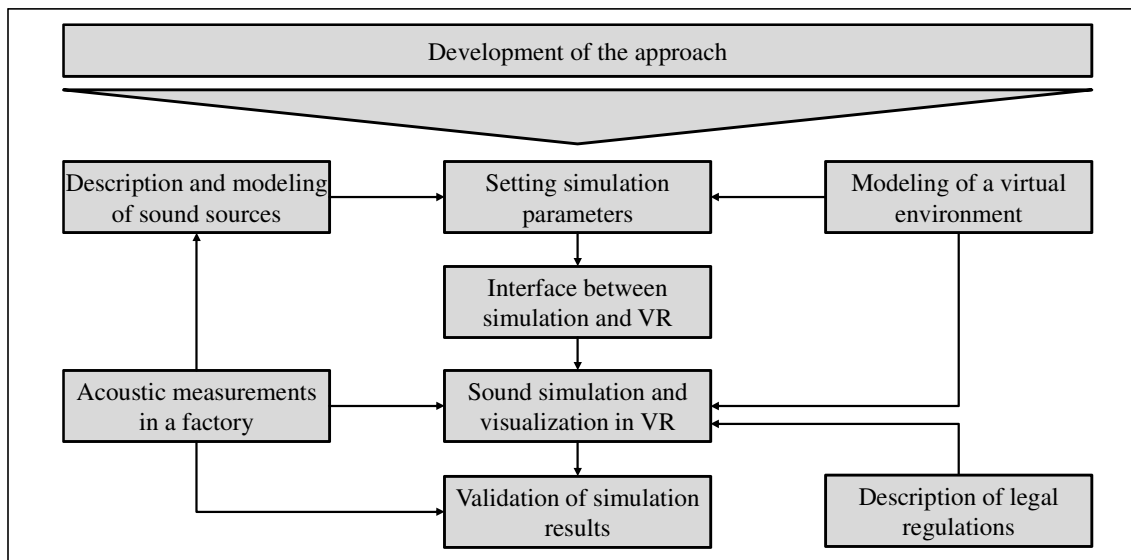❏ Implementation of sound simulation and visualization in VR

Figure 20: A road map of the tasks (objectives)

This road map demonstrates the involved tasks and their contexts. By using acoustic measurements, the necessary data for sound source description and the data for simulation validation are acquired. Before a simulation starts, the parameters are specified according to the knowledge from the acoustic measurements and the interpretation of those measurements. At the same time, a Manufacturing Lab is built into a 3D model which provides a virtual environment for simulation and visualization. A data interface is constructed to enable the data exchange between the simulation and VR system. Then the simulation and visualization are conducted in a virtual environment. The simulation is validated with the measurements from the Manufacturing Lab. Combining with investigation of legal regulations for manufacturing the visualization using simulation results facilitates the analysis of noise issue in a factory.

Several studies are conducted in both manufacturing engineering and computer science fields. The sound simulation and its implementation using a VR system are namely the research focus, which ensure the usability and efficiency of intended approach. Therefore, the following requirements are taken into account:

❑ a comprehensive and simplified solution for the noise issue in manufacturing

❑ efficient and safe data transfer and file converting

❑ a straightforward user interface in virtual environment

❑ enhanced understanding of sound propagation in a factory

❑ simple and understandable visualization

❑ enhanced layout design and planning taking the noise issue into account

❑ extendable software with function modules

❑ and the hardware and software compatibilities

These requirements are considered during the development, implementation, and validation steps of this approach. For example, the user interface design, software tool development and programming language choice steps consider these requirements as assessment criterion.

4 VR Application for Sound Simulation and Visualization

4.1 Development of the approach

This chapter provides an overview of the approach development, which attempts to achieve the objective detailed in the last chapter. Based on the discussed tasks in this thesis, this approach is broken down into five main steps: data acquisition, modeling, sound simulation, an interface to VR, and VR system preparation (Figure 21). Each level is introduced respectively in the next sections.
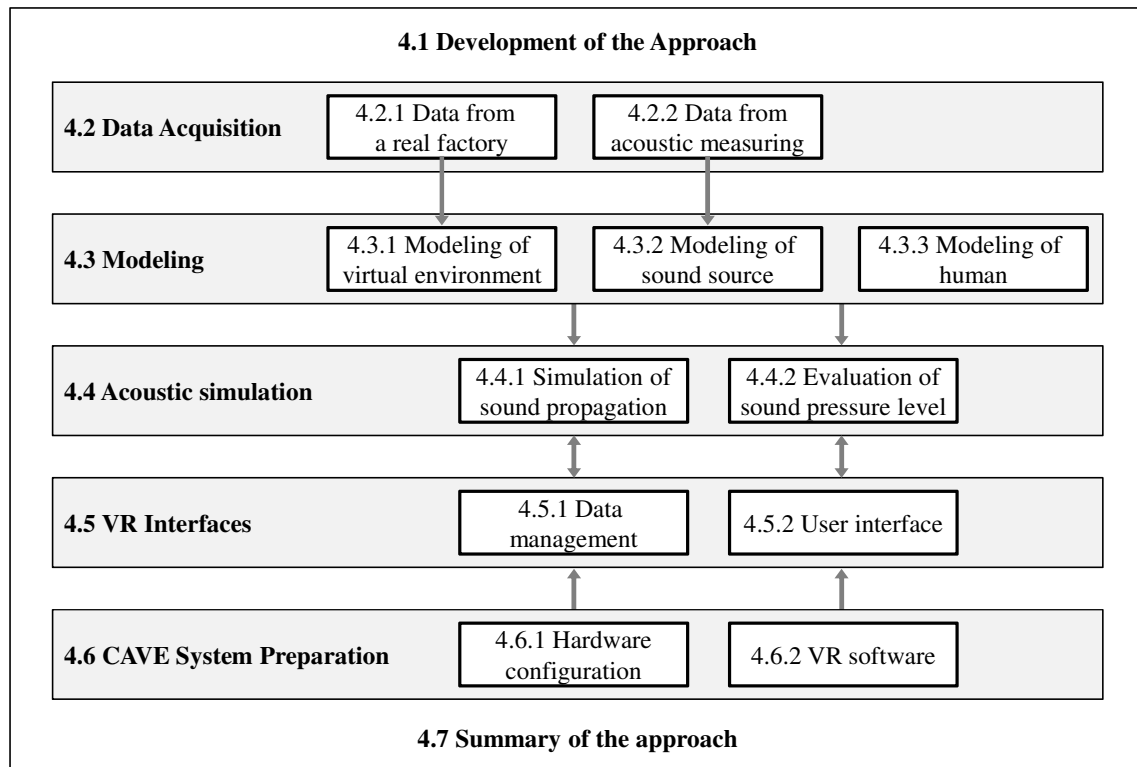
Figure 21: Development of the approach and the structure of chapter 4

The research questions defined in chapter 3 are answered and the subdivided tasks are discussed in terms of main elements in this approach. The data acquisition level is introduced in chapter 4.2, which describes the methods for collecting the required geometric data from a real factory and the sound data from acoustic measurements. An introduction of the Manufacturing Lab at the FBK institute and the essential input information for further acoustic simulation are shown. Chapter 4.3 introduces the methods for modeling a 3D virtual environment, describing a sound source, and building a human model inside a virtual factory. The necessary data for modeling step are supplied from chapter 4.2. Chapter 4.4 involves the sound simulation environment, the setting of simulation parameters, and the setting of evaluation positions. This chapter provides a better understanding of acoustic simulation use in a virtual factory. Furthermore, the approach used to integrate the sound simulation and visualization in a VR system is described, including issues such as data management, visualization methods, and interaction techniques. Finally, the necessary preparation of a VR system for approach implementation is discussed in chapter 4.6. Hardware and software

configuration, as well as system settings, are taken into account. The CAVE system used in FBK is introduced and used as the implementation platform.

4.2 Data acquisition

The data acquisition step, the first step of the approach, provides the necessary data for modeling and simulation. Existing information is analyzed and classified according to the needs of this thesis. Two main data resources are considered: data from real manufacturing environment and data from acoustic measuring.

4.2.1 Data from a real factory

A real manufacturing system contains extensive information which comes from three main sources: the production objects, the production environment, and the people in production. These resources connect with and affect each other. The production objects include machines, transportation equipment, different work tools, storage equipment, etc., which fulfill different jobs in a manufacturing process. The manufacturing environment is usually understood as a given space, e.g. a building or a part of a building, in which the manufacturing processes are implemented. The human is the central factor of a manufacturing system. To consider this factor, some information about the human is required.

Figure 22: Manufacturing Lab in institute FBK

In this thesis, the manufacturing lab is used as a referential data source for an approach development. Figure 22 represents the Manufacturing Lab from two different points of view, in which a middle size and complex system with various manufacturing objects are shown. Due to the need of sound simulation and the complexity of the system, some small and middle sized objects, such as the vernier calipers or the oil bottles, are neglected during the data acquisition step.

Geometry and layout

The fundamental data from a real factory is the geometric data which contains the geometric information of manufacturing facilities, machines, transporters, layout, etc. The shape, location, material feature, textures, and other information of single object in a manufacturing system are represented by 3D-modeling.

The methods of data collection are case-dependent. The general data sources are classified into primary data source (e.g. the blueprint of a factory or original drawing of a machine) and secondary data source (e.g. the measurement data or the estimated parameters). Usually, a construction plan and layout of the manufacturing facility provide a straightforward way to start the data collection step of geometries and layouts. If there are no such plans, a manual measuring is required. In this thesis, a blueprint of the layout was made before measuring (see Figure 23). Number 1 to number 57 refers to objects in the Manufacturing Lab. The names and their classification are detailed in appendix 11.2.
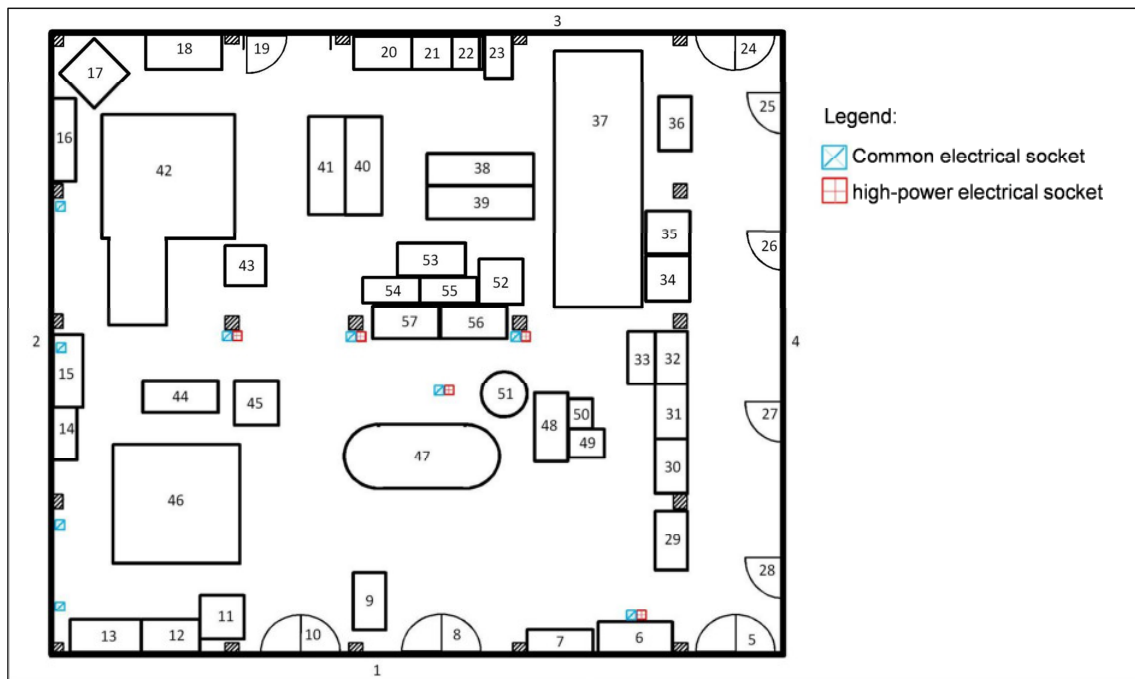

Figure 23: A blueprint of Manufacturing Lab layout

To ensure the completeness of the data collection, an analysis and classification of required information are made in advance. A checklist for the whole Manufacturing Lab is generated to identify and describe the necessary data and chosen methods. In this checklist, the objects in the Manufacturing Lab are listed and information such as identification name, size, manufacturer, position, orientation, color, is recorded. For each of the main machines, e.g. the milling center, tool gridding machine, and CNC cutting machine, an additive checklist is generated to provide more detailed information. Based on such checklists, the needed data from the Manufacturing Lab are measured and documented. Appendix 11.4 shows a filled checklist using the CNC cutting machine as an example. In this case, the requirement for accuracy are low, thus no optical measuring devices are used. Part of the information is directly recorded according to the machine manual from the manufacturer.

Material surface features

As a necessary input parameter for sound simulation, an absorption coefficient for each material is needed, which indicates how much of the sound wave energy is absorbed by a material (for more details about sound wave features see 2.1.1). The absorption coefficient is usually dependent on the material and varies with the frequency of sound: $\alpha_j: \Omega \rightarrow (0, 1]$. The value 0 means there is full reflection, while 1 means full absorption. It is also often described

as an absorption function. Figure 24 shows two typical absorption functions provided by the software CARA [CARA12].

If the surface is not specular, but corrugated, then an acoustic BRDF (bidirectional reflection distribution functions) is needed for each material. Because of the complexity of large environments, the case of corrugated surfaces is not discussed in this thesis. More details about the BRDF implementation in acoustic simulation can be found in [Silt07b].
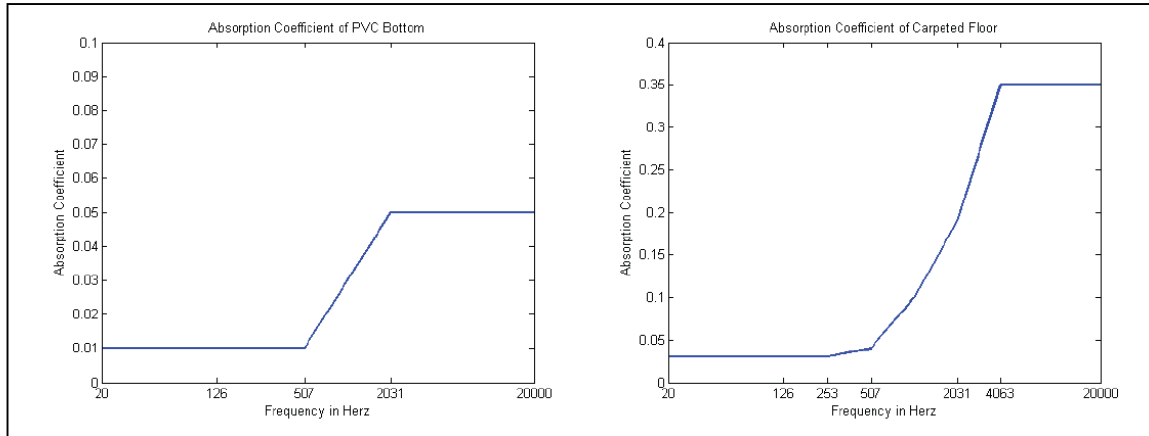

Figure 24: Absorption functions provided by CARA [Dein08]

In this thesis, the absorption coefficients of object materials are taken from existing database, e.g. CARA and WSDG database of common building materials. The data from different databases varies because of different measuring methods and conditions. In Table 4-1, the absorption coefficients of several common materials are shown. More absorption coefficients of materials can be seen in appendix 11.5 [WSDG11].

Description	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Door, oak	0,58	0,22	0,07	0,04	0,03	0,07
Drywall, 1/2"	0,10	0,08	0,05	0,03	0,03	0,03
Floor, Concrete	0,01	0,01	0,01	0,02	0,02	0,02
Floor, Linoleum	0,02	0,03	0,03	0,03	0,03	0,02
Floor, wood	0,15	0,11	0,10	0,07	0,06	0,07
Floor, wood parquet	0,04	0,04	0,07	0,06	0,06	0,07
Floor, carpet, 1/8" pile	0,05	0,05	0,10	0,20	0,30	0,40
Floor, carpet. 1/4" pile	0,05	0,10	0,15	0,30	0,50	0,55
Floor, carpet, 5/16" pile	0,05	0,15	0,30	0,40	0,50	0,60
Glass, normal window	0,35	0,25	0,18	0,12	0,07	0,04
Glass, heavy plate	0,18	0,06	0,04	0,03	0,02	0,02
Glass, laminated	0,18	0,06	0,04	0,03	0,02	0,02
Plywood, 1/4"	0,58	0,22	0,07	0,04	0,03	0,07
Plywood, 3/8"	0,28	0,22	0,17	0,09	0,10	0,11
Plaster, rough finish	0,02	0,03	0,04	0,05	0,04	0,03
Plaster, smooth finish	0,02	0,02	0,03	0,04	0,04	0,03
wood paneling	0,24	0,19	0,14	0,08	0,13	0,10
wood roof decking	0,24	0,19	0,14	0,08	0,13	0,10
Carpet, 3/32" pile	0,10	0,16	0,11	0,30	0,50	0,47
Carpet, 3/4" pile	0,15	0,17	0,12	0,32	0,52	0,57
Carpet, 3/8" pile	0,17	0,18	0,21	0,50	0,63	0,83
Person, adult	2,50	3,50	4,20	4,60	5,00	5,00
Person, child, high school	2,20		3,80		4,50	
Chair, hard seat, up		0,19	0,24	0,39	0,38	
Chair, theatre, heavy upholstery		3,40	3,00	3,30	3,60	
Air, per 1000 cubic feet			0,90	2,30	7,20	

Table 4-1: The absorption coefficient of common materials at different frequencies

4.2.2 Data from acoustic measuring

Running machines and their power supply systems are commonly considered as the sound sources in a manufacturing system. Hence, the features of sound sources are directly related with machine types, machining processes, machining tool selection, work piece materials, etc. Acoustic measuring provides the necessary data for characterization of sound sources and the supplementary data for human modeling. One or more sound sources in the Manufacturing Lab need to be described mathematically by using the values of sound power acquired by sound intensity measurements. Further description of sound sources enables simulation settings and validation of simulation results. Sound pressure level measurements from near the machines are needed in order to evaluate worker's exposure to noise. A machine dependent measurement provides additional data for sound source modeling, while the position-based measurement enables a validation for simulation.

Human hearing can only perceive a limited range of frequencies. Depending on the study, the range can be anywhere from 20 Hz to 20 kHz [Wein08] or from 16 Hz to 16 kHz [Henn08]. The human ear perceives equal sound pressure at varying frequencies differently [Crem78]. Therefore, to estimate the perception of sound pressure for human hearing in a manufacturing environment, a frequency weighting is needed. Different weighting methods are introduced in [Möse07] and indicated by using A-, B-, C-, and D-. The B- and D- weightings have fallen partly into disuse. The A-weighting is commonly used for environmental measurements and as a standard in many SPL meters. In this thesis, the measurement results are estimated by using linear and A-weighted methods.

4.2.2.1 Sound power

Sound power is one of the most essential sound features which indicates the total energy of a sound wave per unit of time and is measured in watts. Part of a machine's technical features is to describe the total emitted energy as sound waves.

Experimental setup

The sound power can be measured by using sound pressure methods or sound intensity methods. The advantages and disadvantages of both methods are compared and represented in Table 4-2 [Schi06 and Möse07].

Measures	Pro	Con	Standards
Sound pressure method	❑ Simple implementation ❑ Simple measurement method	❑ Correction of environment ❑ Correction of interference sound level ❑ No near-field measuring	DIN EN ISO 3741, 3743, 3744, 3745, 3746, 3747
Sound intensity method	❑ Direct measure of sound intensity ❑ No effect by interferential sound sources ❑ No effect by reflexion	❑ High cost and complex measurement	DIN EN ISO 9614-1, 2, 3

Table 4-2: A comparison of sound power measurement methods

Due to the distinct advantage of accuracy, the sound power is measured by using the sound intensity method and is determined by sound intensity level, which is usually expressed as sound power level (sound watts level, SWL) L_w. Considering the high cost and complexity, the measurement is only made on a lathe machine as reference in the Manufacturing Lab. The selected methods, measuring settings, and self-developed supporting equipment can be used for other machines. A sound intensity probe, which shown in Figure 25a, is often used for sound intensity measuring. This probe is made from two condenser microphones and a distance holder between them. For more details of its construction refer to [Brüe91]. The sound intensity can be determined by using the difference between two measured SPLs, which are recorded by both microphones [Henn08]. Before the measurement, a pressure calibrator is needed to calibrate the microphone. See Figure 25b for the calibrator and calibration setup.
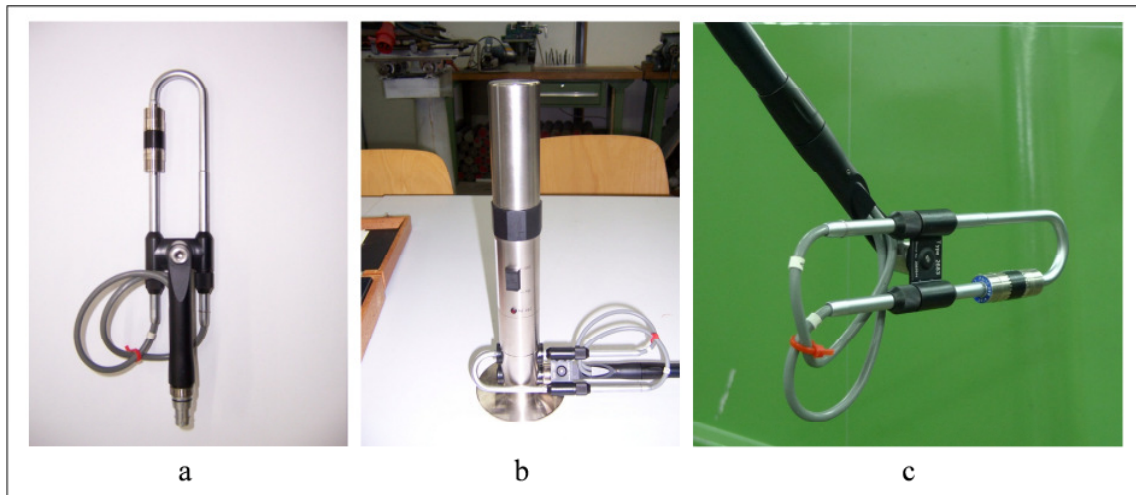

Figure 25: Devices for sound intensity measurement: a) a sound intensity probe, b) a pressure calibrator, and c) setting of the probe
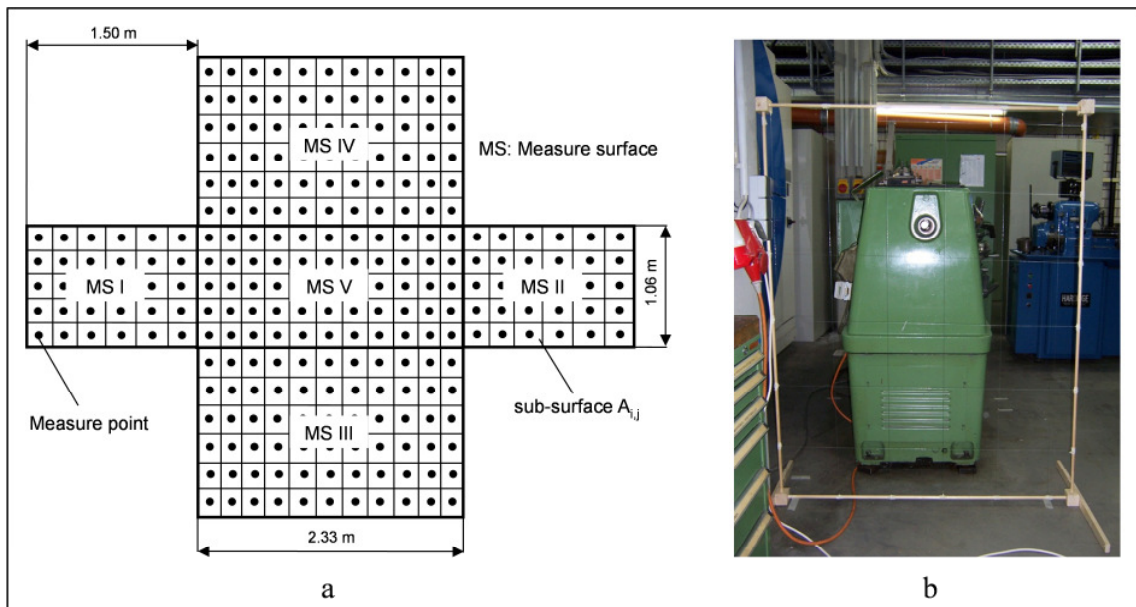

Figure 26: Measuring surface and measuring positions

DIN EN ISO 9614-1 [DIN09b], 9614-2 [DIN96], and 9614-3 [DIN10c] define an enveloping surfaces method. The measurements are conducted around a selected machine, directly facing the five surface sides (front, back, left, right, and top) with a measurement distance of 0.5 meters from the machine. According to the guideline, each measurement for every surface should be repeated at least 10 times per square meter [DIN09b]. To complete the measurements, all 5 surfaces and 247 measuring points of the lathe are firstly drawn as a sketch (Figure 26a). Based on this blueprint, a grid is made from several wood frames and thin cords to assist with the measurements around the lathe (Figure 26b). This grid defines the sub-surfaces for measuring and helps the operator find the right position to place the intensity probe.

Result of the measurements

Using the grid the sound intensity measurements are repeated in the middle of each sub-surface $A_{x,y}$ (see Figure 27a). The machine speed during measurement is 1120 rpm without cutting a work piece. The sound power of each sub-surface $L_{w,i}$ is visualized in Figure 28 as a 2D and 3D illustration. The point of maximum SWL, which was thought to be near the cutting tool, is actually close to the electric motor. Near the back side of the motor, the SWL reaches 82.9 dB because the back cover is thinner than the front one. Due to the reflexion of floor, the SWL shows a higher value of 86.3 dB at the bottom of the electric motor (Figure 27b). The 3D representation of SWL distribution, shown in Figure 28b, enables a straightforward understanding of sound power of a sound source and provides detailed data for a more realistic modeling of the sound source. The SWL of a sound source L_w is estimated by summing all parts of the $L_{w,i}$. The estimation can be made both with linear and A-weighted methods. Figure 29 shows the SWL which is represented according to third-octave band frequencies. The result the of linear summation L_w is 92.8 dB and the A-weighted value is 92.5 dB (A).
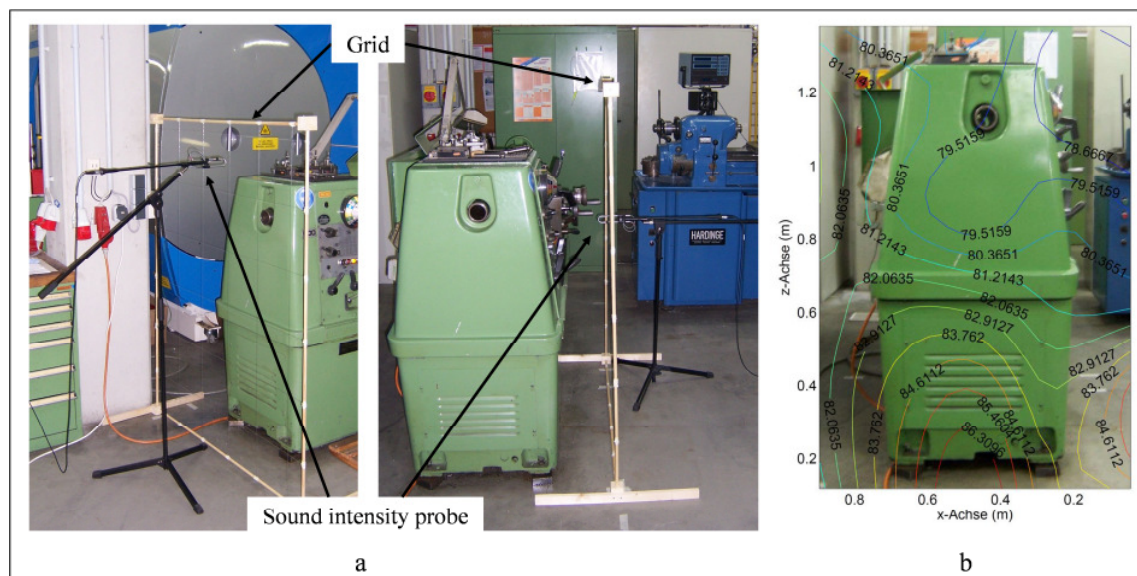

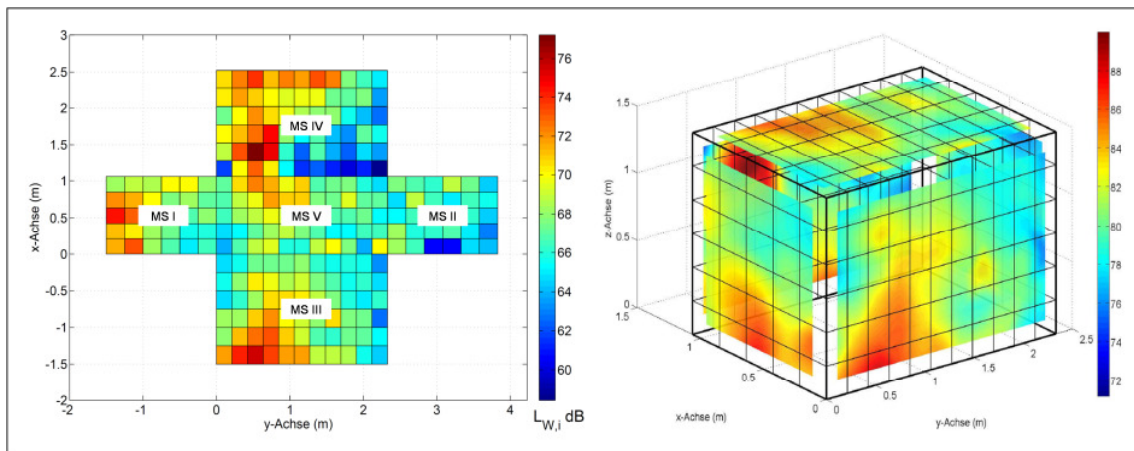Figure 27: Measurement setting for sound energy

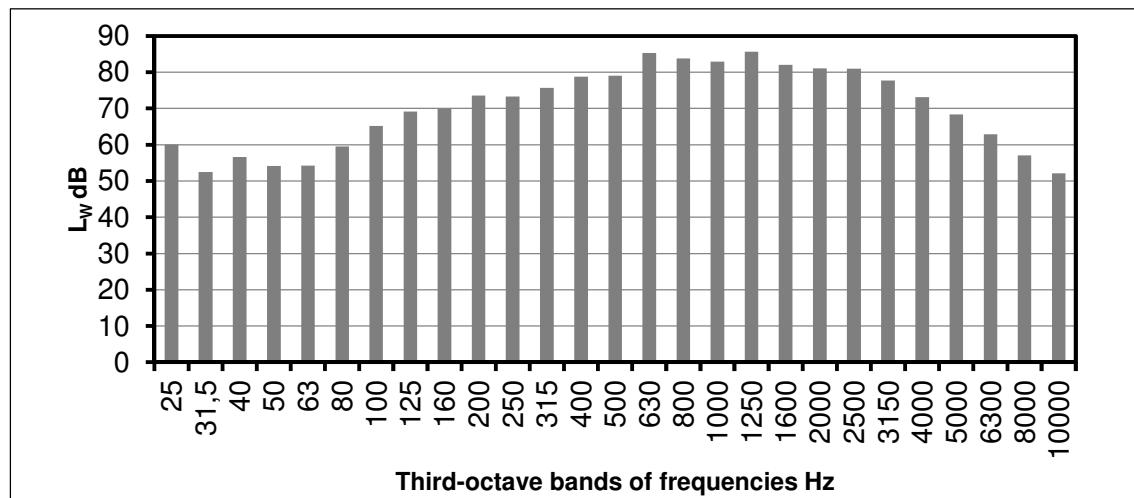Figure 28: SPLs of sub-surfaces at spindle speed =1120 rpm/SWL 92.8 dB

Figure 29: Linearly estimated SWLs of turning lathe

4.2.2.2   *Sound pressure*

Sound pressure is calculated by the difference between local pressure and atmospheric pressure caused by a sound wave. The SPL indicates the effective sound pressure relative to a reference value, defined in ANSI S1.1-1994 [ANSI94]. 20 µPa at 1000 Hz, the zero dB, is commonly understood as threshold of human hearing [Gelf90]. This index is often used to identify the sound impact on humans (for different effects see section 2.1.1). SPL is measured on a logarithmic scale and ranges from 0 to 140 dB [Henn08]. Every 3 dB increase of SPL means a doubled value of sound pressure.

Experimental setup

A SPL meter is used to measure the SPL. This equipment is normed by IEC 60804 [DIN02], IEC 60651 [DIN03a], and DIN EN ISO 61672-1 [DIN10c]. Figure 30 shows a widely used set of products from company Brüel&Kjær. A portable display (model: "Investigator", type: 2260) allows for parameter settings, the storage of measurement results, and result visualization (Figure 30b). Refer to [Möse10a] for the basic design and mechanisms of this type of SPL meter. Figure 30a shows the condenser microphone which is used to record the sound. Because the microphone has a spherical characteristic, high frequency measurements are accrual (to 10 kHz) [Brüe96]. However, significant errors will appear when measuring

sound waves at extra high frequencies. More investigation and discussion about measurement error caused by the SPL meter can be found in [Brüe94, Payn04]. In this thesis, this type of errors is not taken into account because the extra high frequency sounds are not commonly found in a factory.

Before being used, a calibration of the microphone is done by using an airborne sound calibrator, which is normed by IEC 60942 [DIN04]. This calibrator is placed in front of the microphone and generates a reference sound wave with pre-defined pressure and frequency. The calibrator and calibration setup are shown in Figure 30c. During measurement, the microphone is positioned by using a tripod with an extension arm. The microphone is adjusted to the head position and viewing the direction of the operators with a distance of 0.10 meters and a height of 1.55 meters. More details about microphone placement for different situations can be found in DIN EN ISO 9612 [DIN09a]. For example, in Figure 33a, the microphone is placed to face the control panel or operation side.
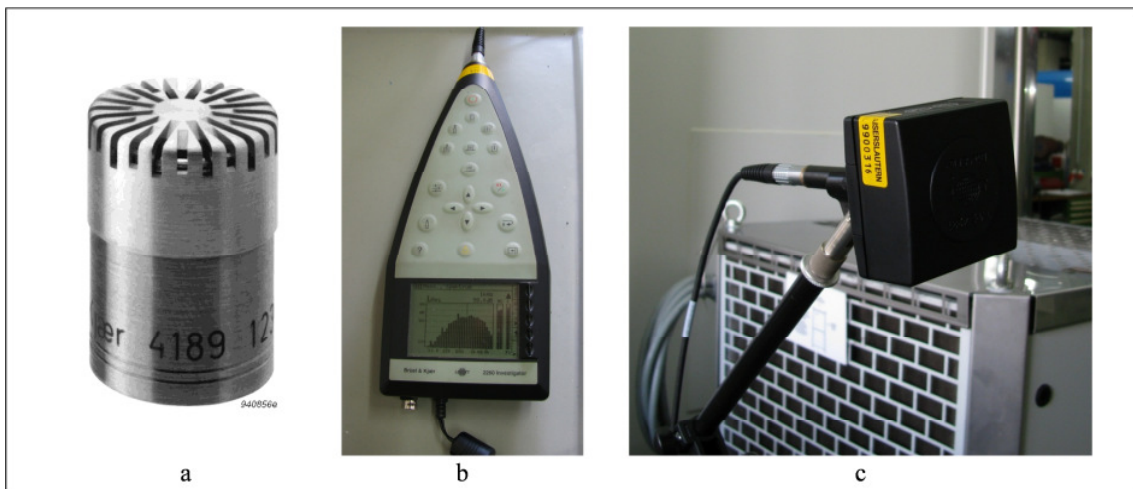

Figure 30: Devices for SPL measurement from company Brüel&Kjær: a) condenser
microphone, b) SPL meter, and c) microphone calibrator

Result of the Machine-based SPL measurements

The SPL measurements are taken in both machine-based and position-based setups. Firstly, the investigation and analysis of SPLs at working areas in the Manufacturing Lab are machine-based, based on the guidelines DIN 45645-2 [DIN97] and DIN EN ISO 9612 [DIN09a]. When it's feasible, the measurements should be conducted in front of running machines without the influence of operators or other machines. However, this optimal simulation is not usually possible in practice. The measurements are made in five main manufacturing facilitates in Manufacturing Lab (CNC milling center, CNC grinding machine, CNC machining center, and two different models of turning lathe), during 3 typical machining processes (idling, normal machining speed, and high machining speed).

The time-averaged sound level (energy equivalent) L_{eq}, peak SPL LC_{pk}, as well as the L_{eq} over third-octave frequency bands are determined by the previously described measuring devices, methods, and setups. L_{eq} and LC_{pk} enable an evaluation of noise emission level in a manufacturing environment. In laws and guidelines of manufacturing noise, the noise

exposure L_{ex} is commonly equal to L_{eq}. And the L_{eq} over third-octave frequency bands provides additional data for sound source modeling.
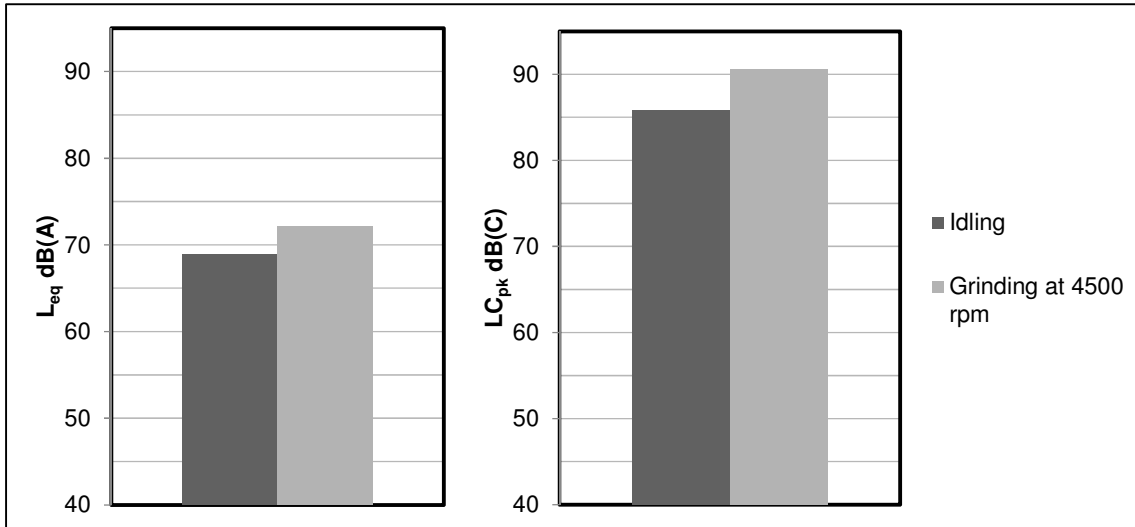

Figure 31: Comparison of average SPL of grinding machine during idling and machining

Using the CNC grinding machine as an example, Figure 31 shows the average SPL and peak SPL at idling status and at grinding speed of 4500 rpm, while Figure 32 shows the L_{eq} over third-octave frequency bands. Significant differences of L_{eq} between idling and middle speed grinding is not found, but the peak SPL shows a considerable increase during the 4500 rpm grinding. Seen in Figure 32, the highest sound pressures are found between 250 Hz and 2500 Hz. Since 2500 Hz is lower than 10 KHz, the measurement error caused by condenser microphone can be ignored.
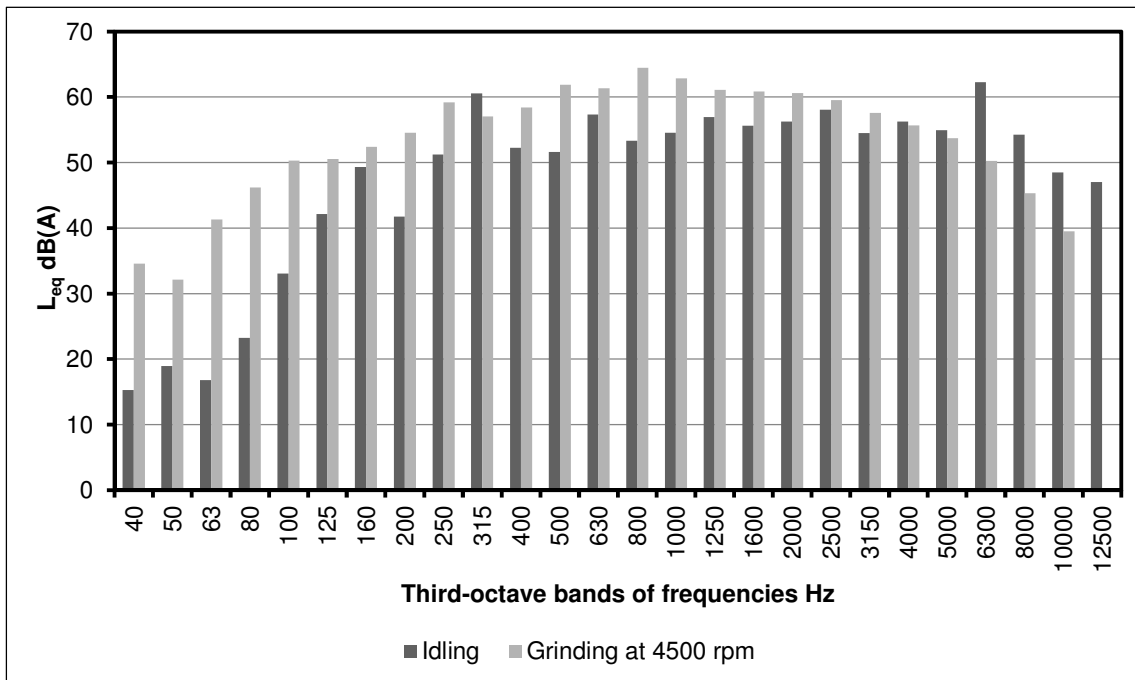

Figure 32: Comparison of average SPL of grinding machine during idling and machining

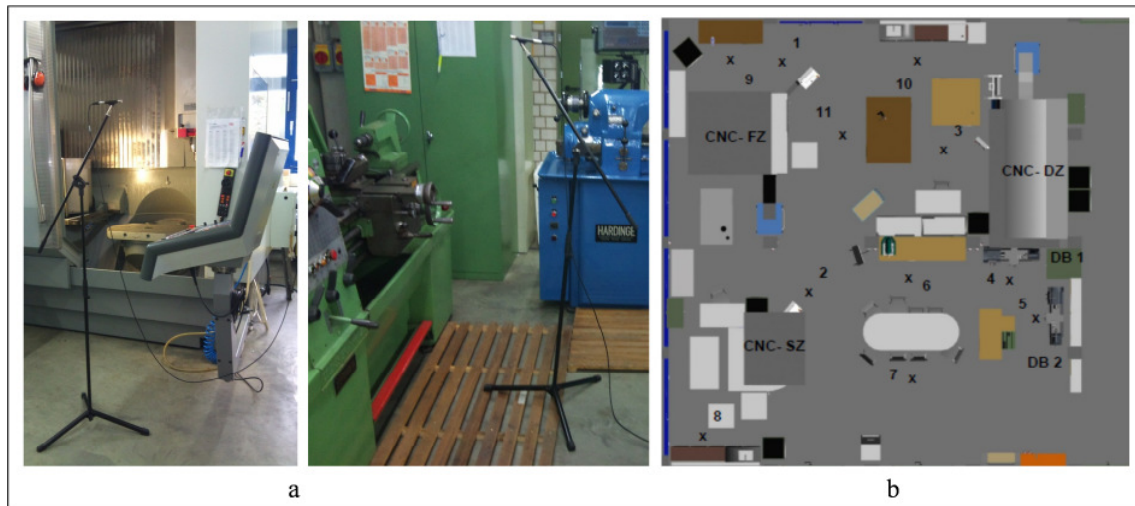**Result of the position-based SPL measurements**

Figure 33: Measurements setup and measured positions in Manufacturing Lab

The measurements are conducted at 11 pre-defined positions in the Manufacturing Lab during a typical workday. These positions are usually used as operation positions in the Manufacturing Lab. In Figure 33, the measuring positions are illustrated on Manufacturing Lab layout from 1 to 11. The detailed description, coordinate, and microphone orientation are shown in Table 4-3.

Position Nr.	Description of measurement positions	Coordinate (x,y)	Microphone orientation (x,y)
1	operator station of the milling center	(4.13, 13.08)	(0,-1)
2	operator station of the grinding machine	(4.57, 4.38)	(0,-1)
3	operator station of the CNC machining center	(10.8, 9.75)	(1,0)
4	operator station of the turning lathe 1	(12.2, 5.80)	(1,0)
5	operator station of the turning lathe 2	(12.57, 4.78)	(0,1)
6	operator station of the drilling machine	(8.22, 6.35)	(1,0)
7	position of the desk	(8.37, 3.46)	(1,0)
8	position of sink nearby the grinding machine	(2.30, 1.23)	(-1,0)
9	workbench of the milling center (facing the wall)	(2.33, 13.05)	(1,0)
10	position of sink nearby the CNC machining center	(8.84, 13.01)	(1,0)
11	Position of the table between the milling center and the CNC machining center (facing the CNC lathing center)	(5.65, 10.85)	(0,1)

Table 4-3: Description of the measurement positions

The typical machining speeds as well as the setups of the five machines during measurements are shown in Table 4-4. This information is used as reference for manufacturing setup to evaluate noise exposure in a workday. The noise level will be different when the setup is changed, however the evaluation describes an average measure.

Machine	Running speed	Description
DMU Deckel Maho 70eVolution II (CNC milling center)	18000 rpm	Milling 3 mm HSK 63, without cooling
WALTER Helitronic Vision (CNC grinding machine)	idling	Active ventilation
Boehringer NG 200 (CNC machining center)	4500 rpm	With chuck, without cooling
Triumph 2000 (Turning lathe 1)	1120 rpm	With chuck, without cooling
HARDINGE (Turning lathe 2)	3000 rpm	Without cooling

Table 4-4: Operation status of five machines during measurement

Figure 34 shows the average SPLs at different positions during operation of the turning lathe 1 (Triumph 2000) located at position 4. The maximum L_{eq} appears at position 4, which is directly facing the running lathe, while at position 9 has the lowest L_{eq}.
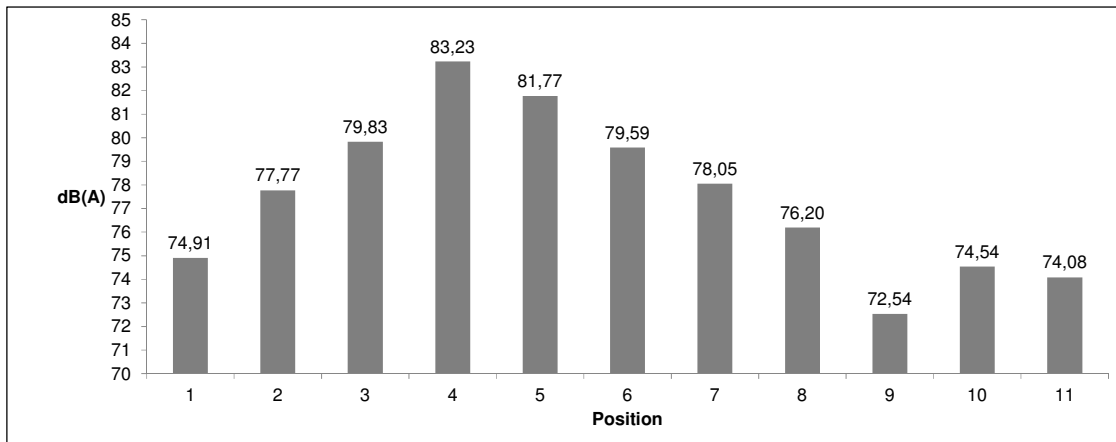

Figure 34: Average SPLs at 11 measured positions in the Manufacturing Lab

The determination of acoustic power is an essential factor for further sound propagation simulation. Due to complexity and time, finding out the acoustic power and sound pressure of every noise source in a large factory is a challenge. First, there is a large number of sound sources including fans, engine powered equipment, turbines, electric pumps, etc. Second, for economic reasons, the manufacturing can't be stopped in order to measure every each single sound source.

One solution is using the detailed technical acoustic information provided by facility manufacturer. Various other solutions by different authors exist in the literature. For example, GUASCH et al. introduced an inversion modeling method to obtain the sound source power in a

large factory. This method is based on a large number of measurements and the support of sound propagation software [Guas02]. Another computer aided solution using ray tracing is discussed in [Luzz86]. This solution uses geometric acoustic model and acoustic ray method to identify the sound source and estimate the sound power in a closed room. However, the both solutions are dependent on acoustic measurement results and detailed description of geometric features. For a large room with a complex layout and large number of objects, the solutions are not practical.

4.3 Modeling

Based on the acquired data from the manufacturing environment, the modeling step is used to bridge the real world and the virtual world. This means the digital or analogue data describing from factories, machines, sound sources, etc. are transformed to specific formats, so that the information can be used for simulation and visualization in a VR system [Kels98, Souz06]. In this section, different software and methods are introduced and the rebuilt virtual world with different production objects and a human avatar is represented.

4.3.1 Modeling of the virtual environment

To visualize a virtual environment as well as the sound simulation, the geometric data and description of a sound source are needed. The measurements from the factory provide the basic data for the 3D geometric models. Figure 35 illustrates this process from a (a real factory) to b (check list for data collection, also see Appendix 11.4) and then c (a 3D geometric model). A geometric model of the environment provides the following information:

❑ environment features, such as the building geometries, machine layout, environment lighting, etc.

❑ shape, size, coordination, position and orientation of the objects in the environment

❑ surface features of the objects, such as material, texture, color etc.
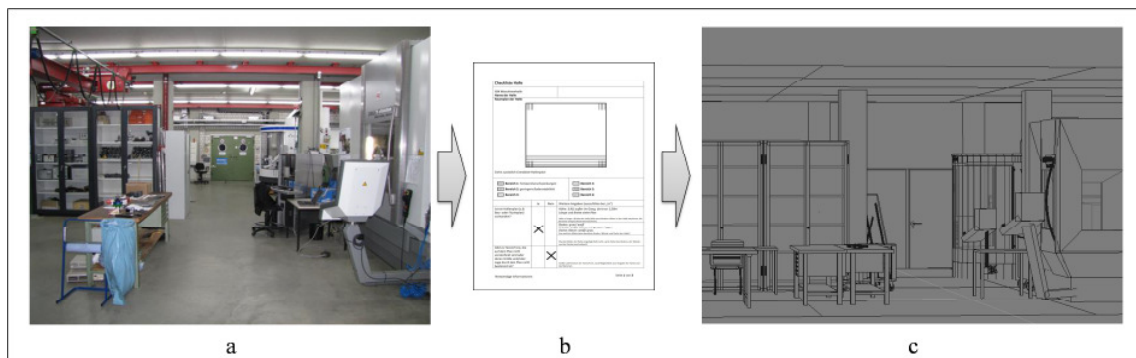
❑ process-based interrelationships among the objects

Figure 35: Modeling of a virtual environment

Unlike visible light, audible sound has wave lengths between 0.2 and 17 meters. The reflections are primarily specular on large and smooth surfaces. The diffractions often occur around big objects (such as lathes), while small objects (such as bottles) have little effect on

the sound propagation. Therefore, the 3D geometric models for sound simulation need less detail than the models for computer graphics.

A common method to create a virtual environment and related objects is using Computer Aided Design (CAD) software, such as "SolidWorks," "Solid Edge" and "CATIA," which enables precise 3D description of objects. However, this precision leads to a huge number of polygons which decrease the computing performance of both the simulation and visualization. Also, the modeling of the environment features, such as the lighting in a factory, and the modeling of object features, such as the surface textures, is limited using the CAD software. Therefore, the modeling software, such as "3ds Max" or "Blender," are used to improve the visual effect of a virtual environment. Figure 36 shows a comparison between a photo of a grinding machine and a virtual model rendered using 3ds Max. The number of polygons is optimized to balance the visual effect and computing performance. The surface material features and lighting effect are enhanced as well.
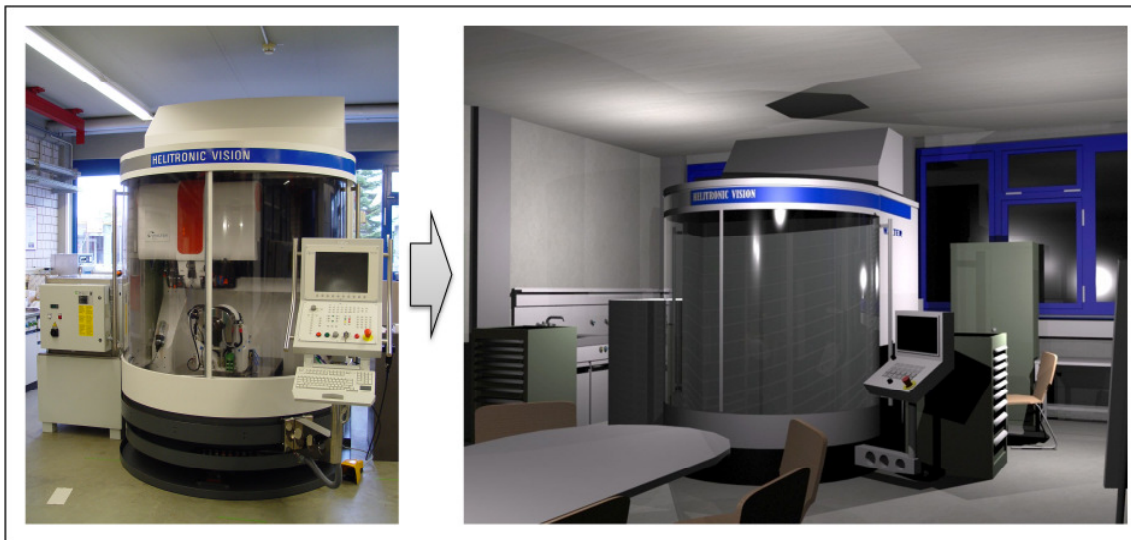

Figure 36: 3D modeling of a virtual environment with real lighting effects

In addition to CAD and modeling software, several computer languages provide libraries and tools for direct modeling. VRML, X3D and Java 3D are some examples. These languages enable the data to be converted to a VR-compatible file format. The VRML is the specified modeling language for VR applications, which was established at 1997 and accepted by ISO as standard ISO 14772 [ISO97]. It is widely used for VR applications, e. g. the assembly design, machining process simulation, evaluation and visualization of the planned facility or the training of employees, all while keep the production running [Oliv07 and Brec09]. The advantages of VRML language for engineering applications are significant:

❑ The VRML description is a text file format (ASCII or UTF-8).

❑ Associations can be structured between URLs and graphical objects, so that the web-based uses of VRML models are enabled.

❑ The most important feature of VRML is the "Nodes", which are the basic elements for creating a specific function in a scene graph. Each kind of Node has a specific field, values and children statements.

❏ The VRML Nodes offer a customized link to different positioning and allocations between different objects. The needed user interface with icons and description field can be easily adjusted.

❏ Program code written with Java or JavaScript can be embedded in VRML using Script-Node, which allows the implementation of calculations, mathematical results or databases into the VRML script as well.

❏ The Proto Node enables the user to construct a set of customized Nodes, e.g., building a Chip-Geometric Node. Consequently, Proto offers an increasing usability of VRML and allows creating different objects, interactions, and Scripts.

❏ Using VRML, the integration of multimedia applications in a virtual environment is possible, e.g. text, images, audios and movies.

❏ VRML Viewer integrated browsers and editing tools for the creation and modification of VRML files are widely available for many different platforms (platform independent).

VRML imports different graphic objects with various geometries from simple polygons all the way up to complex CAD files. It provides the ability to use and combine dynamic 3D objects within a VRML world and thus allow reusability. Objects in CAD file can also be exported as VRML files (.WRL) and visualized in VR. JavaScript enables the implementation of mathematical functions, which describe the different manufacturing processes.

As the successor to VRML, X3D is also standardized by ISO and contains most of the VRML features. For current applications X3D has no remarkable advantages compared to VRML. VRML, however, has many more users developed Nodes (functions), application programming interfaces (APIs) and extension modules. Using plain text description and existing Nodes, the development of applications is accelerated and facilitated. Therefore, in this thesis, VRML is used as the modeling language and scene graph standard for VR application. SolidWorks is used for basic object modeling, 3ds Max is used for virtual environment modeling, and "VrmlPad" is used for WRL file modification and modeling. Detailed implementation of VRML files using "VrmlPad" will be shown in chapter 5.

4.3.2   Modeling of sound source

In this thesis, the phonon tracing algorithm is implemented. To do this, a sound source needs to be modeled. The basic idea is to represent the energy emission of a sound source as a simplified sphere. Hence, the modeling method developed by DEINES is implemented [Dein08]. Figure 37 illustrates a sound source with its energy enveloping surface.

And the following information is needed during modeling:

❏ Position of the sound source

❏ Emission distribution of the sound source according to the reference position

❏ Number of phonons that will be traced from the sound source

Sound source modeling is still an essential issue in acoustic and computer science research. In this thesis the sound source position and number of phonons are implemented as simulation parameters, which are set before simulation start. The emission energy is based on the acquired data during measurement and the emission enveloping surface is simplified as a

sphere-like shape. This model provides a straightforward and relatively accurate sound source model for acoustic simulation.
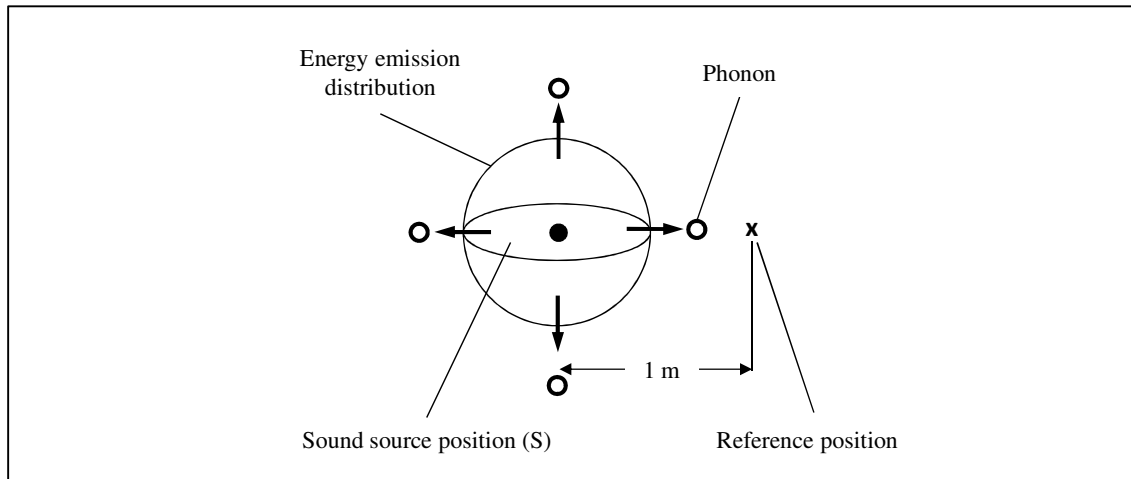

Figure 37: Representation of a sphere-like sound source

4.3.3   Modeling of human

The needs of 3D avatar modeling are various considering the different implementation and use scenarios. In [Span10], the most frequently used human models, such as the "Human Builder," "Jack" and "RAMSIS," are represented in Figure 38a. They are widely used for manufacturing operation investigation, ergonomic research and visualization function. For example, the software "eM-Human" by TECHNOMATIX allows users to simulate the work load in a virtual factory [Tecn03]. However, no human model (avatar) provides an indication of noise level through color. For more discuss about human model use in a digital factory, see [Zülc05].

The sound issue is strongly affects humans. In this thesis, the human model is used to define the positions of SPL estimation during simulation, as well as an indicator to show the reached limits. Hence, the human model should involve essential information, such as scale, position, texture, etc.
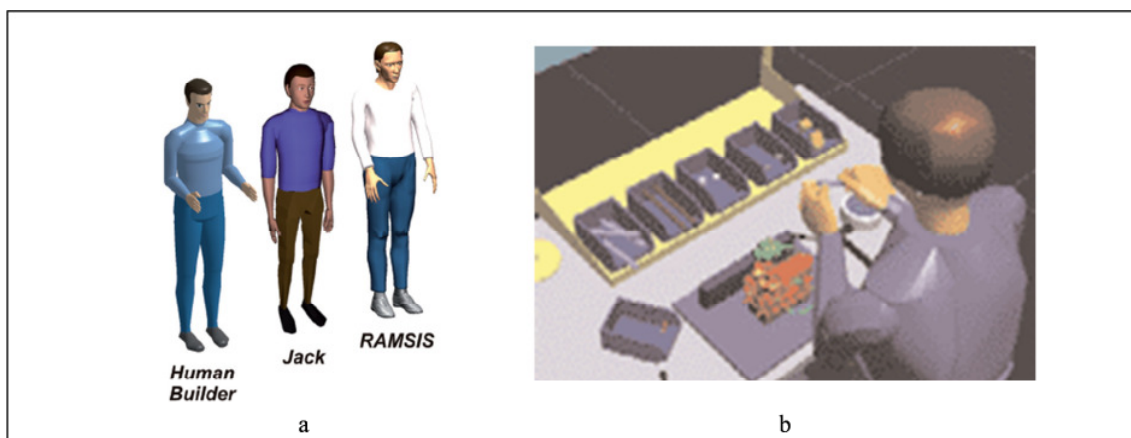

Figure 38: Different human models [Span10] (a) and the ergonomic study using software eM-Human [Tecn03] (b)

Several companies offer catalogs with human models, at different levels of detail. Compared to creating models themselves, it is cheaper and faster for users to buy models directly. The

basic geometric model shown in Figure 39a is directly acquired from open source database. The model height is set at 1.7 meter and could be modified again considering the real situation before simulation. For example, during measurements the microphone is commonly set at 1.55 meter, which is the ear height of a 1.7 meter high person.
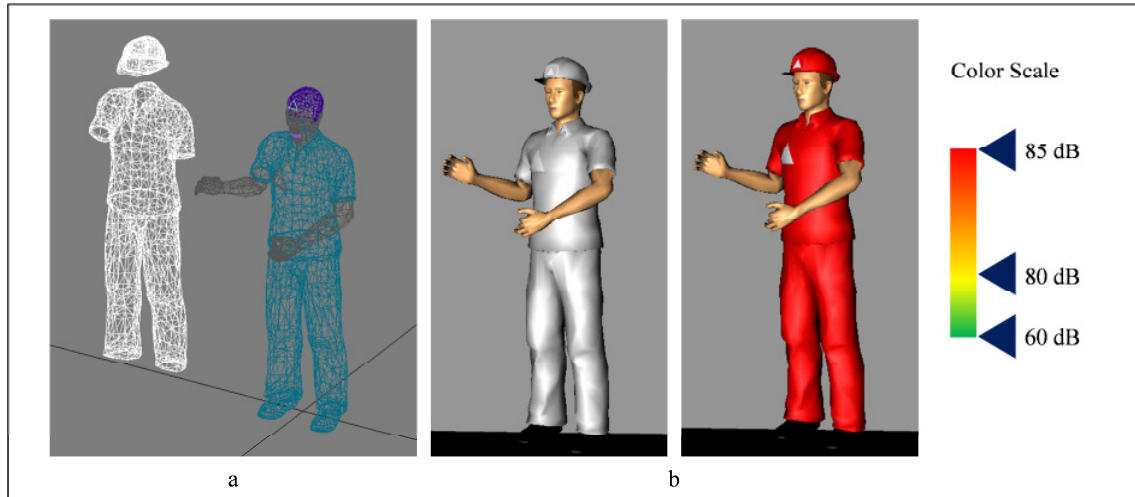

Figure 39: Human model and used color scale

The position of human model can be defined directly in a virtual environment and also used in the SPL visualization step (see section 5.3.2). Based on LärmVibrationsArbSchV of BMAS, the lower and upper action values of SPL are at a daily/weekly noise exposure of 80 dB (A) and 85 dB (A) respectively (Table 2-1). The material diffuse color of the clothes of this human model is set as a SPL-related variable. Considering the lower and upper limit, which are regulated by law, the color of clothes change gradually from green (SPL=60 dB) to yellow (SPL=80 dB) to red (SPL=85 dB). Figure 39b illustrates the human model and different cloth colors.

4.4 Acoustic simulation

In this thesis, a phonon tracing algorithm is implemented for acoustic simulation, which is illustrated and compared to other algorithms in section 2.2.2. The phonon tracing method considers sound waves as a particle system involving many fragments (phonons) of the whole sound energy. The algorithm consists of two separate steps: phonon tracing and phonon collection. In the first step, sound energy propagation is simulated as traced phonons. In the next step, the SPLs are estimated at given positions. The implemented approach is described in more detail in the following section.

4.4.1 Simulation of sound propagation

The phonon tracing is a geometric acoustics method, which needs geometric data as input. The geometric data contains the 3D models of factories, facilities, and different machines, etc. This data is provided by the modeling step, which was described in the previous chapter. Besides the geometric data, the following input data is needed:

❑ a triangulated scene with tagged surface material

❑ absorption coefficients/functions for different materials

❑ position of one or more sound sources

❑ emission distribution of the sound sources

❑ sound energy of the sound sources

❑ number of phonons to be traced

❑ number of reflections to be traced

❑ the threshold energy of phonons at the end of simulation

Using the given sound emission level, the distribution of sound energy is modeled as a sphere surface, which was illustrated in Figure 37. From a defined sound source, the phonons are sent out and travel as a ray to the surfaces (boundary of medium) they meet. The number of phonons is defined by the user. A high number of phonons provide simulation data with higher details for visualization and auralization. However, the human ear is not capable to locate the origin of a sound source as exactly as the eye locates a light source. Therefore, a lower number of phonons are sufficient for auralization and efficient for simulation as well. The sound speed in air is considered as constant value 314 meter/second.

The phonons from sound source intersect with the surfaces and these intersection points contribute to the global phonon map. The new phonons reflect with specular with respect to the local surface normal and also contribute to the phonon map at the next intersection. This simulation process is repeated when listener positions are changed. At the intersection point, the absorbed energy is calculated using absorption coefficients.

To terminate a simulation, either the number of phonons or the number of reflections can be used. In the first case, if the energy of a phonon becomes lower than the minimum energy threshold and the minimum number of reflections has been computed, a new phonon is emitted from the source. After a defined number of phonons have contributed to the global phonon map, the simulation is terminated. In the second case, if the threshold of energy is not exceeded but a pre-defined number of reflections are computed, the simulation will be terminated as well. The process of phonon emission is illustrated in Figure 40.
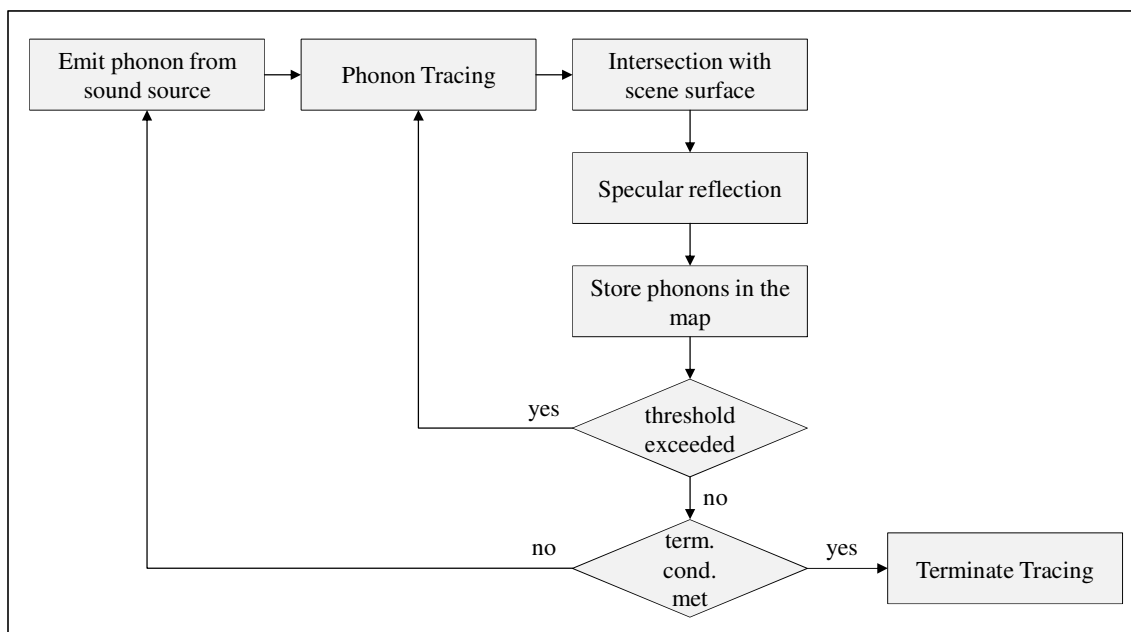

Figure 40: Flow chat diagram of the phonon tracing step [Dein08]

To simplify the simulation parameter setting, a software tool is developed. It provides graphic user interface (GUI) and data interface to VR systems, from desktop based non-immersive system to CAVE based full immersive system. Using this software, the user can perform the simulation straightforwardly. A connection between simulation and VR could improve the usability and user experience in an immersive environment. For example, the user would be able to replace the sound source or evaluate the noise level at different position directly.

4.4.2   Evaluation of sound pressure level

After the phonon tracing step, the phonon map is generated and saved for next step. This step is called phonon collection and visualization. The SPL at different listener positions are evaluated and visualized. Using a similar principle as the enveloping surfaces method used for sound power measuring in section 2.2.2, an enveloping surface for each listener position is created for phonon collection (see Figure 41). The phonons that fly through this enveloping surface are documented and calculated as a SPL.

The human ear can distinguish sound frequencies in the spectrum from 20Hz to 20000Hz, but cannot sense equal sound pressure at different frequencies equally. Hence, the finite impulse response (FIR) filters for each listener position are implemented in phonon collection step. The spectrum of the filters is generated by using 2^{14} samples. To limit the non-causal effect, the widest filters for 40, 80, 160 and 320 Hz are combined as one. Therefore, there are seven pre-defined FIR filters: 320, 640, 1280, 2560, 5120, 10240, and 20480 Hz. The production of FIRs is made in advance to reduce the computing time. The collection is cut off after 6.5^{-3} second. Afterwards, the energy sum of collected phonons is calculated to estimate the corresponding SPL. The method of phonon collection can be found in [Dein08].
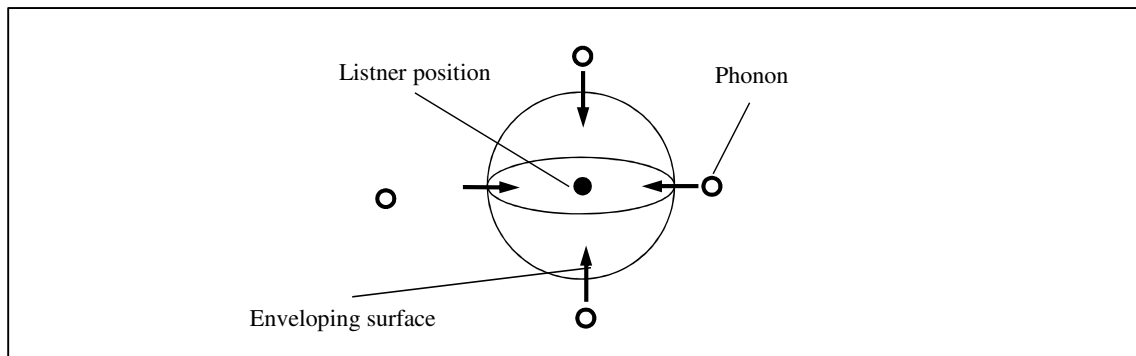

Figure 41: Illustration of phonon collection

Based on the simulation, the phonon paths are traced and able to be visualized. The phonons are shown as small spheres propagating from a sound source and reflecting at surfaces. The propagation can also be illustrated as a sound wavefront. In the simulation step, the intersections of phonons and surfaces are documented in phonon mapping. It enables the visualization of absorbed energy on surfaces. Different visualization methods can be used according to the need of applications. The visualization examples are shown in the implementation chapter.

4.5 VR interfaces

As an innovative platform, a VR system provides various interfaces for device connections, data input/output, function module integration, etc. In other words, this platform is a customizable system, able to support various hardware, software and data files. Current research shows that data interface issues are often found because of different data file formats, programming standards and hardware features. The development of interfaces according to user specified applications is needed, since one fixed standard for all users and developers are not possible.

To enable the implementation of sound simulation and visualization tools in VR operated by COVISE, the interfaces at the software level are investigated in this section. Based on the understanding of the execution process of COVISE basis modules, the interfaces include the data interface and user interface. The data interface enables data transfer among more modules and simulation and visualization integration. The user interface creates a straightforward use of simulation tools and human-computer interactions in VR.

4.5.1 Data management

Each software system has its own native file format for data storage and access, which is often not compatible with other systems. For example, the binary format ".3ds" can only be viewed and modified using 3ds Max software. Hence, a data interface enables data transfer, data conversion, and data storage among multiple systems. However, there are issues such as data safeties and transfer/conversion time. Figure 42 shows a typical data flow model of COVISE within one workstation. The various modules communicate with the central controller named "covise" and local data manager named "crb". The control messages are sent and received through TCP/IP sockets. In the case of local application, as in Figure 42, the data is stored in local shared memory and accessible from different modules. The data flows according to the arrangement made by module mapping.
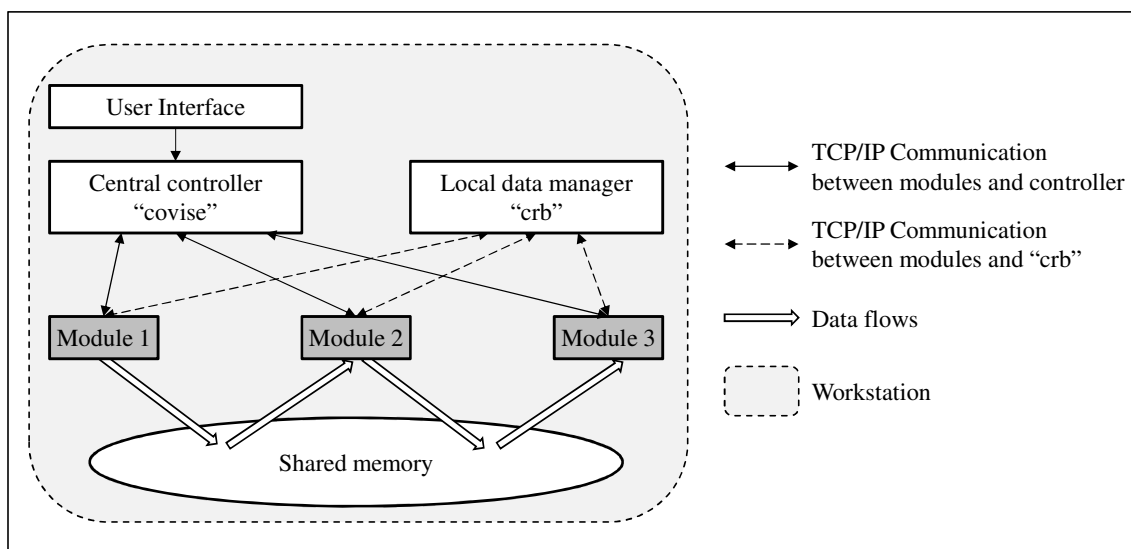

Figure 42: Data flow of COVISE within one workstation

In FBK VR laboratory, the computing is executed using a VR cluster. In other words, the different modules are executed on different client workstations. To do that, more COVISE request brokers (crbs) are needed in each workstation to coordinate the distributed computing.

The module mapping and central controller are executed on the master workstation. Whether a local executed application or distributed computing, both data and control communication are hidden within the COVISE libraries. The distributed processes are illustrated in Figure 43. The communications among the central controller, local data management, and COVISE modules are via a TCP/IP connection. The data in the master workstation is transferred to the shared memory of client computers and accessed by their modules.

There are three approaches to create the connection between sound simulation and the COVISE system. The first approach is to create a COVISE module involving sound simulation functions. The second one is to develop a plugin for acoustic simulation and visualization using the COVISE development API. The third approach is to develop the sound simulation as a separate software tool with a connection port to COVISE. The first approach provides considerably better system compatibility and efficiency than the other two. The first one, however, needs the longest time, while the third one enables the fastest implementation. Furthermore, the third approach provides unlimited connections to different VR systems, but the other two can only work with COVISE system. The objective is to develop interfaces enabling the implementation of sound simulation and visualization in both desktop and CAVE based systems. To achieve this goal, a platform-independent solution makes more sense. Hence, the third approach is selected to be implemented.
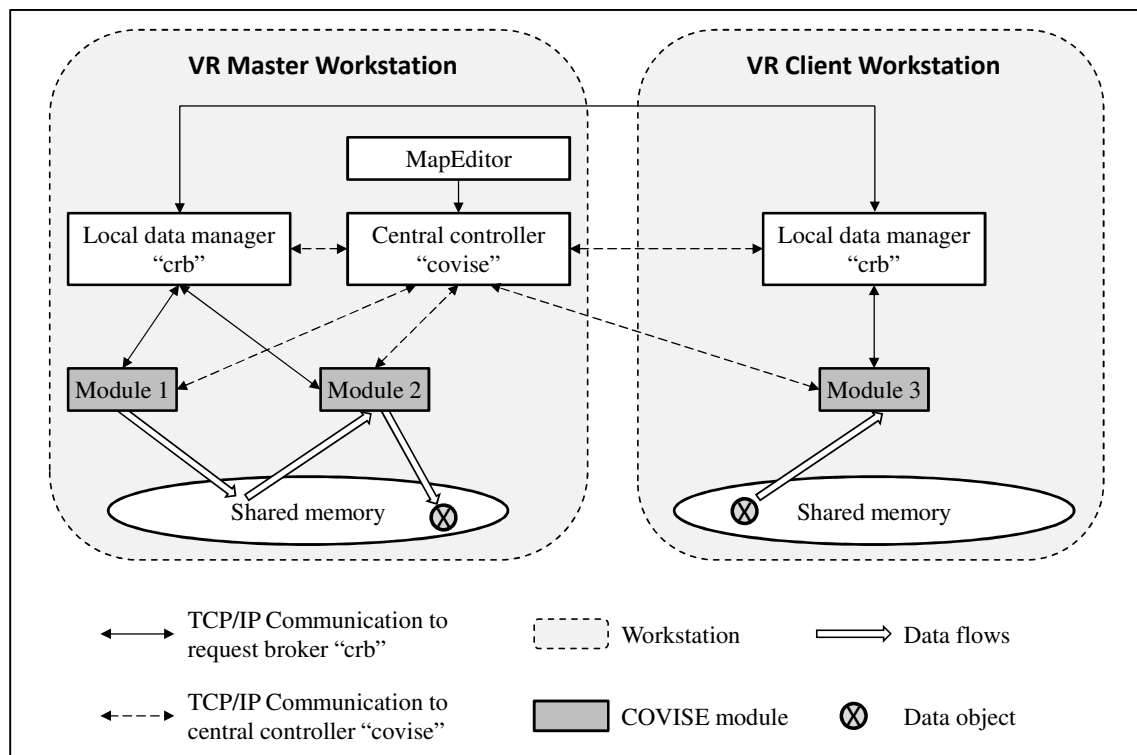
Figure 43: Data flow of COVISE using a distributed computing

Figure 44 shows the data flow among simulation and COVISE modules. For example, input data, such as the basic geometric data with VRML format, is read by the input port of a "Read/Write" module into master workstation directly. At the same time, this data will be read by a converter, which converts VRML files to OBJ files and transfers them to a simulation server. As the simulation server receives the data from the converter, additional data is generated, e.g. VRML or JavaScript code for GUI. The additional data is read by the

input port of Read/Write module as well. From the output ports, the simulation server receives data from the COVISE modules as feedback or update message. The input and output ports of various modules share the data through their local data manager (also refer Figure 43).
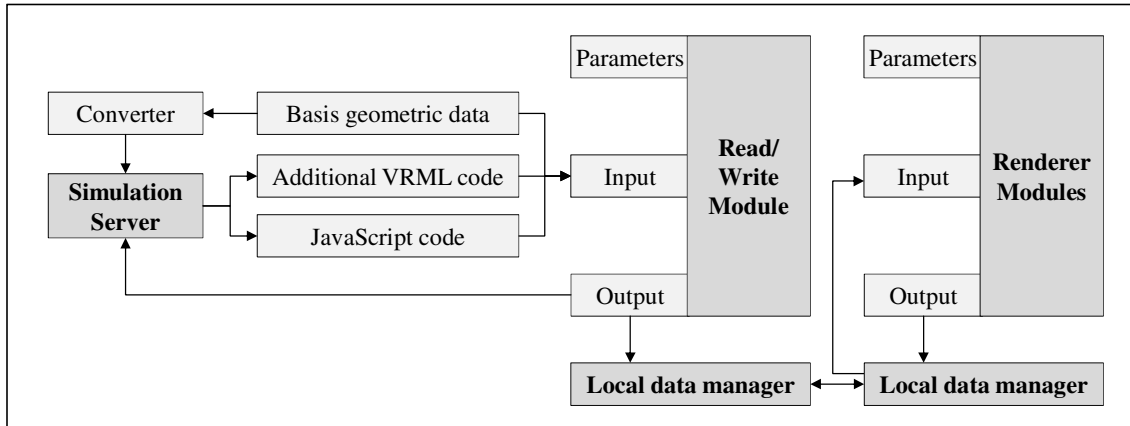

Figure 44: Data flow among simulation server and COVISE modules

4.5.2   User interface

The user interface using the selected approach enables users to manage the files, to set the simulation parameters, to start/stop a simulation, to place one or more listener positions, to visualize the simulation, or to analyze the simulation results. Two user interfaces for simulation and VR in this thesis are designed. The user interface of the simulation tool allows the user to manage the simulation and monitor the simulation processes. Basic functions such as file storage, error documentation, or process status view are included and a GUI in virtual environment is designed. Some simulation and visualization-specific functions, text information, and buttons are added inside the virtual environment. For example, the user is able to load a new VRML file, start a new simulation or define listener positions in a virtual environment directly, without leaving the CAVE. The user can also view the sound propagation and control the propagation speed using virtual slide function. Such 3D GUI is defined using VRML Node "Billiboard", so that all GUI-involved elements are facing the user automatically.
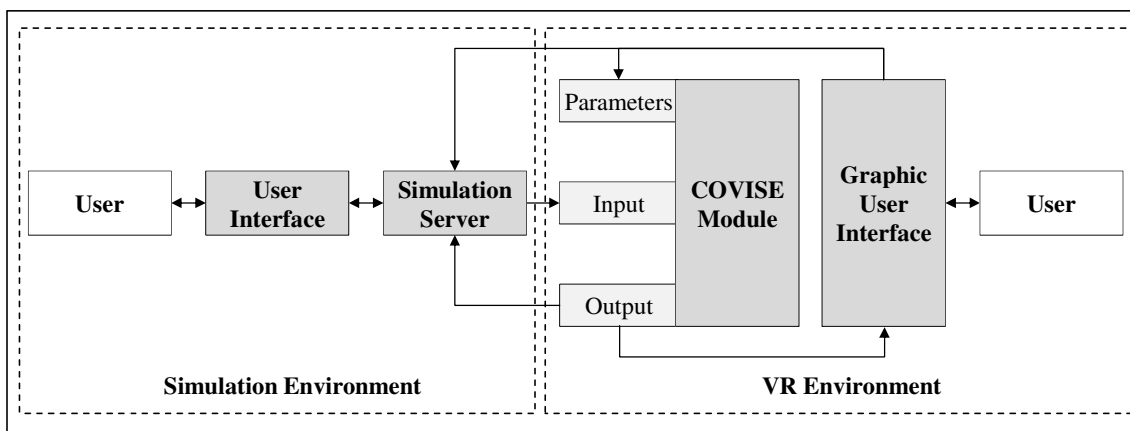

Figure 45: User interfaces for both simulation and VR

Combined with the COVISE main menu, users are also able to change modules and simulation parameters in a virtual environment through GUI. For example, the parameters of a

renderer module can be the viewpoint, the camera position, the rendering module, the navigation module speed, etc. Such changes are reacted to by the parameter port and call for a renewed rendering. The changes of simulation are communicated to the simulation server directly and are used for next simulation execution. Hence, the user has a straightforward interactive interface for simulation and visualization within a virtual environment.

4.6   CAVE system preparation

To implement the applications in a VR system, essential preparations of hardware and software components are required. This section describes the basic configurations of an immersive VR system, namely a CAVE system (e.g. the basic needs of hardware, VR operation system, and programming environment of applications, etc.). Due to the various system designs of CAVE systems, this description is based on the configuration and author's experience of the Four Walls CAVE system in FBK institute.

4.6.1   Hardware configuration

To fulfill the implementation requirements for a CAVE system, first, enough space is needed. A typical Four Walls CAVE system, like the one in FBK institute, needs at least 144 m^2 spaces for basic hardware configuration. A design without the use of mirror could extend the space to more than 200 m^2. Hence, the mirrors are used to reduce the projection distance in many CAVE systems. For an overhead placement of the mirror, the room needs to be at least 10 meters high. Furthermore, the brightness of the entire room should be adjustable by using windows and artificial lighting. Thus, the room can be darkened for better projection and also illuminated for maintenance work. To integrate a sound system in a CAVE, acoustical properties of the room need to be considered.

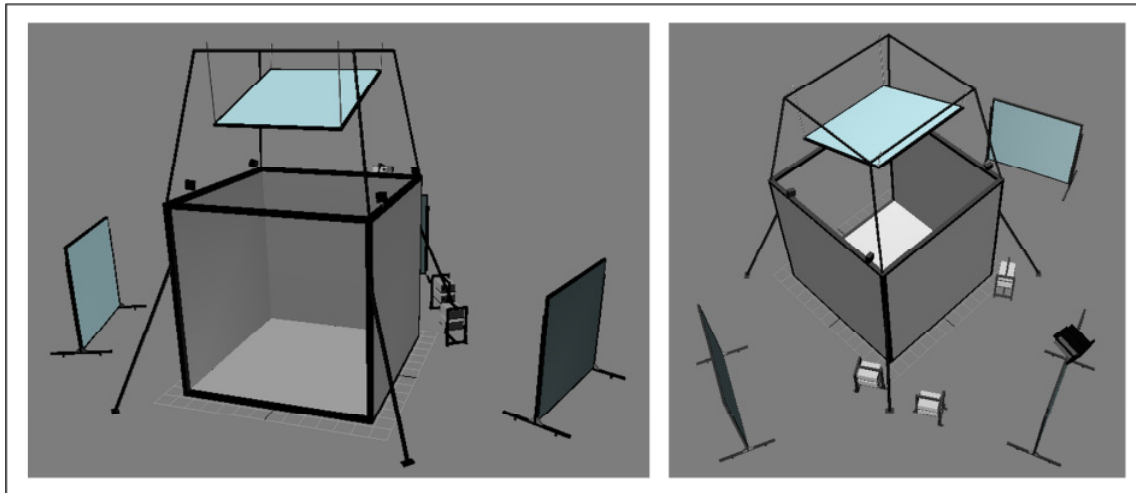Figure 46: Illustrated CAVE system from front side (left) and back side (right)

There are several other infrastructure requirements: a good ventilation system, enough power supply for all the projectors and workstations, and network connection. The exact specifications, such as the energy need and minimum network speed, are dependent on the specific hardware configuration and software application. The CAVE solution is generally not

only complex and expensive but also needs more space and maintenance during its operating time. Figure 47 shows the layout of FBK CAVE system with a check list of basic hardware.
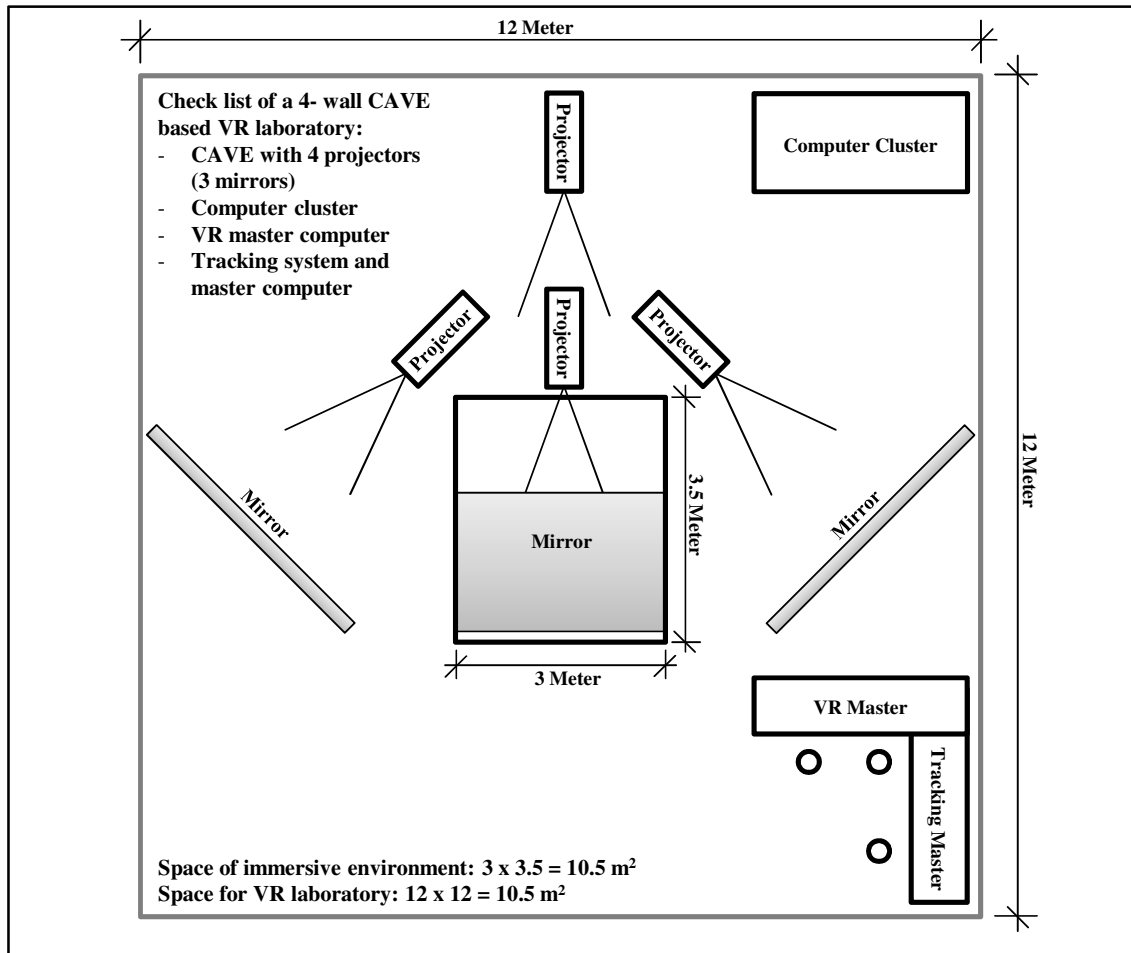

Figure 47: Layout illustration of a CAVE based immersive VR system

The FBK CAVE system illustrated in Figure 48 consists of 8 projectors, 2 projecting on each of the 4 walls with highest solution of 1280 x 1042 pixels. Three mirrors are used to reduce the projection length. This CAVE system offers an immersive virtual environment more than 17 m^3. Passive stereo technology with circular polarization is used for stereoscopic rendering of the 3D environment.

The CAVE is operated by a VR cluster, which contains 1 master and 8 client workstations (see Figure 49a). The master workstation is configured with two quad core 2.5 GHz Central Processing Units (CPU), graphics card FX 4800 with 1.5 GB memory, and 24 GB main memory. The client computers are configured with single quad core 2.5 GHz CPU, the same graphics card as the master, and 12 GB main memory. All the workstations communicate with each other using TCP/IP protocol.

The user can interact with the system via different input devices, such as a fly stick (see Figure 49) or a wireless keyboard. Four infrared (IR)-cameras (see Figure 49) from A.R.T. Company are used for the user tracking [ART12]. Six tracking markers are fixed on the fly stick, so that the hand position of the user can also be known by a tracking server. The head position is also tracked through tracking markers on the 3D glasses. The absolute positions

(the real world position of the fly stick and the glasses) are transferred to the tracking server, which is operated on a separate computer. According to calibrated reference coordinates, the absolute positions are calculated to relative positions (the virtual world positions of the fly stick and the glasses) and are sent through tracking module of COVISE to the VR master. Then, the master computer adapts the perspective of the virtual environment according to the user's viewpoint. This mapping between real user position and virtual environment enables the most basic interaction (movement) in VR and enhances the immersive experience.
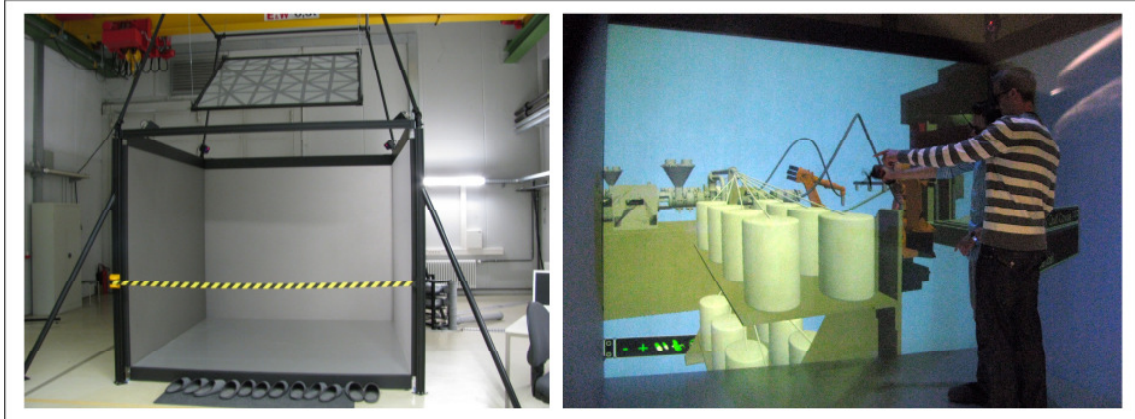
Figure 48: The CAVE system at FBK

Even if only one user is tracked by the system, several people can work jointly inside the CAVE. This allows a team to analyze the processes in a virtual environment and speeds up the analysis and decision making process.
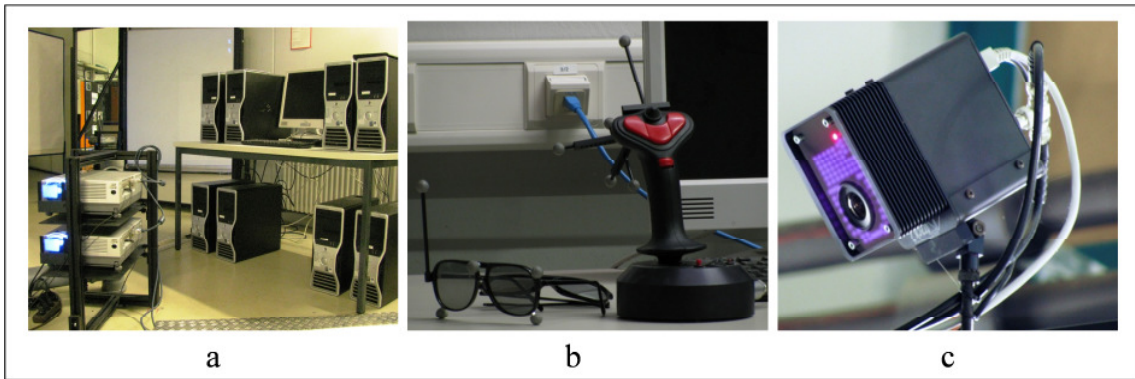
Figure 49: The devices contained in CAVE system: a) projectors and VR cluster, b) fly stick and 3D glasses with tracking markers, and c) IR-camera

The A.R.T. Company assisted with the calibration of the IR-camera and fly stick using standard software. Usually, when there are no changes or upgrades to the hardware, the calibration is done only once. Maintenance of hardware and devices is performed at specified time intervals.

4.6.2 VR software

In the FBK VR laboratory, both desktop based non-immersive VR systems and full-immersive CAVE systems are used for various applications. The advantages and disadvantages of both systems are discussed in 2.3.3. As a useful complement to CAVE system, the desktop based VR system enables users to implement the applications with low

costs and short configuration time. For example, the VRML viewer is used to view and manipulate WRL file compatible applications. Within Microsoft Windows operating system, different software can be used, such as the "Instant Player," "Cosmo Player," "GLview," and "Cortona3D Viewer". In Figure 50, the user interfaces of GLview (a) and Cortona3D Viewer (b) are shown. Both of them are implemented as internet browser plugins and can be executed online. Using such software, users can check created VR models and make changes from a web-based database. However, the file loading speed file and computation speed are limited by the computer configuration and network capability. A VRML file with a large number of objects could be bigger than 100 Mb, which is not optimal for web browser VRML viewers.
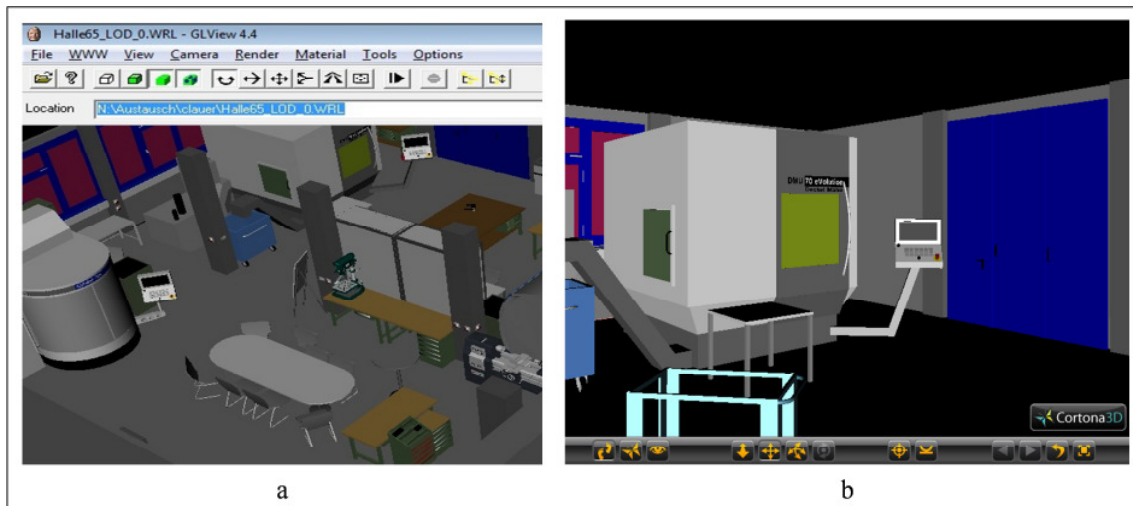

Figure 50: a) user interfaces of GLview and b) Cortona3D Viewer

For the CAVE system, basic software to run the virtual environment and implement various applications is needed. As a platform, the software "COVISE" was selected due to its wide range of supported hardware devices and the variety of different functionality modules. The software was developed at the High Performance Computing Center (HLRS) in Stuttgart in collaboration with the Department of Computer Science at the University of Cologne. It is modular constructed software, so that the applications are implemented through the execution of one or more modules. For more details about the advantages COVISE and the COVISE based application implementations, see [Lang04].

The execution process of a single COVISE module is shown in Figure 51. The "Constructor" creates the module layout and connects with a COVISE controller. A start message is sent by the "Constructor" to COVISE. Next, in order to avoid timeout condition, a time consuming initialization "PostInst" is executed before the process goes into main loop. In the "main loop", COVISE can receive and execute different events. Each module has three event handlers to control execution processes, namely the parameter handler "param()", the event executer "compute()", and the data socket "sockData()". Each change of module parameters is submitted to "param" and reacted to by the "param" subroutine. Then, the controller "covise" tells the module to read input data or create output data. The data will be shared in a local data manager, which will be described later. The data socket "sockData" monitors the data arrival.

Ports establish the connections of a module to other modules. Three typical ports are usually involved in each module: parameter port, input port, and output port. The parameter port reads

the values set by the user. The input port receives data and the output port sends data to other modules. For more details about ports and execution processes of different modules, refer to COVISE documentation [Aumü08a and Aumü08b].
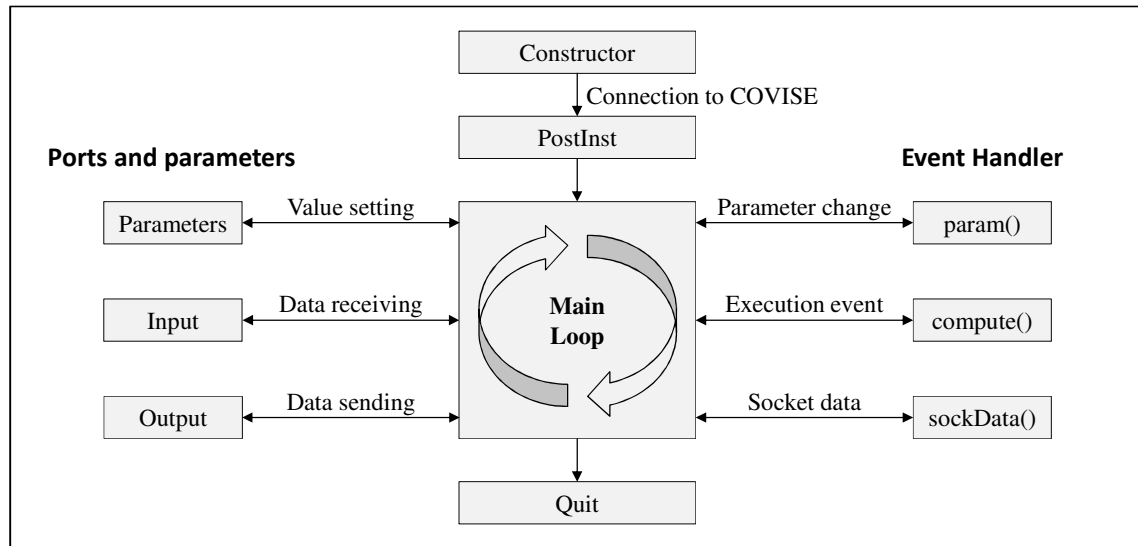
Figure 51: Illustration of a typical COVISE module

To organize and combine the different modules, the module mapping tool "MapEditor" is implemented. The users are able to choose and connect the necessary modules for their applications. Users can also define connections between the modules. Figure 52 shows the user interface of this tool and illustrates the approach used to define connections among modules. The black lines show the data flow from a data output port to a data input port. The required data and allowed data formats of each module are pre-defined. Extended data types are usually implemented by using plugins and user-programmed subroutines.
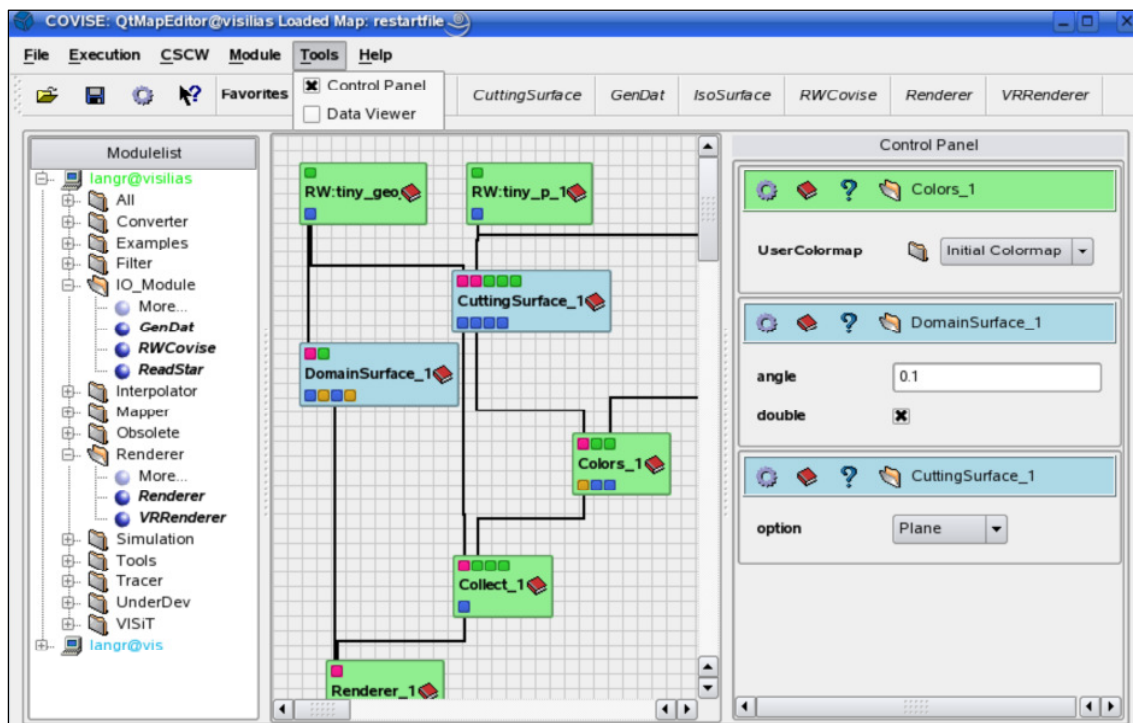
Figure 52: Module browser and mapping tool "MapEditor" of COVISE [Aumü08b]

COVISE also provides extension interfaces for normal users and programmers. By using read/write plugins, users can make more types of data input and output that COVISE can support. Other plugins enable a direct connection between COVISE and different simulation software, such as the multi body simulation or FEM simulation.

Figure 53 shows a visualization example using COVISE in both a desktop-based display (a) and a CAVE system (b). The graphical user interface in both systems is the same. The main menu includes three different modules of navigation: Walk, Fly and Drive. Other functions such as the "Zoom World," "Scale World," "View All," and "Move World" are also involved. The extension menu enables users to customize the navigation in the virtual environment. The VRML menu provides functions such as scene graph reloading, animation starting, or viewpoint changing. By using predefined API, the users can add features to the main menu themselves. However, some interactions, such as the distance sensor or touch sensor, are only possible by using the fly stick in CAVE. Figure 53 also shows the difference between immersions. The visualization in CAVE provides a much bigger projection surface and wider field of view.
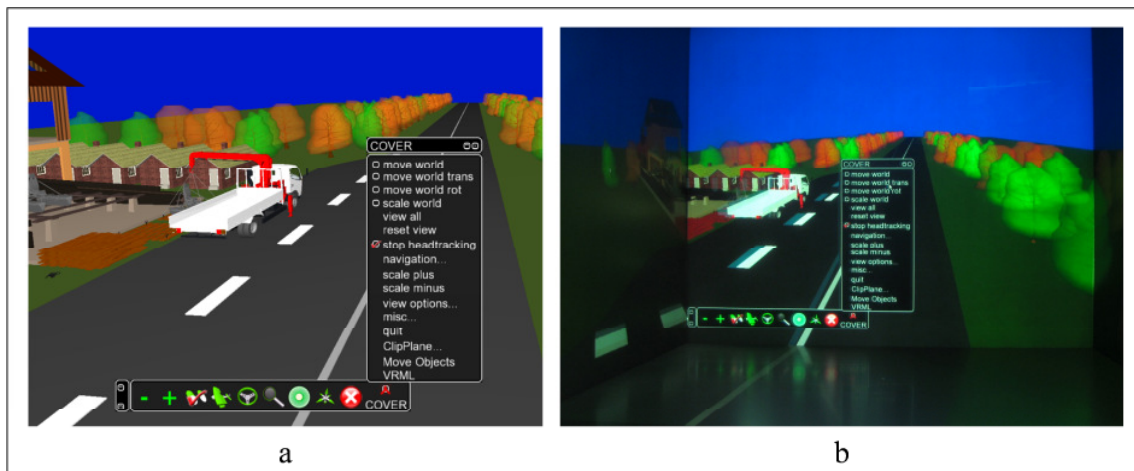
Figure 53: A scene graph visualized using COVISE in display (a) and in CAVE (b)

Using COVISE software modules, the connections to a tracking server or a sound system are also possible. In FBK laboratory, the tracking software for the IR-camera is connected via TCP/IP to COVISE and enables user-movement mapping in a virtual environment. Furthermore, the audio output module supports for a 3D sound system to improve the immersive experience in CAVE. Further connections with other customized functions, such as a tactile simulator, is enabled by using module/plugin extensions.

4.7   Summary of the approach

Based on the research objectives defined in chapter 3, this chapter explained an approach to integrate sound simulation and visualization in VR. Five implementation levels within this approach were discussed. The approach starts with the data acquisition from different resources in section 4.2. Several types of data acquisition were shown, such as the basic geometric data, the data of a sound source and legal regulation data. Table 4-5 listed a short summary of acquired data, used symbol, acquisition methods, and used standards/guidelines. The data formats of acquired data vary. For example, the geometric data file could be ".3ds"

or ".OBJ" files, while the noise exposure level acquired using sound pressure meter could be exported as different sheet formats.

The determined $L_{eq, 8h}$ is considered as $L_{ex, 8h}$, and together with the index LC_{pk} is used for evaluation of noise exposure to employees. L_w is seen as an value to indicate the noise emission from the workplaces to environment. This value could also be provided by facility manufacturers.

Data	Symbol	Acquisition Method	Used Standard
Object geometries		Measurement, Data from facility manufacturer	
Factory layout		Measurement, Building blueprint	
Absorption coefficient	α_j	Measurement, Architecture database	DIN EN ISO 10534-1, 2
Sound power level (SWL)	L_w	Sound intensity measurement	DIN EN ISO 9614-1, 2, 3
Machine- and position-based SPL	L_{eq}	Sound pressure measurement	IEC 60804, 60651 DIN EN ISO 61672-1, 9612 DIN 45645-2
Peak SPL	LC_{pk}		
Noise exposure level per working day	$L_{ex, 8h}$	$L_{ex, 8h} = L_{eq, 8h}$	ArbStättV TA Lärm
Peak SPL of noise exposure	LC_{pk}	Measurement and calculation	

Table 4-5: A brief summary of data acquisition

Based on the collected data, the virtual environment including its objects is created. The sound source models and the human models for sound simulation were discussed as well. The modeling methods were described in section 4.3. Methods of sound propagation simulation and SPL evaluation were also discussed. The phonon tracing and phonon collection algorithms were introduced in section 4.4. Section 4.5 showed the need of the VR system configurations and preparation work. To combine the both simulation and VR systems, the data interface and user interface in VR are constructed considering the current VR hardware and software platform. The data interfaces enable file transfer and conversion among multiple software modules and the user interfaces allows an interaction using a virtual environment. By means of this approach, the user is able to implement a VR-supported software application to improve the implementation of sound simulation and visualization for manufacturing design. In the next section, the implementation of software tool according to developed approach will be discussed.

5   Software Implementation

Section 4.5 described the basic requirements and methods to integrate the simulation and visualization in VR. To implement the data and user interfaces for VR, a simulation server is created, allowing users to manage the geometric files, to configure and execute the simulation, and to interact with VR system. Furthermore, the connection via TCP/IP enables a web-based application.

5.1   Software architecture

Five main functions modules are included in the software: "WRL2OBJ Convertor," "Simulation Engine," "Visualization Engine," "GUI Generator," and "HTTP Port Controller." The function diagram of this software tool is illustrated in Figure 54, in which the arrows show the data flow. The "WRL2OBJ Convertor" transforms WRL files to OBJ files for "Simulation Engine." Based on the generated OBJ file and given surface absorption coefficients, the "Simulation Engine" executes and computes the phonon tracing processes. The results after the simulation are transferred to the "Visualization Engine" via TCP/IP to the VR system directly. In "Visualization Engine", the SPLs are calculated according to the given listener positions and FIR filter files, and then a new WRL file is generated. This file is visualized in VR systems as well. The "GUI Generator" provides additional VRML and JavaScript code to create a straightforward user interface in virtual environments. All communications between the simulation software tool and VR systems are connected through HTTP by using the "HTTP Port Controller". Both simulation and visualization user interfaces will be described in the next chapter.

Figure 54: Function diagram of simulation and visualization software tool
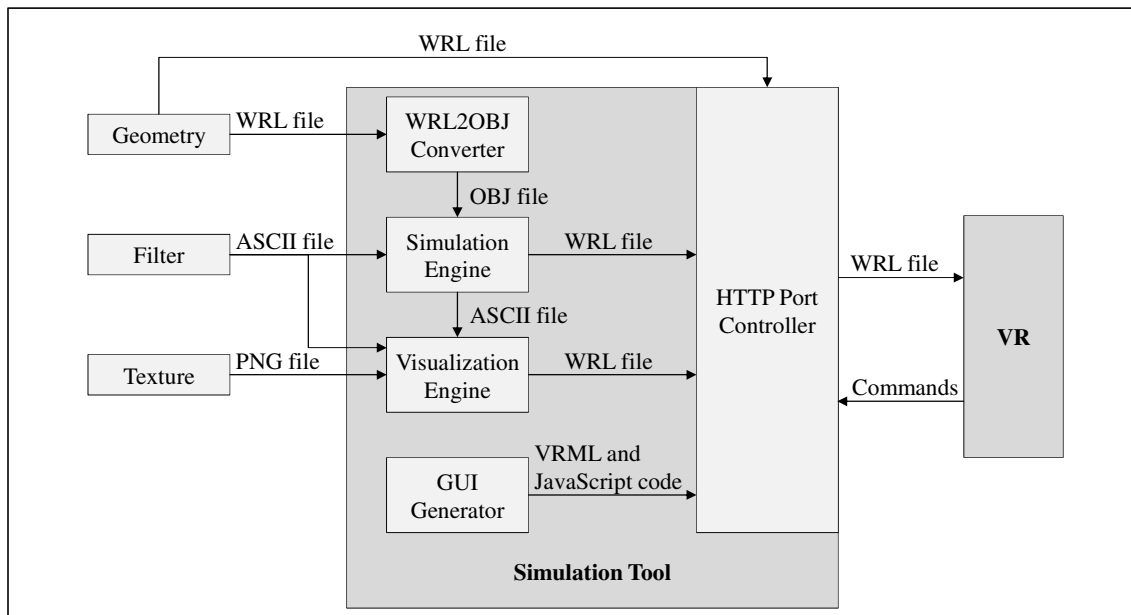
The implementation is completed based on Microsoft Windows system using C++ code and Qt programming environment [Qt12]. Qt facilities an easy GUI to start the server on selected network ports and generates an initial WRL file which has to be opened by the VRML viewer application. Additionally, Qt provides a simple interface for managing network sockets which

is a basis for an HTTP connection. Qt implementations are also portable to major operating systems. One only has to recompile the source code for Windows, Linux/Unix, or Mac OS. MinGW is used as a C++ compiler which is a minimalist development environment for Microsoft Windows applications [MinG12]. The software architecture creates a platform independent and web-based software tool. Users can run software using different operating systems and hardware configurations.

To compile the source code, several essential Dynamic Link Libraries (DLLs) are needed, which are partly provided by Qt and partly by open source libraries. These libraries are all free for research and fulfill the minimal requirements of sound simulation and visualization. They are listed as follows:

❑ QtCore4.dll: contains Qt -core non-GUI functionality (basic Qt-classes and functions).

❑ QtGui4.dll: extends the QtCore4 module with GUI functions, which enables users to create widgets, windows, buttons, etc.

❑ QtNetwork4.dll: contains the most common network protocols, many utilities, and also provides classes to make network programming easier and portable.

❑ QtOpenGL.dll: enables the connection between programs and the necessary OpenGL library, which are essential for visualization.

❑ mingwm10.dll: provides header files and imports libraries for the default C runtime library, which is required by MinGW compiled programs running on Microsoft Windows operating system.

❑ fftw.dll: a collection of fast C routines for computing the Discrete Fourier Transform (DFT) in one or more dimensions.

❑ gcc.dll: provides mostly basic arithmetic operations that the processor cannot perform directly and is basis for runtime of MinGW compiled program.

❑ CGAL: this C++ library allows users to execute efficient and accurate geometric algorithms, such as the triangulations, polygons, or mesh generations [CGAL12].

❑ GLUT: a toolkit for user to write OpenGL small and medium sized programs using a simple API. The current GLUT API version is 3 [GLUT12].

The necessary input data is stored as the required format. The geometric files are exported as WRL files using the VRML 2.0 standard. The texture information is saved as PNG or JPG files. The FIR filters are saved as ASCII plain text files.

5.2 Data basis

A specific file format is needed to enable the visualization of geometric data in VR. To represent a virtual environment and its objects, the VRML 2.0 standard is implemented. The software "3ds Max" supports WRL file imports and exports. To modify the VRML file, the software tool "VrmlPad 3.0" from ParallelGraphics is used. This tool allows users to view and change a VRML file using several essential functions without special programming knowledge (e.g. the illustration of routing mapping, 3D representation of objects, view of tree-like data structure, etc.). Position, material features and textures can also be modified. JavaScripts can be written directly in a VRML file. The sensor Nodes and interaction routings

are allowed to be defined in VrmlPad directly as well [Vrml12]. Figure 55 shows the GUI of VrmlPad. The visualized Scene Tree, Routing Map and Resource on the left side make the editing straightforward. The single geometric element is also visualized on the right side. The program supports a side-by-side view and allows editing of more than one VRML file at the same time, so that files can be merged easily.
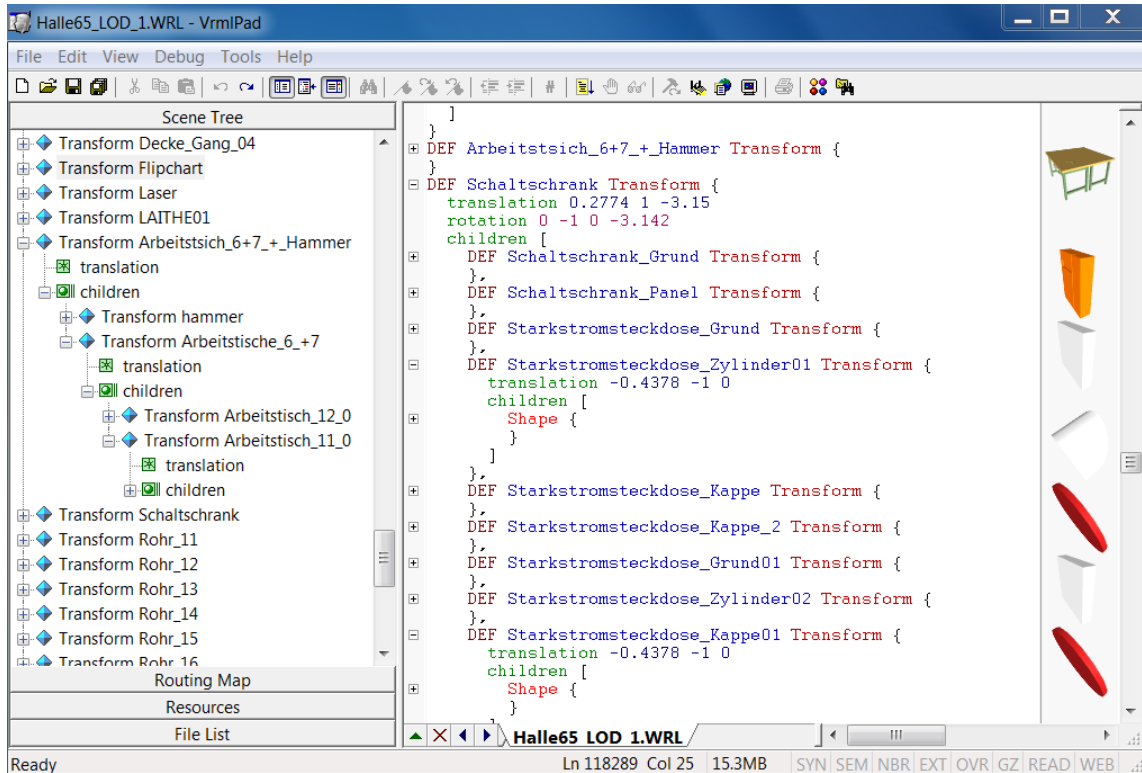
Figure 55: Modifying VRML file using software tool VrmlPad

Other software also exists (e.g. "Caligari TrueSpace 3.0" and "Platinum VR Creator 2.0") to edit WRL files. A feature comparison of commonly used VRML editors is shown in Table 5-1. Geometry modeled using a WRL file, which modeled FBK Manufacturing Lab as a virtual environment, is illustrated in Figure 50 and Figure 56.

Figure 56: Geometric modeling as data basis for software implementation

	Caligari TrueSpace 3.0	Paragraph Internet Space Builder 2.1	Platinum VR Creator 2.0 Learning Edition	Rendersoft VRML Editor 1.3	ParallelGraphics VrmlPad 3.0
File Import					
VRML 1.0	yes	no	yes	yes	Yes
VRML 2.0	no	yes	yes	no	Yes
3DStudio .3ds	yes	yes	no	no	no
AutoCAD .dxf	yes	no	no	no	no
File Export					
VRML 1.0	yes	no	no	yes	Yes
VRML 2.0	yes	yes	yes	yes	Yes
User Interface					
multiple view windows	yes	yes	yes	no	Yes
real-time shading	yes	yes	yes	yes	Yes
scene graph	no	yes	yes	no	Yes
publish tool	yes	yes	yes	no	Yes
customisable	no	yes	yes	no	Yes
context-sensitive help	no	yes	no	no	Yes
tutorials	yes	yes	yes	no	Yes
Modelling Features					
primitive shapes	yes	yes	yes	yes	yes
polygon editor	yes	yes	no	no	no
boolean ops	yes	yes	no	no	no
File Formats					
texture image	BMP, JPEG, TGA, TXR	BMP, GIF, JPEG	BMP, JPEG	BMP, JPEG	BMP, JPEG
movie	AVI	animated GIF	none	none	AVI
audio	-	WAV, MIDI	WAV	none	WAV
VRML 2.0 Support					
URL Anchor	yes	yes	yes	yes	yes
Background	yes	yes	yes	yes	yes
Billboard	no	no	no	no	yes
ElevationGrid	no	no	no	no	yes
Fog	yes	no	no	no	yes
Inline	yes	no	yes	no	yes
LOD	yes	no	yes	no	yes
Sound	yes	yes	yes	no	yes
Text	yes	yes	yes	yes	yes
Viewpoint	yes	yes	yes	no	yes
lights	yes	no	yes	yes	yes
PROTO	no	no	no	no	yes
Animation					
key-frame editor	yes	no	yes	no	yes
Sensors and ROUTES	-	no	yes	no	yes
JavaScript	no	no	yes	no	yes
Libraries					
objects	yes	yes	yes	yes	yes
materials	yes	no	yes	no	yes
textures	yes	yes	yes	no	yes
behaviours	no	no	yes	no	yes
drag-and-drop	no	yes	yes	no	yes

Table 5-1: An overview and comparison of VRML software tools

The human model discussed in 4.3.3 is stored as WRL file as well. When the listener positions are defined by the user, the model will be added to the scene graph automatically (see Figure 39). The modeling of a sound source is based on the description in 4.3.2 and the parameter setting of a sound source is based on the measurements described in 4.2.2. A texture file is prepared to visualize the phonons. And the filters for phonon collection are generated as ASCII files separately according to frequencies. The material absorption coefficients are saved according to material type in ASCII files as well. The legal limits to evaluate the SPL at different positions are entered as fix values directly in the simulation server. All the data is prepared for simulation implementation and stored in a main folder, which is accessible by local or remote workstations. A database can be used for large data sets.

5.3   User interface

A well designed user interface ensures the implementation of designed software functions and improves the user experiences. GUIs for simulation server and for virtual environment are implemented. In the GUIs, basic functions, such as setting the parameters and starting a new simulation, are provided. For sound visualization, an interactive navigation menu is implemented to enable the user to view and analyze the simulation results. The 3D GUI for simulation and visualization has a similar design with a sphere in the middle and six connected poles to show the orientation. A touch sensor attached to the sphere allows the user to show and hide the main menu.

5.3.1   Simulation interface

The implemented GUI for simulation server is shown in Figure 57. Different sub segments on the main menu are highlighted and labeled. The output window on the right side can be brought up from main menu.

The simulation setting panel allows users to set the simulation parameters, such as the pressure of the sound source, the number of phonons to be traced, the number of phonons to be visualized, the type of human model, the evaluation method, default file path, etc. The message window shows current server status. Users are also allowed to generate a start file (a VRML file to connect the simulation and VRML viewer) or open a new simulation scene. The generated VRML file containing the simulation results can be viewed in the VRML output window before saving. In the case of distributed computing, the software allows the user to store updated simulation data from the simulation server without viewing it in the VR system.

As the start file is read by a VRML viewer, the server loads the VRML file and adds additional VRML code for user interface elements for interaction in the scene (see Figure 58a). Interactive elements like buttons and sliders are implemented using VRML and JavaScript. Their visual appearance is modeled using simple VRML geometry, such as spheres and boxes. These geometries are connected to TouchSensor Nodes for buttons and to PlaneSensor Nodes for sliders. The sensors emit events which are routed to Script nodes containing simple interaction code written in JavaScript. Through the "Inline" Node, the additional VRML and JavaScript codes are embedded to main VRML files.
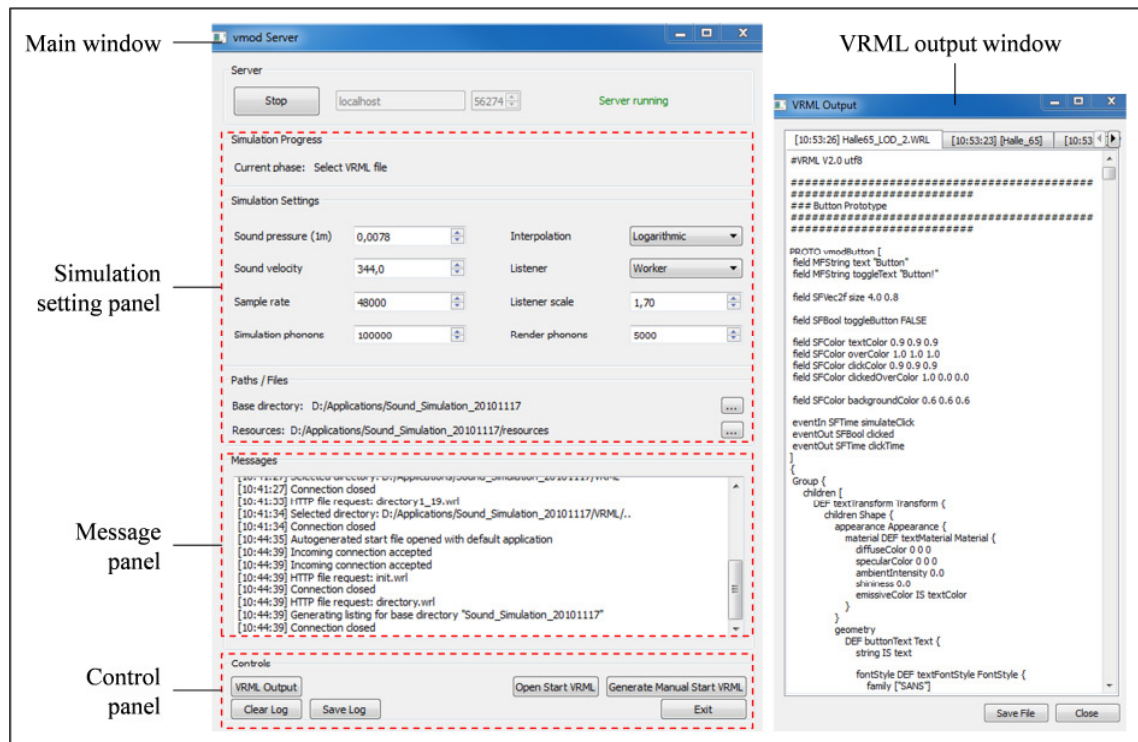
Figure 57: Main interface (left) and output monitoring (right) of simulation server

The file navigation menu is constructed with a slider and button combination, which provides good handling for both mouse interaction on a desktop PC and fly stick use in the CAVE. The main control panel to set the sound source and start the simulation is designed as a sphere with six attached sticks oriented along the coordinate axes (shown in Figure 58b). The user can conveniently explore the virtual environment interactively without leaving the virtual environment. For example, users can place the sound sources within the viewer application, start/stop a simulation or load a new geometric file.
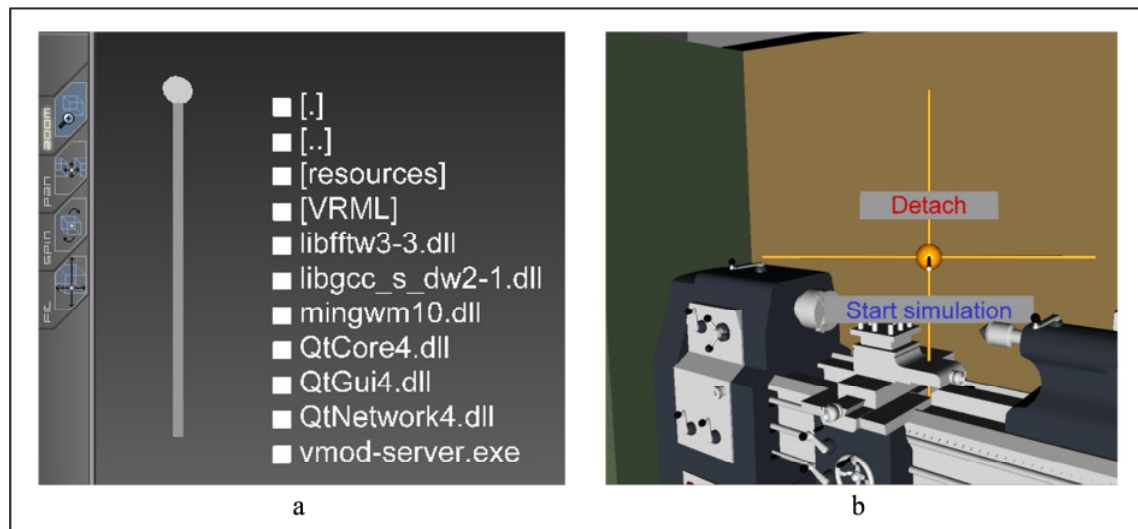

Figure 58: a) file navigation and b) simulation start in Cortona3D viewer

Commands of the user are sent back to the server by loading a special URL which encodes the action. Then, the simulation parameters are configured according to the commands and the

calculation is executed by the server. Afterwards the simulated data is delivered back to the viewer again. The viewer opens a new connection using an HTTP request asking for a file encoding commands. The server calculates and answers with a new VRML file delivered by this existing HTTP connection. Figure 45 and Figure 54 illustrate the process. The data flow behind the processes is depicted in Figure 44.

5.3.2 Visualization interface

After the simulation engine has finished the computation, the simulated data will be stored in shared memory for further visualization. The geometric model with the simulated data is loaded into the viewer application. At the same time, a navigation and control panel is generated by a simulation software tool and visualized in the virtual environment. This panel follows the user viewpoint by using the "Billboard" Node and can be attached at any defined position. Using the Node, the user can investigate the sound propagation inside the room by looking at animated phonon paths, which are shown in Figure 59 by using green sphere textures. The size and color of illustrated phonons can be changed by the user. The playback speed can also be adjusted using the "++" and "--" buttons, and the current simulation time interval can be selected using a slider.

This software tool enables the user to place and remove listeners interactively. The human avatar is depicted by two different models, a simplified shape or a concrete human form, which can be chosen by the user. Then, a command to calculate the SPL "Collect" at the listener positions is issued.

The color of the listeners are updated according to the SPL: green for an SPL lower than 80dB, yellow/orange for a critical SPL louder than 80dB and lower than 85dB, and red for above 85dB. The detailed description of the color scale and human model is shown in Figure 39.

Figure 59: Visualization of phonon propagation and SPL at operation position

The visualization is first implemented in a desktop-based VRML viewer, such as the "Cortona3D Viewer", which enables the user to execute and view the simulation results on

any workstation with a VRML viewer plugin. Compared to the CAVE, the experience of navigation using the mouse is poor and the view field is very small. However, the time needed to start and configure the system is short and the interaction is familiar to the users without any experience with an immersive VR system.

Figure 60 shows the phonons building a wavefront emitted from a machine. The red colored cones show the sound particles reflected from the ceiling and floor and the color intensity indicates the absorption of the surfaces. The effects of different materials on the spectral energy/pressure distribution can be observed. The first few reflections already show whether certain frequency bands are rapidly absorbed and how much sound energy is reflected back into the scene causing a higher noise level. Scene materials of high reflectance can be identified and replaced in the virtual model reducing the SPL in the virtual environment.
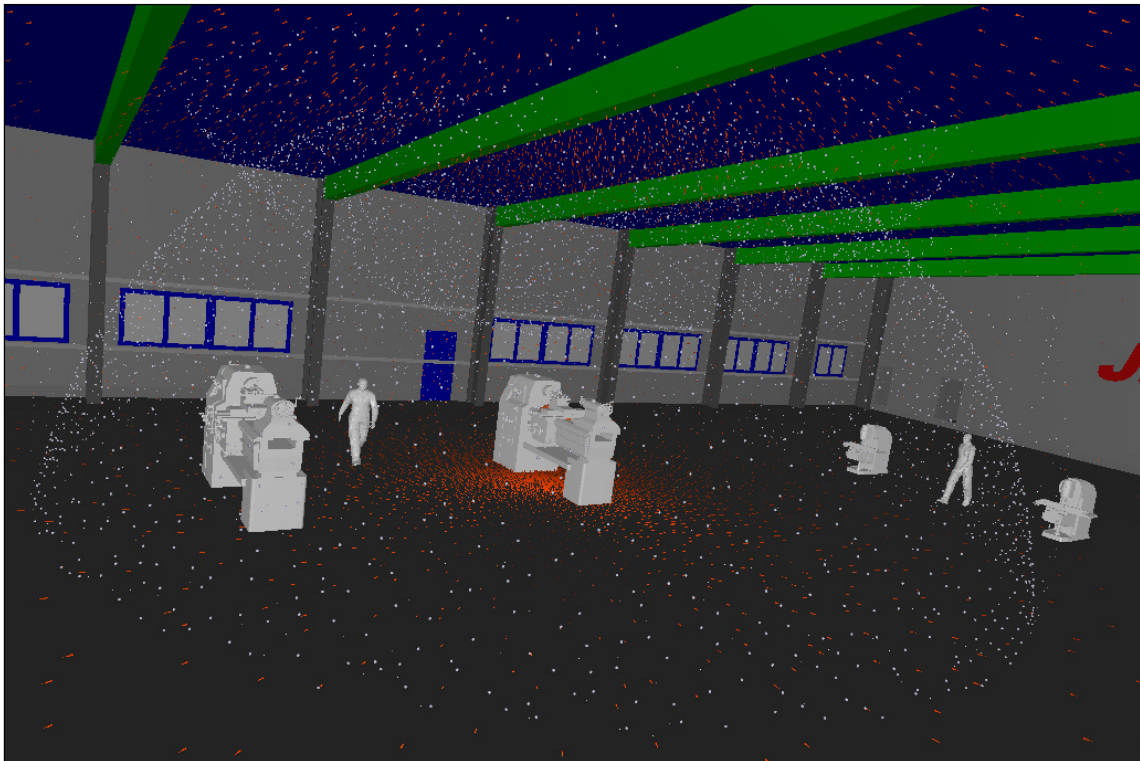

Figure 60: Sound particle (phonon) propagation and reelections on surfaces

Afterwards the visualization is implemented in the CAVE system. The master workstation of the COVISE cluster communicates with the simulation server and updates the scene graph for all eight clients. The 3D GUI, data flows and the computing processes in the CAVE system are identical with those in the desktop environment (see Figure 65). The computation time in both desktop-based and CAVE based systems are similar when using same geometric file and same simulation settings. However, because of the large projection surface, the rendering time for CAVE system is comparably longer. The visualization in CAVE enhances the representation quality of simulation data and the understanding of sound propagation processes within an immersive environment.

5.4 Distributed computing

The three main functions (data management, sound simulation, and visualization of simulation results) are executed in three different workstations at different locations. To implement this distributed computing approach, TCP/IP protocol is used to enable the communications among HTTP ports.

The implementation framework is illustrated in Figure 64. Workstation 1 serves as the data manager and provides the necessary geometric data for the simulation server. Workstation 2 executes the sound simulation and sends the simulation results back to workstation 1. Workstation 3 obtains the simulated scene graph from workstation 2 and is responsible for handling user interactions. When the visualization is displayed in a CAVE system, workstation 3 additionally serves as the VR master. This workstation distributes the rendering jobs to each VR client, which provides the output for the projection system. Workstation 3 also receives the user commands and data from the tracking system, which means the commands or scene graph updates are sent to the simulation server through workstation 3 for renewed simulation.
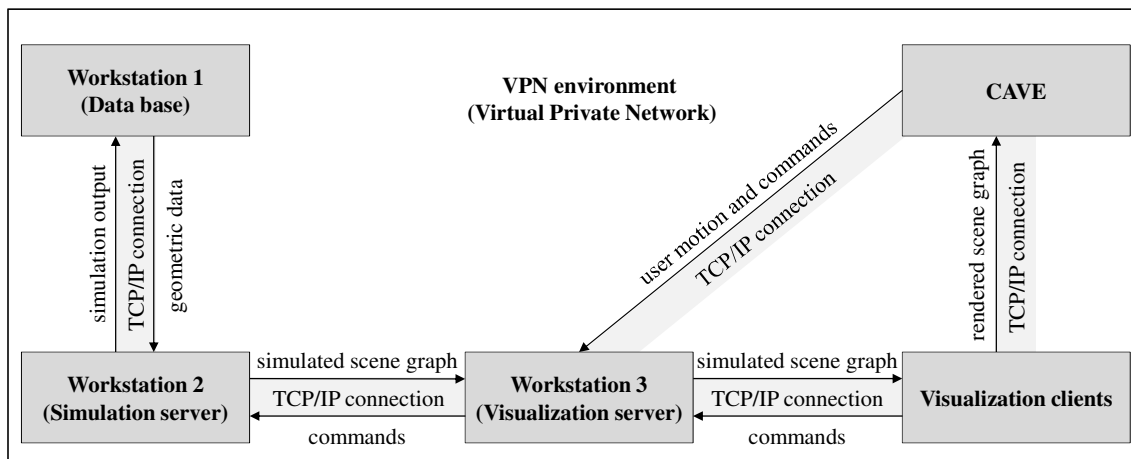

Figure 61: Distributed application based on TCP/IP protocol

This distributed computing provides a few benefits for collaborative research and development. In typical use scenario, the geometric data is provided by the manufacturing enterprises and the simulation and visualization are implemented by a research institute. To improve simulation performance, the institute could rent a supercomputer-powered server or a cloud computing service from other companies. For example, the native CAD file of a factory layout and involved facilitates is sent to the simulation server and converted directly to the simulation suitable file, but not sent to the researcher in the institute. This ensures the safety of the native data. The use of external computing for simulation enables the user overcoming computational bottleneck and reduces the simulation time.

5.5 Implementation results

Through the software implementation, the simulation can be visualized on a desktop-based or CAVE-based virtual environment. This subsection summarizes the proposed noise analysis system implementation and discusses some results.

First, the user has a simulation server which not only executes the sound simulation and visualizes the simulation result, but also provides the connection to VR systems. Whether using a desktop-based display or a CAVE-based full-immersive system, users are able to investigate and gain a better understanding of the noise issue in a manufacturing system. Second, based on the message communication and data transfer method, the implementation is considered a server/client approach. VRML visualization is used as a front-end GUI for the user and provides a programming interface for JavaScript coding. Third, using JavaScript, the limits of the VRML standard are partly overcome and the functions are extended. Using this implementation method, the VRML applications can be generated for different platforms and are enabled for further development.

A few visualization examples are shown in the figures below. Figure 62 shows the modeling of a sound source (left) or more sound sources (right). Commonly, there are more sound sources that determine the acoustic effect in a factory.

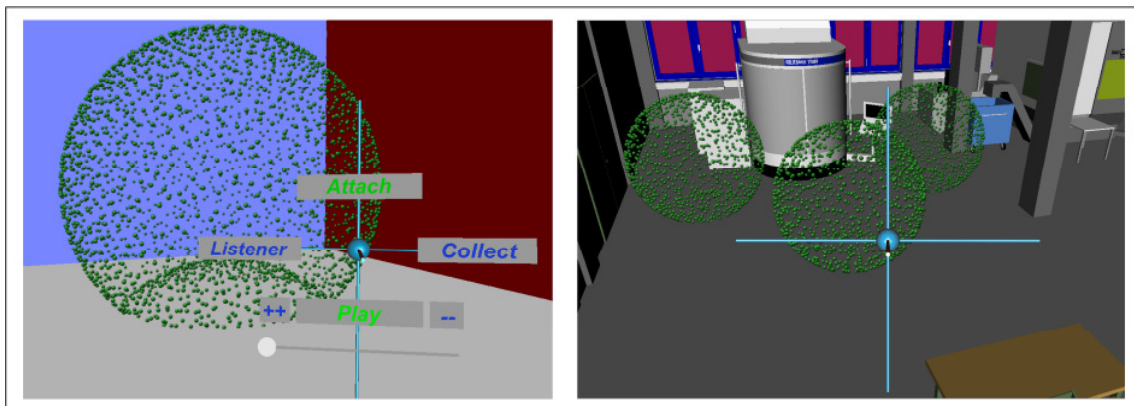Figure 62: Visualization of single source and multi-sources of sound

Figure 63 shows the phonon propagation from a lathe in the Manufacturing Lab. A worker is standing in front of the lathe and exposed to an SPL of under 85dB. The green spheres illustrate the traced paths of sound particles, while the red color shows the legal limit of noise level is exceeded and a protection method is needed.
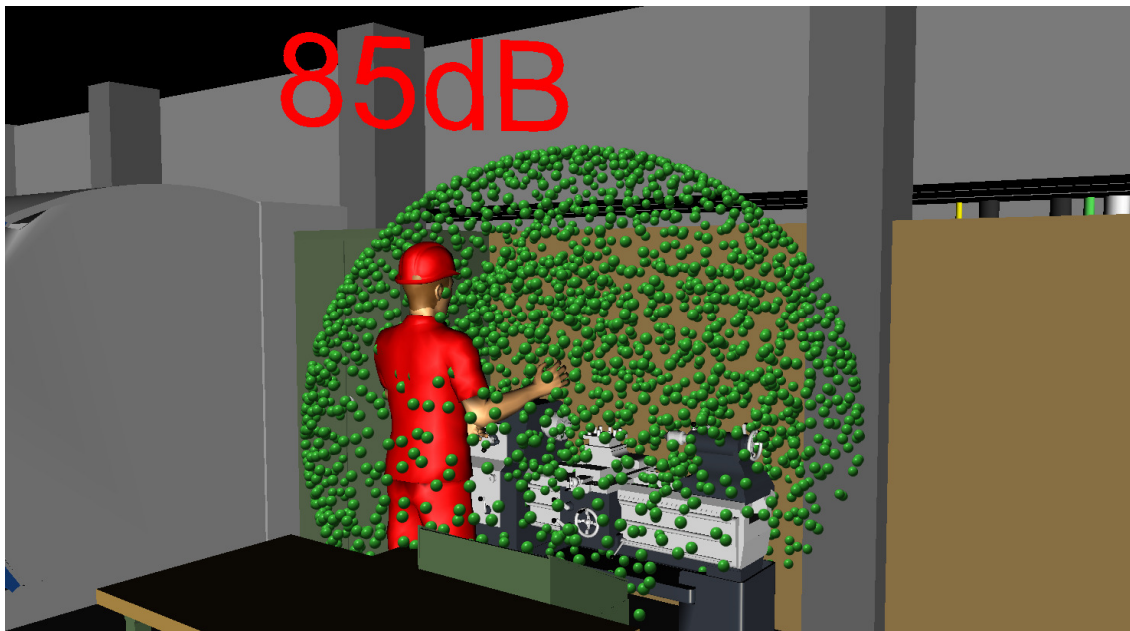
Figure 63: Visualization of phonon propagation and SPL at an operation position

Figure 64 shows the estimated SPLs at more operation positions which are monitored at the same time, which gives an overview of the noise levels over the whole Manufacturing Lab. The user can easily repeat the simulation using different simulation settings and compare the differences among them afterwards. The computation time is relative short compared to FEM or BEM simulation methods. Even a common office computer could be used for simulation. The navigation and analysis in a visualized scene is straightforward and intuitive.

Figure 64: Visualization of SPL at more operation positions

Furthermore, the proposed system is implemented in a CAVE environment. Using HTTP protocol, the simulation server communicates with COVISE modules. Two necessary COVISE modules are "VRML renderer" and "VR" module. The former enables the VRML visualization of a scene graph in CAVE and the latter provides basic interaction functions, such as navigation and user tracking. Figure 65 shows the basic user interface with added interface elements for the simulation software. Using the three button fly stick, the user can

navigate and interact with the virtual environment more intuitively, compared to using a desktop display and mouse. Navigation and selection are basic interactions in this environment. After viewing the factory layout and the machines, the user can set the sound source position and the positions which are required to be evaluated positions. After the simulation, the user can analyze the results directly in the CAVE. The user can also restart or reconfigure a simulation using the file navigation GUI without leaving the CAVE.
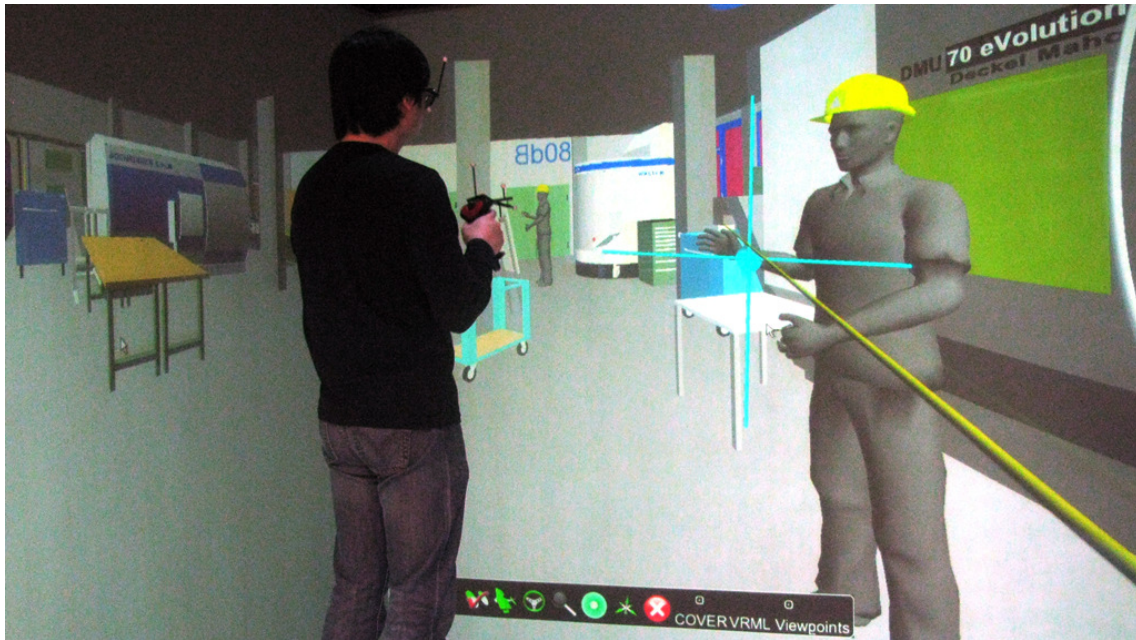
Figure 65: Simulation and visualization interface in CAVE

As an additional implementation, sound rendering [Darv95, Rabe97, Sven02, Lenz07 and Dein10] is also possible after the simulation. This method enables a realistic 3D audio rendering (also known as "Auralization") for VR applications inside the CAVE. Most of the sound files used in current VR systems are sampled sounds. Modeling and simulation based sound offers new possibilities to improve the user immersive experience in a VR system, especially in a CAVE system. However, this implementation is not included in this thesis.

6   Examples of Software Use

The implemented software tool demonstrates that the proposed approach is effective and produces realistic results. In this section, this software is tested using four different situations. The first situation shows quick evaluation after layout adaption. The second situation shows verification between simulation and measurement data. The third situation shows integration effects in the CAVE system by using auto play animation and the software tool. Finally, the last situation shows the implementation of the proposed method of distributed simulation and visualization. Through these four situations, the usability, system reliability, simulation efficiency, and visualization effects are well tested.

Situation 1 – reduce the noise in specified area

The first use case has a clearly defined objective: to reduce the noise in specified area by changing the layout of the factory, in which gears of the agricultural manufacturer are produced. To demonstrate the software tool, this use case focuses on the shaft manufacturing process chain. The chain consists of three processes: turning, milling and grinding. The original layout with machine tools is shown in Figure 66 with process chain being presented by A, B, and C. In this initial situation, the lathes have low reliability and are not able to cover the increasing production volume. Also, CNC-programming is not supported by these lathes and the set-up time is very long. In order to solve this identified bottleneck, the lathes are to be replaced by a new CNC turning machine. For the replacement, experts suggest three possible solutions. These three solutions are shown in Figure 66 by number 1, 2, and 3.

In the lower right corner of the layout, a small area with tables and a flip chart is found -the area for CIP workshops- in which the noise level has to be considered. Since the CNC turning machine can have different positions, the layouts of three implemented solutions are shown in Figure 67. The sound simulation tool is then applied in each of the positions.
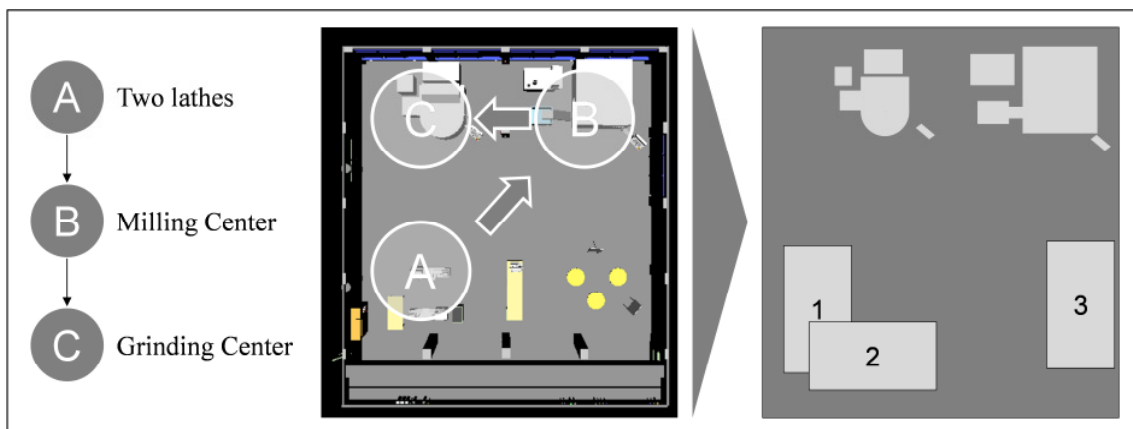
Figure 66: The initial situation of use case 1 and three reschedule possibilities

The 3D models of three different solutions are prepared using 3ds Max and the sound source parameters are kept unchanged for all three simulations. The preparation for the simulations is time consuming, because a direct position change of objects in the software-generated VRML scene graph is not possible. Therefore, a further development is considered.
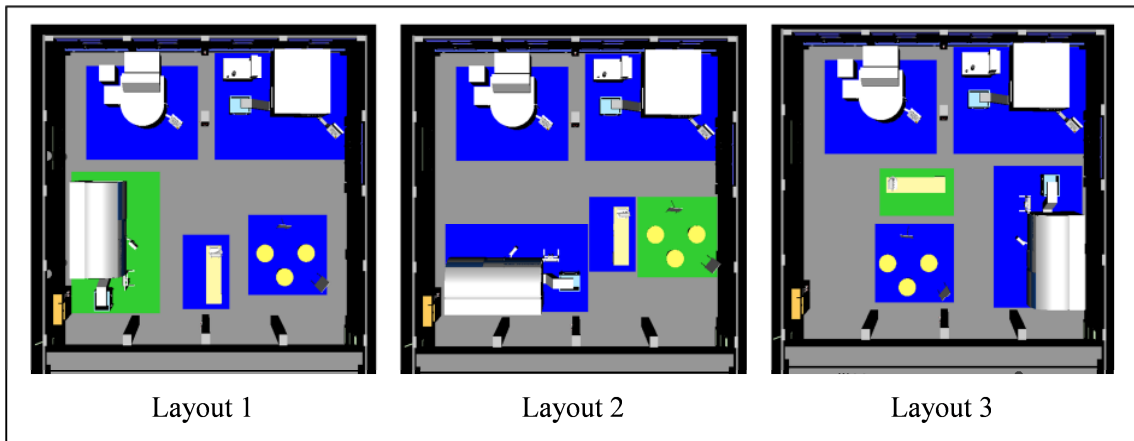
| Layout 1 | Layout 2 | Layout 3 |

Figure 67: Three rescheduled layout solutions

From manufacturing process point of view, there are no essential differences among solution 1, 2 and 3. In order to minimize the noise in the CIP workshop area, the SPLs of the three positions are simulated and visualized by using a color scale. The results are illustrated in Figure 68. According to the simulation results, position 2 is the preferred solution, because the employee is exposed to lowest sound level at 72 dB.

	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
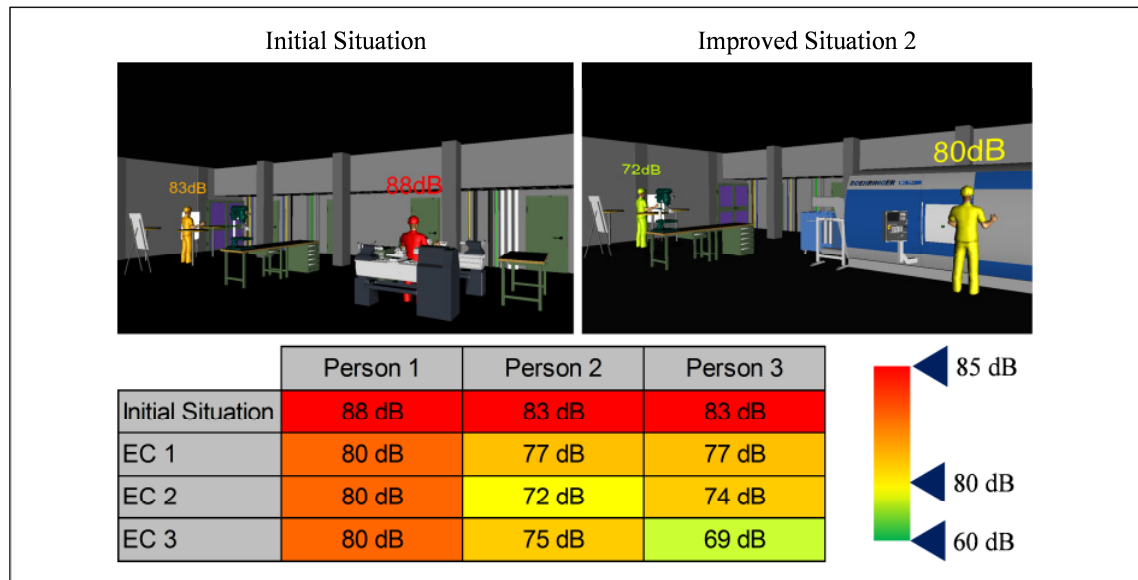
Figure 68: Improved noise situation after change 2

Although modeling the layout for three different solutions is not straightforward, this method allows for quick decision making. The quick decision making is essential since users need a fast and systematic method to adjust their manufacturing systems. However, this software also needs to be further extended to be able to work with other software together.

Situation 2 – compare the simulation with the measurements

The SPL measurements which are described in section 4.2.2 provide necessary data for simulation validation. Figure 69a illustrates the position based measurements in FBK Manufacturing Lab. Figure 69b shows the simulation based on 11 positions using the data

from Figure 69a. The results comparing measured values and simulation results are shown in Table 6-1.
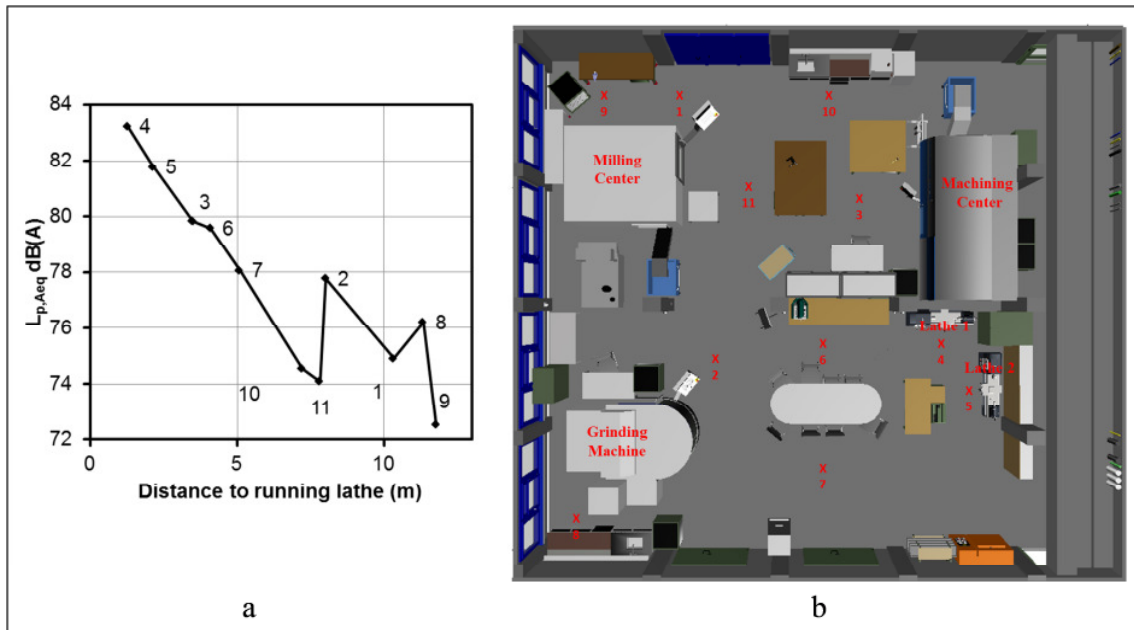
Figure 69: Measurement results (a), defined 11 positions for measuring (b)

Figure 70: Color scaled SPLs

Position Nr.	1	2	3	4	5	6	7	8	9	10	11
Measurement	74.9	77.8	79.3	83.2	81.8	79.6	78.1	76.2	72.5	74.5	74.1
Simulation	62.7	82.1	68.8	85.2	84.3	84.9	81.0	75.8	62.1	67.3	70.0

Table 6-1: Description of the measurement positions

The differences between the simulation and measurement data are most likely caused by three reasons. First, the absorption coefficients can only be estimated, not selected from the existing database, since the facilities are mostly non-standard and old. Second, compared to the wave-based methods, the phonon tracing method as well as other geometric methods fails in the low frequency range. Due to the limitation of geometric methods, a combined approach could provide more ideal and more accurate simulation. For example, DEINES suggested an additional wave-based method implementation to simulate the sound wave propagation at low and middle frequencies [Dein08].

Situation 3 – integration in the CAVE system

To integrate the acoustic simulation into a CAVE system, there are two different methods available. The first one is to convert the simulation result and the geometric file used for the simulation to a VRML file. The phonon propagation is saved as an animation and embedded in VRML for autoplay. Figure 71 shows the animation of sound propagation in a classroom. The number of phonons is fixed as the animation is created and the playback speed is changeable by COVISE. The animation is repeated automatically from the beginning once it is finished. This method is simple and stable and the animation can be presented using almost any computer system. However, an interactive user interface and renewed simulation are not useable.
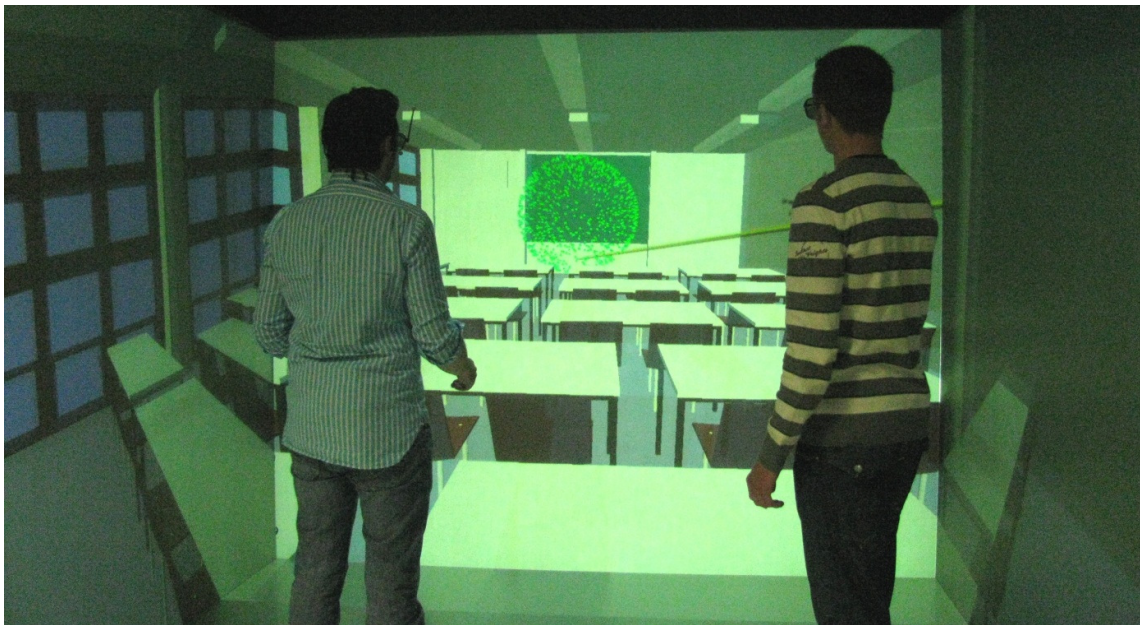
Figure 71: An animation auto play of phonon propagation

The second method is to use software tool introduced the in chapter 5, which enables users to execute the simulation and view the results interactively. In other words, after viewing the last simulation, the user can configure the simulation parameters results and restart the simulation. By using the embedded interactive GUI, the playback speed can be changed and the autoplay can be stopped at any step. Furthermore, the simulation result can be stored as a VRML file for further viewing and comparison.
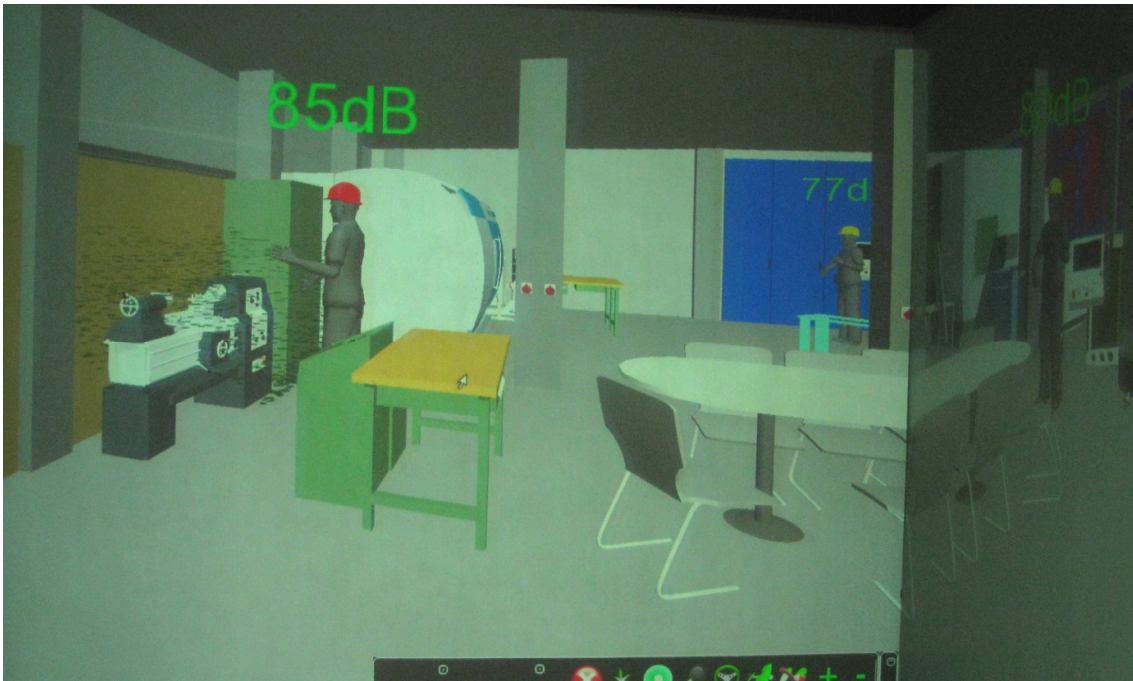
Figure 72: Interactive animation of phonon propagation

This situation is based on the use of the VR software COVISE. Using other VR software could change the interactions. However, many current VR software tools are implemented based on the OpenSceneGraph library, which means the visual effect showed in this section is analogous to the effects of other software systems.

Situation 4 – distributed implementation

Using the web-server, the communications via HTTP enable the distributed sound simulation and visualization. A prototypical test is made by using two computers and a shared data base within an established Virtual Private Network (VPN). The framework is illustrated in Figure 73. The database is stored on computer 1 with the geometric files, the texture files and necessary libraries. The web server is installed on computer 2 and provides relatively high performance computation power when compared to computer 3. Computer 3 is configured with an usual internet browser-supported VRML viewer. The users are able to start the simulation and view the results, computed by computer 2, without installing the web-server software. The original geometric files can also be viewed by using computer 3 without request computer 2.

In the case of complex simulation and visualization jobs, this distributed computing can use the full performance of all the computers, which is the main advantage of distributed systems. In this case, both computer 2 und 3 are notebook computers with relatively low computational power. Therefore, the advantage of distributed computing is not clearly shown. Still, the implementation is proven to be successful and efficient. Computer 1 is an institute server, which enables a large storage capacity and provides access for other users in the same institute or users from outside with access rights. Therefore, the geometric database can be maintained by third party, for example by the enterprise which provided the models.
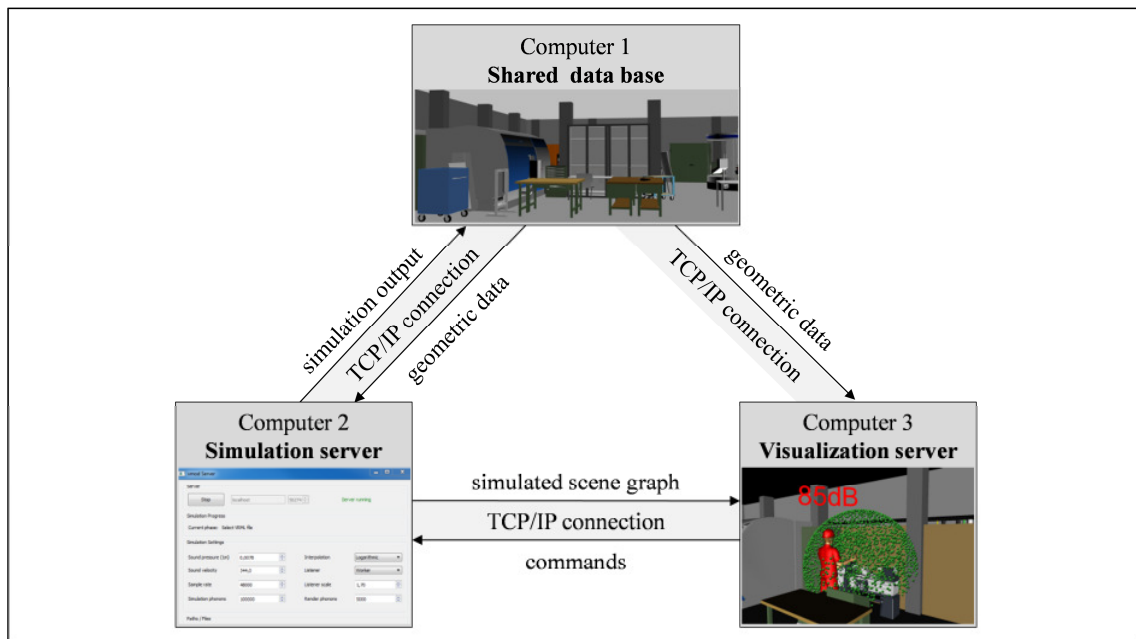
Figure 73: Distributed implementation of sound simulation and visualization

However, this VRML-based method is not the ideal solution for a parallel and distributed simulation. Firstly, the VRML script is not efficient enough for data storage and conversion, as compared to the native OBJ standard. In the case of a large data set, the file transfer and converting time does not to meet the needs of the user. Secondly, the interactive user interfaces have to be generated by JavaScript each time as the VRML file is reloaded in the viewer program, which takes a lot of storage and CPU power from both the web-server computer and visualization client. This problem may be solved by an integrated GUI in the VRML viewer or other VR software which improve the application usability. On the other hand, the GUI-generator even without improvement could be used in any system with a VRML loader. Thirdly, the web-server is not adapted for multi-core CPU processing. For the special need of a distributed sound simulation and visualization, a hardware adapted implementation is necessary.

7   Conclusion and Future Work

This thesis developed an interactive and straightforward noise investigation using VR application. Based on the established concept, a few research issues were addressed and the main research question was answered. In this chapter, the development and implementation of the approach is briefly summarized. Finally, several extension possibilities for further research are described.

Conclusion

First, the noise issue in a manufacturing system and the related legal regulations were studied to later enable investigation in a virtual environment. Sound simulation and visualization methods were described in detail and two main groups of simulation algorithms were introduced and compared using pre-defined features. Then, a relative detailed review of VR technology and current applications in industry was made, which provided a solid basis for concept development and software implementation. However, this review covers only the VR applications in fields of industry.

Based on the study of existing VR applications and their technical solutions, a development concept with five detailed implementation steps was demonstrated. The five steps are: data acquisition, environment/sound source/human modeling, acoustic simulation and visualization, VR interface and VR system preparation. Both non-immersive and full-immersive VR systems were considered. VRML was considered to be the suitable VR language and modeling method for this proposal. A web-server based implementation approach was then established as the interface between simulation and VR. This concept could be used for other simulation integrations and extended for other industrial applications.

Using the introduced concept and implementation approaches, a software tool was made. This software can be used to facilitate determining noise levels at working positions and test different improvement options. The software was specifically adapted for virtual manufacturing environments, e.g. machine halls or factories. Essential required tasks were accomplished, such as the converter for OBJ file, 3D interactive user interface, web-server for simulation and VR connection, and the visualization in a CAVE system. Due to the mentioned advantages of VR, the noise simulation and visualization was made better for use in factory planning and workplace design. Furthermore, this tool provides a straightforward method to check if the noise level is over the limits of legal regulations.

Four example situations showed typical application scenarios in a manufacturing system. The implemented software was used in the different situations to fulfill the planning requirements:

❑ Reducing the noise in specified area through layout change

❑ Comparing the simulation with the measurements

❑ Visualizing the sound propagation in a CAVE system

❑ Using application with distributed computing

The results validated the positive improvement of sound investigation in virtual environment. Furthermore, the simulated data is well visualized using VR systems and easy to understand. Therefore, this software can be considered a support tool for manufacturing designers and

planners. The know-how obtained through implementation can be further used for other applications.

Outlook

Currently, this software tool provides only basic interactive features for sound investigation. For example, a change of factory layout or modification of room acoustic properties can only be made in modeling step; a direct change in VR is not allowed. This could be extended to provide an interactive adjustment of absorption coefficients and machine positions, e.g. for simulation of different noise control solutions. This extension could make the virtual planning and rescheduling possible.

In addition to the visualization of sound propagation in VR, the auditive representation of sound simulation results is called auralization. In a VR system, the immersion degree is enhanced significantly through integrated auralization. Using simulation generated phonon mapping could be converted and exported to stereo audio data file which would enable the auralization in a CAVE system. This issue could also be considered in further research.

Another potential extension is the integration of sound simulation into the VR-based CIP-workshop. Combined with auditive representation in CAVE, noise in a manufacturing environment can be perceived realistically by participants (workers, designers, executives etc.). The suggestions and ideas could be tested directly without applying them in reality. Hence, this approach would reduce downtime during the conventional CIP-workshops and allow the tests of various improving scenarios without high costs and potential risks.

The noise issue is not only related to working safety and health, but also relates to ergonomics and workplace design. The approach developed in this thesis provides the basic know-how to integrate noise analysis in a digital factory as well as VR concept. The implemented software tool could be considered a prototype for further development involving more essential ergonomic issues, such as the lighting quality, air pollution, heat, chemical emission, etc. In other words, a comprehensive simulation and evaluation of the quality of the working environment, considering the possible negative factors, could be made before the industrial facilities are setup. Possible changes, rescheduling and redesigns are then able to be made in a virtual world. The solution implementation in a real manufacturing system will only be made if the solution completely optimized and validated.

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11 Appendix

11.1 IIDB assessment from 2003/04 to 2008/9

Table IIDB 2003/04-2008/09

Prescribed industrial diseases; non - lung diseases in England, Wales and Scotland by disease[a]

England

Disease	2003/04[d]	2004/05[d]	2005/06[d]	2006/07[d]	2007/08[d][e]	2008/09[d][e][p]
Musculoskeletal[b]	310 (185)	325 (215)	210 (125)	180 (110)	210 (120)	955 (80)
Occupational deafness	240 -	205 (5)	155 -	135 -	170 -	170
Vibration white finger	725 (5)	610 -	470 -	380 (5)	615 -	660 -
Carpal tunnel syndrome	570 (60)	495 (35)	370 (35)	335 (30)	385 (40)	350 (25)
Allergic Rhinitis	70 (5)	65 (5)	35 (5)	35 (10)	30 (5)	35 (5)
Dermatitis	140 (30)	125 (40)	105 (30)	100 (30)	80 (15)	60 (20)
Others	65 (10)	55 (5)	50 (10)	55 (15)	55 (10)	45 (5)
Total	**2115**	**1880**	**1395**	**1225**	**1550**	**2275**

Wales

Disease	2003/04[d]	2004/05[d]	2005/06[d]	2006/07[d]	2007/08[d][e]	2008/09[d][e][p]
Musculoskeletal[b]	20 (10)	20 (10)	10 (10)	15 (10)	30 (5)	135 -
Occupational deafness	30	25	20	15	5	15
Vibration white finger	125	105	75	65	280	70
Carpal tunnel syndrome	125 (5)	80 (10)	60 -	45 (5)	45 -	30
Allergic Rhinitis	15	15	10	5 -	5	-
Dermatitis	10 (5)	20 (5)	20 (5)	5 -	10 (5)	5 -
Others	5	5 -	5 -	5 -	5	-
Total	**330**	**270**	**200**	**160**	**375**	**260**

Scotland

Disease	2003/04[d]	2004/05[d]	2005/06[d]	2006/07[d]	2007/08[d][e][p]	2008/09[d][e][p]
Musculoskeletal[b]	20 (5)	20 (5)	20 (5)	20 (10)	15 (5)	175 (5)
Occupational deafness	60 -	25	35	20	35 -	20
Vibration white finger	165	150	95 -	70	110	120
Carpal tunnel syndrome	125 (20)	100 (20)	90 (20)	55 (15)	100 (20)	85 (10)
Allergic Rhinitis	5 -	15 (5)	5	-	-	5
Dermatitis	20 (5)	20 (5)	20 (5)	10 -	15 -	10 (5)
Others	5 -	5 -	5 -	15 -	10 -	10 -
Total	**390**	**335**	**280**	**190**	**290**	**420**

Great Britain[c]

Disease	2003/04[d]	2004/05[d]	2005/06[d]	2006/07[d]	2007/08[d][e]	2008/09[d][e][p]
Musculoskeletal[b]	345 (200)	370 (230)	245 (145)	215 (125)	255 (130)	1265 (85)
Occupational deafness	330 (5)	255 (5)	210 -	175 -	215 -	205
Vibration white finger	1015 (5)	865 -	645 -	515 (5)	1005 -	850 -
Carpal tunnel syndrome	820 (90)	675 (65)	520 (55)	435 (45)	530 (65)	465 (30)
Allergic Rhinitis	90 (10)	90 (10)	50 (5)	45 (10)	40 (5)	40 (5)
Dermatitis	170 (35)	165 (50)	145 (35)	115 (35)	105 (20)	75 (25)
Others	75 (10)	65 (10)	60 (10)	75 (15)	70 (15)	60 (5)
Total	**2845**	**2490**	**1880**	**1575**	**2215**	**2960**

Notes:

(a) Figures are for years ending 30 September, except for occupational deafness where calendar years 1996 - 2009 are shown. Bracketed figures are for females. Where not shown, all cases are male (except for occupational deafness before 1998, when the gender breakdown was not available).

(b) New regulations for Prescribed Disease A14 came into force on the 13th July 2009 resulting in an increase in claims and assessments.

(c) Figures for Great Britain include a small number of cases not included in England, Wales and Scotland breakdowns. These individuals developed industrial diseases from employment in Great Britain, but subsequently went to live overseas.

(d) From April 2002 the figures include a small number of cases where the claimant has been assessed as suffering but with no loss of faculty, or where the percentage disability had not been coded at the time of publication due to the provisional nature of the data.

(e) New regulations for Prescribed Disease A11 came into force on the 1st October 2007 resulting in an increase in claims and assessments.

(n/a) Not available.

(p) Provisional.

- Nil or negligible.

To maintain the anonymity of customers all 100% data has been rounded to the nearest 5. Therefore totals may not sum.

SOURCE : DWP
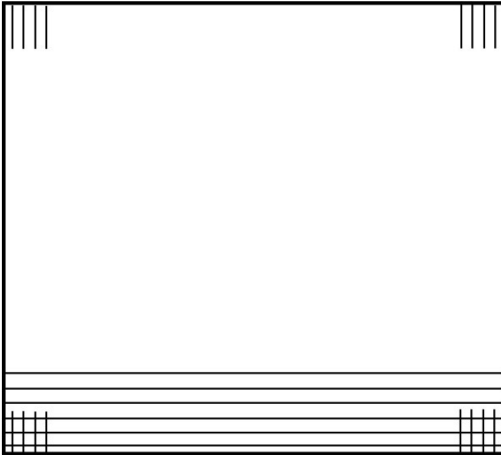
11.2   Some features of legislation in various countries [Embl97]

Country (Jurisdiction)	8-hour average A-weighted sound pressure level (dB)	Exchange rate (dB)	8h-average A-wtd limit for engineering or administrative controls (dB)	8-h-average A-wtd limit for monitoring hearing (dB)	Upper limit for peak sound pressure level (dB)
Argentina	90	3			110 A Slow
Australia (varies by State)	85	3	85	85	140 unwgted peak
Austria (a), (c)	85		90		
Brazil	85	5	90, no exposure > 115 if no protection, no time limit	85	130 unwgted peak or 115 A Slow
Canada (Federal)	87	3	87	84	
(ON, PQ, NB)	90	5	90	85 (b)	140 C peak
(Alta, NS, NF)	85	5	85		
(BC)	90	3	90		
Chile	85	5			140 unwgted peak or 115 A Slow
China	70-90	3			115 A slow
Finland (c)	85	3	90		
France (c)	85	3	90	85	135 C peak
Germany (c), (d)	85	3	90	85	140 C peak
Hungary	85	3	90		140 C peak or 125 A Slow
India	90				140 A peak
Israel	85	5			140 C peak or 115 A Slow
Italy (c)	85	3	90	85	140 C peak
Japan	90		85 hearing protection mandatory at 90	85	
Netherlands (c)	85	3	90	80	140 C peak
New Zealand	85	3	85	85	140 unwgted peak
Norway	85	3		80	110 A Slow
Poland	85	3			135 C peak or 115 A Slow
Spain (c)	85	3	90	80	140 C peak
Sweden (c)	85	3	90	80	140 C peak or 115 A Fast
Switzerland	85 or 87	3	85	85	140 C peak or 125 ASEL
United Kingdom	85	3	90	85	140 C peak
USA (e)	90 (TWA)	5	90	85	140 C peak or 115 A Slow
USA (Army and Air Force)	85	3		85	140 C peak

11.3 A list of to be modeled objects in FBK Manufacturing Lab

Nummer	Objektname	Objektklasse
1	Wand 1	Wand 1
2	Wand 2	Wand 2
3	Wand 3	Wand 1
4	Wand 4	Wand 2
5	Doppeltür 1	Doppeltür
6	Schaltschrank 1	Schaltschrank
7	Regal 1	Regal 1
8	Doppeltür 2	Doppeltür
9	Laser 1	Laser
10	Doppeltür 3	Doppeltür
11	Werkzeugschrank 1	Werkzeugschrank 1
12	Spüle 1	Spüle 1
13	Arbeitstisch 1	Arbeitstisch 1
14	Schrank 1	Schrank 1
15	Arbeitstsich 2	Arbeitstisch 2b
16	Arbeitstisch 3	Arbeitstisch 3
17	Werkzeugschrank 2	Werkzeugschrank 1
18	Arbeitstisch 4	Arbeitstisch 4
19	Hallentor	Hallentor
20	Spüle 2	Spüle 1
21	Arbeitstisch 5	Arbeitstisch 1
22	Kühlschank 1	Kühlschrank 1
23	Kühlschank 2	Kühlschrank 2
24	Doppeltür 4	Doppeltür
25	Tür 1	Tür
26	Tür 2	Tür
27	Tür 3	Tür
28	Tür 4	Tür
29	Regal 2	Regal 2
30	Regal 3	Regal 2
31	Regal 4	Regal 2
32	Schrank 2	Schrank 1
33	Schrank 3	Schrank 1
34	Werkzeugschrank 3	Werkzeugschrank 1
35	Werkzeugschrank 4	Werkzeugschrank 1
36	Schrank 4	Schrank 1
37	Drehmaschine 1	NG 200
38	Arbeitstisch 6	Arbeitstisch 5
39	Arbeitstisch 7	Arbeitstisch 5
40	Arbeitstisch 8	Arbeitstisch 9
41	Arbeitstsich 9	Arbeitstisch 9
42	Bohr/Fräszentrum 1	DMU
43	Arbeitstsich 10	Arbeitstisch 8
44	Arbeitstisch 11	Arbeitstisch 2
45	Werkzeugschrank 5	Werkzeugschrank
46	Werkzeugschleifmaschine 1	Walter
47	Arbeitstisch 12	Arbeitstisch 6
48	Arbeitstisch 13	Arbeittisch 5
49	Werkzeugschrank 6	Werkzeugschrank 2
50	Werkzeugschrank 7	Werkzeugschrank 3
51	Stehtisch 1	Stehtisch 1
52	Werkzeugschrank 8	Werkzeugschrank
53	Arbeitstisch 14	Arbeitstisch 2
54	Schrank 4	Schrank 2
55	Schrank 5	Schrank 2
56	Arbeitstisch 15	Arbeitstsich 5
57	Arbeitstisch 16	Arbeitstisch 5

11.4 A filled check list of modeling of machine NG 200

Checkliste Halle

FBK Maschinenhalle
Name der Halle

Raumplan der Halle

Siehe zusätzlich Extrablatt Hallenplan

Bereich 1: *Temperaturschwankungen*	**Bereich 4:**
Bereich 2: *geringere Bodenstabilität*	**Bereich 5:**
Bereich 3:	**Bereich 6:**

	Ja	Nein	Weitere Angaben (auszufüllen bei „Ja")
Ist ein Hallenplan (z.B. Bau- oder Fluchtplan) vorhanden?	X		*Höhe: 3,40, außer im Gang, dort nur 2,30m* *Länge und Breite siehe Plan* Höhe x Länge x Breite der Halle (falls verschiedene Höhen in der Halle existieren, die Bereiche entsprechend kennzeichnen)
			Boden: grau/ weiß *Wände: weiße Steine mit grauen Fugen* *Decke: Beton: weiß/ grau* Aus welchen Materialien bestehen Boden, Wände und Decke der Halle?
			Wurden Bilder der Halle eingefügt (falls nicht, grob Farbe des Bodens, der Wände und der Decke beschreiben)?
Gibt es Türen/Tore, die auf dem Plan nicht verzeichnet sind oder deren Größe und/oder Lage durch den Plan nicht bestimmt ist?		X	Größe und Position der Türen/Tore, nach Möglichkeit auch Angabe der Farbe und des Materials

Notwendige Informationen

Seite **1** von **3**

Name der Halle: *FBK Maschinenhalle*

Frage			Beschreibung
Wurden Versorgungsanschlüsse (Strom, Druckluft, KSS, Kühlwasser, Gase, etc.) auf dem Plan gekennzeichnet?	X		Position und Art der vorhandenen Anschlüsse
Gibt es Bereiche der Halle, die besonderen Temperaturschwankungen ausgesetzt sind (durch große Tore oder große Glasflächen am Gebäude) oder speziell klimatisierte Bereiche?	X		*Im Bereich des Lichteinfalls durch die Fenster* Position und Größe der Bereiche mit der jeweils möglichen Temperatur bzw. den Temperaturschwankungen
Gibt es Bereiche der Halle, in der die Luftfeuchtigkeit stark schwankt oder extreme Werte annimmt?		X	Position und Größe der Bereiche mit der jeweils möglichen Luftfeuchtigkeit
Gibt es Bereiche der Halle, die speziell beleuchtet sind oder in der die Beleuchtung stark schwankt (z.B. durch große Tore oder Fenster)?	X		*Durch große Fensterfront teilweise natürliche Beleuchtungssituation* Position und Größe der Bereiche mit jeweils genauen Beschreibung der Beleuchtungssituation
Gibt es Bereiche in der Halle, die frei zu halten sind (Fluchtwege, Transportwege, Kranabsatzflächen, etc.)	X		*Gang sowie Zugänge zu Türen* Position und Größe der freizuhaltenden Bereiche
Weist der Boden der Halle unterschiedliche Tragfähigkeiten auf (z.B. Produktion auf verschiedene Etagen verteilt oder unterschiedliche Fundamente)?		X	Position und Größe der verschiedenen Bereiche und deren Tragfähigkeit
Gibt es Bereiche in der Halle, an die spezielle Lautstärkeanforderungen gestellt werden (z.B. durch umliegende Gebäude)?		X	Position und Größe der verschiedenen Bereiche mit der jeweils zulässigen Lautstärke (in dB)

Wichtige zusätzliche Informationen

Seite **2** von **3**

Name der Halle: *FBK Maschinenhalle*

Namen der Maschinen, die aus der Halle modelliert werden sollen (für jede zu modellierende Maschine muss die „Checkliste Maschine" ausgefüllt werden):

NG 200

Walter

Deckel Maho

Sonstige Gegenstände, die modelliert werden sollen (Tische, Stühle, Regale, (Werkzeug-)Schränke, etc.), jeweils mit einer ungefähren Angabe bezüglich Größe, Position, Material und Farbe. Nach Möglichkeit sollten alle Objekte fotografiert werden.

Siehe Extrablatt „Liste aller modellierten Objekte"

Zusätzliche Informationen

Seite **3** von **3**

11.5 Absorption coefficient of common building materials [WSDG11]

Material	Description	Thickness	Mounting	Unit Size	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
ASCPac Acustadek B	Steel deck, perforated webs, absorptive backing	1,50	A	108 x 96	0,23	0,67	1,21	0,82	0,46	0,24
ASCPac Acustadek B	Steel deck, total perforated absorptive backing	1,50	A	108 x 96	0,23	0,48	0,92	0,97	0,95	0,76
ASCPac Acustadek BF	Steel deck, pan perforated absorptive backing	1,50	A	108 x 96	0,53	0,58	0,75	0,97	0,86	0,57
ASCPac Acustadek N	Steel deck, perforated webs, absorptive backing	3,00	A	108 x 96	0,38	0,94	1,18	0,90	0,44	0,24
ASCPac Acustadek N	Steel deck, total perforated absorptive backing	3,00	A	108 x 96	0,43	0,61	1,01	1,05	1,00	0,76
ASCPac Acustadek NF	Steel deck, pan perforated absorptive backing	3,00	A	108 x 96	0,80	0,78	1,16	0,88	0,69	0,47
AWI Type 2906	Fiberglass panel with perforated vinyl film facing	0,63	E-400	24 x 48	0,68	0,68	0,67	0,84	0,86	0,71
AWI Type 2907	Vinyl-faced fiberglass with vinyl film facing	0,63	E-400	24 x 48	0,53	0,37	0,50	0,82	0,82	0,72
AWI Type 2921	Vinyl membrane facing over fiberglass lay-in panel	1,50	E-400	24 x 48	0,57	0,79	0,77	0,90	0,71	0,47
AWI Type 2925	Vinyl-film-faced, fiberglass lay-in panel	1,00	E-400	24 x 48	0,55	47,00	0,72	0,80	0,74	0,54
AWI Type 2942	Fiberglass lay-in panel with microperforated vinyl facing	1,50	E-400	24 x 48	0,62	0,83	0,90	1,10	1,06	0,94
AWI Type 2946	Microperforated vinyl film-faced fiberglass panel	1,00	E-400	24 x 48	0,77	0,89	0,75	1,01	1,04	0,93
AWI Type 3101	Cloth-faced, fiberglass lay-in panel, painted	0,75	E-400	24 x 48	0,71	0,87	0,62	0,86	0,96	0,91
AWI Type 3103	Woven glass fibers adhered to fiberglass board, painted	1,00	E-400	24 x 48	0,70	0,95	0,75	0,99	1,04	1,01
AWI Type 3105	Cloth-faced fiberglass lay-in panel, factory painted	1,50	E-400	24 x 48	0,74	0,97	0,85	1,03	1,05	1,00
AWI Type 3301	Cloth-faced, fiberglass lay-in panel, painted	0,75	E-400	24 x 48	0,48	0,35	0,71	0,96	1,05	1,04
AWI Type 537	Fissured mineral fiber, fire-resistive lay-in panel	0,63	E-400	24 x 48	0,35	0,34	0,48	0,69	0,88	0,92
AWI Type 584	Mineral fiber lay-in panel with factory-applied paint	0,75	E-400	24 x 48	0,29	0,33	0,53	0,73	0,86	0,92
AWI Type 602	Ceramic and mineral fiber, non-combustible, lay-in panel	0,63	E-400	24 x 48	0,23	0,24	0,50	0,77	0,91	0,86
AWI Type 704	Fissured mineral fiber, "Cortega" lay-in panel	0,63	E-400	24 x 48	0,35	0,27	0,47	0,65	0,74	0,82
AWI Type 737	Surface-textured, mineral, "Minatex" lay in panel	0,63	E-400	24 x 48	0,36	0,28	0,47	0,65	0,76	0,82
AWI Type 769	Fissured mineral fiber, "Cortega" lay-in panel	0,63	E-400	24 x 48	0,31	0,32	0,51	0,72	0,74	0,77
AWI Type 775	Surfaced-textured, mineral, "Minatex" lay in panel	0,63	E-400	24 x 48	0,30	0,28	0,43	0,64	0,76	0,68
AWi Type 821	Mineral fiber, lay-in, with polymeric membrane	0,63	E-400	24 x 48	0,29	0,54	0,30	0,79	0,78	0,60
AWI Type 823	Fissured mineral fiber, fire-resistive lay-in panel	0,63	E-400	24 x 48	0,33	0,36	0,50	0,78	0,84	0,84
AWI Type 863	Vinyl-faced aluminum surface mineral fiber, lay-in panel	0,63	E-400	24 x 48	0,35	0,36	0,55	0,90	0,74	0,46
BHS Limpet	Spray-on mineral-fiber material	2,50	A	NONE	0,05	0,30	0,75	1,00	1,07	1,05
BHS Pyrok	Spray-on, medium structure material	2,00	A	NONE	0,06	0,14	0,30	0,59	0,92	0,56
BradIns	Glasswool building blanket	(50)	A	120cm x 15m	0,68	0,75	1,05	1,04	1,05	1,11
BradIns	Glasswool building blanket with perforated foil facing	(50)	A	120cm x 15m	0,55	0,69	1,07	1,07	0,99	1,00
BradIns	Glasswool building blanket with perforated foil facing	(50)	A	120cm x 15m	0,56	1,03	0,93	0,41	0,21	0,14
BradIns	Glasswool building blanket with perforated foil facing	(75)	A	120cm x 15m	0,47	0,87	1,09	1,03	0,97	0,86
BradIns	Glasswool building blanket with perforated foil facing	(100)	A	120cm x 15m	0,75	0,93	1,14	1,04	1,03	0,97
BradIns	Suspended rockwool panels enclosed in polypropylene film	(50)	hung	50cm x 120cm	0,18	0,44	0,83	1,25	1,14	0,96
BradIns	Glasswool building blanket with perforated foil facing	(75)	A	120cm x 15m	0,47	0,96	1,11	1,05	1,01	0,88
BradIns Fibertex 350	Rockwool blanket	(25)	A	90cm x 150cm	0,18	0,29	0,69	0,86	1,05	1,20
BradIns Fibertex 350	Rockwool blanket	(50)	A	90cm x 150cm	0,29	0,70	1,19	1,04	1,14	1,06
BradIns Fibertex 350	Rockwool blanket	(75)	A	90cm x 150cm	0,60	1,03	1,13	0,99	1,07	1,01
BradIns Fibertex R4	Duct liner	(25)	A	120cm x 150 cm	0,18	0,29	0,69	0,86	1,05	1,20
BradIns Fibertex R4	Duct liner	(50)	A	120cm x 150cm	0,29	0,70	1,20	1,04	1,14	1,06
BradIns Fibertex R4	Duct liner, perforated foil facing	(25)	A	120cm x 150cm	0,36	0,21	0,30	0,97	1,06	0,67
BradIns Fibertex R4	Duct liner, perforated foil facing	(50)	A	120cm x 150cm	0,31	0,83	1,15	0,99	0,90	0,78
BradIns Fibertex R6	Duct liner	(25)	A	120cm x 150cm	0,11	0,20	0,80	1,10	1,02	1,12
BradIns Fibertex R6	Duct liner	(50)	A	120cm x 150cm	0,36	0,91	1,19	1,20	1,07	1,05
BradIns Fibertex R6	Duct liner, perforated foil facing	(25)	A	120cm x 150cm	0,12	0,27	0,80	1,17	1,16	0,80
BradIns Fibertex R6	Duct liner, perforated foil facing	(50)	A	120cm x 150cm	0,26	0,91	1,10	1,00	1,08	0,85
BradIns Flexitel	Glasswool building blanket	(25)	A	120cm x 15m	0,33	0,28	0,61	0,89	1,01	1,05
BradIns Flexitel	Glasswool building blanket	(25)	A	120cm x 15m	0,03	0,33	0,68	1,04	1,15	0,95
BradIns Flexitel	Glasswool building blanket	(50)	A	120cm x 15m	0,42	0,64	0,92	1,07	0,98	1,02
BradIns Flexitel	Glasswool building blanket	(50)	A	120cm x 15m	0,39	0,84	1,08	1,20	1,06	1,01
BradIns Supertel	Glasswool blanket	(25)	A	120cm x 240cm	0,12	0,41	0,63	0,90	1,01	0,99
BradIns Supertel	Glasswool blanket with perforated foil facing	(25)	A	120cm x 240cm	0,08	0,39	0,73	1,02	1,12	0,84
BradIns Supertel	Glasswool blanket with perforated foil facing	(25)	A	120cm x 240cm	0,13	0,32	0,59	0,83	0,99	0,97
BradIns Supertel	Glasswool blanket with 23um Mylar film facing	(25)	A	120cm x 240cm	0,15	0,45	0,67	1,07	1,08	0,71
BradIns Supertel	Glasswool blanket with 50 um Mylar film facing	(25)	A	120cm x 240cm	0,13	0,44	0,92	1,14	0,82	0,45
BradIns Supertel	Glasswool blanket with 23um Mylar film facing	(50)	A	120cm x 240cm	0,20	0,55	1,20	1,15	1,04	0,83
BradIns Supertel	Glasswool blanket with 59um Mylar film facing	(50)	A	120cm x 240cm	0,30	0,60	1,16	1,07	0,85	0,59
Conweb Tufflex G-37	Cellulose, nonwoven panel core	1,00	A	NONE	0,12	0,29	0,65	0,94	1,05	0,91
Conweb Tufflex G-37	Cellulose, nonwoven panel core	0,75	A	NONE	0,12	0,16	0,55	0,72	0,91	0,89
Conweb Tufflex G-40	Cellulose, nonwoven panel core	0,63	A	NONE	0,15	0,13	0,42	0,72	0,93	0,87
CTeed Ib150	Unfaced fiberglass board, bonded with thermosetting resin	1,00	A	24 x 48	0,19	0,62	0,72	0,82	0,88	0,89
CTeed IB150	Unfaced fiberglass board, bonded with thermosetting resin	1,50	A	24 x 48	0,19	0,51	0,82	0,86	0,95	0,97
CTeed IB150	Unfaced fiberglass board, bonded with thermosetting resin	2,50	A	24 x 48	0,41	0,78	0,96	0,94	0,93	0,97
CTeed IB150	Unfaced fiberglass board, bonded with thermosetting resin	2,50	F-25	24 x 48	0,54	0,85	0,97	0,96	0,93	0,97
CTeed IB200	Unfaced fiberglass board, bonded with thermosetting resin	1,00	A	24 x 48	0,15	0,55	0,73	0,86	0,92	0,94
CTeed IB250	Unfaced fiberglass board, bonded with thermosetting resin	1,00	A	24 x 48	0,25	0,52	0,71	0,83	0,89	0,95
CTeed IB250	Unfaced fiberglass board, bonded with thermosetting resin	1,00	A	24 x 48	0,08	0,33	0,69	0,81	0,92	0,97
CTeed IB250	Unfaced fiberglass board, bonded with thermosetting resin	3,00	A	24 x 48	0,44	0,91	1,07	0,99	1,02	0,99
CTeed IB300	Unfaced fiberglass board, bonded with thermosetting resin	1,00	A	24 x 48	0,19	0,49	0,69	0,87	0,92	0,94
CTeed IB420	Unfaced fiberglass board, bonded with thermosetting resin	1,00	A	24 x 48	0,33	0,40	0,70	0,94	1,00	0,98
CTeed IB420	Unfaced fiberglass board, bonded with thermosetting resin	1,50	A	24 x 48	0,09	0,45	0,91	0,99	1,02	0,96
CTeed IB420	Unfaced fiberglass board, bonded with thermosetting resin	3,00	A	24 x 48	0,54	1,01	1,05	0,98	1,01	0,97
CTeed IB600	Unfaced fiberglass board, bonded with thermosetting resin	1,00	A	24 x 48	0,12	0,52	0,68	0,87	0,93	0,99
CTeed IB600	Unfaced fiberglass board, bonded with thermosetting resin	2,50	A	24 x 48	0,53	0,99	1,02	0,84	1,00	0,94
CTeed MBP	Fiberglass blanket, flexible, unfaced	3,50	A	rolls	0,38	0,90	1,00	0,93	0,94	0,99
CTeed MBP	Fiberglass blanket, flexible, unfaced	5,00	A	rolls	0,68	1,11	1,06	0,94	1,00	0,97
CTeed MBP	Fiberglass blanket, flexible, unfaced	6,00	A	rolls	0,88	1,19	1,03	0,96	1,02	1,00
CTeed Ultracoustic	Fiberglass blanket with flexible internal septum	3,00	A	roll	0,43	0,91	0,99	0,98	0,95	0,93
CTeed Ultralite	Fiberglass duct liner with surface coating	1,00	F-25	roll	0,34	0,42	0,47	0,84	0,80	0,79
CTeed Ultralite	Fiberglass duct liner with surface coating	1,50	F-25	roll	0,29	0,55	0,72	0,85	0,89	0,89
CTeed Ultralite	Fiberglass duct liner with surface coating	2,00	F-25	roll	0,32	0,71	0,83	0,91	0,95	1,01
CTeed Ultralite	Fiberglass duct liner with surface coating	1,00	F-25	roll	0,23	0,47	0,57	0,74	0,85	0,87
CTeed Ultralite	Fiberglass duct liner with surface coating	1,50	F-25	roll	0,33	0,57	0,79	0,91	0,92	0,89
CTeed Ultralite	Fiberglass duct liner with surface coating	2,00	F-25	roll	0,39	0,69	0,92	0,98	0,93	1,00
CTeed Ultralite	Fiberglass duct liner with surface coating	1,00	F-25	roll	0,23	0,47	0,61	0,79	0,88	0,91
CTeed Ultralite	Fiberglass duct liner with surface coating	1,50	F-25	roll	0,37	0,63	0,80	0,90	0,89	0,90
CTeed Ultralite	Fiberglass duct liner with surface coating	2,00	F-25	roll	0,36	0,79	0,96	0,99	0,93	0,97
CTeed Ultralite	Fiberglass duct liner with surface coating	1,00	A	roll	0,10	0,28	0,50	0,70	0,82	0,83

Curriculum vitae

Xiang Yang

School:

Sep 1986 – Jul 1992   Primary school Yucai, Yangzhou, China

Sep 1992 – Jul 1998   Gymnasium Yangzhou, Yangzhou, China
Certificate: Higher education entrance qualification

Education:

Sep 1998 – Jun 2001   Department of Architecture, Zhejiang University, Hangzhou, China

Oct 2002 – Sep 2008   Department of Industrial Engineering, University of Kaiserslautern, Kaiserslautern, Germany
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Professional Activities:

Jun 2001 – Sep 2001   Intern, Yaxing-Benz Co., Ltd., Yangzhou, China

Sep 2005 – Feb 2006   Intern, Heidelberger Druckmaschinen AG, Wiesloch, Germany

Jun 2006 – Mar 2008   Research Assistant, Institute for Composite Materials, Kaiserslautern, Germany

Oct 2008 – Oct 2012   Research Engineer, Institute for Manufacturing Technology and Production Systems, Kaiserslautern, Germany

Since Dec 2012   Employee, Daimler AG, Böblingen, Germany

Scholarship and Exchange Program

Oct 2008 – Oct 2011   Fellowship of DFG IRTG 1131

Nov 2009 – Apr 2012   Visiting Scholar, Institute for Data Analysis and Visualization, University of California, Davis, USA