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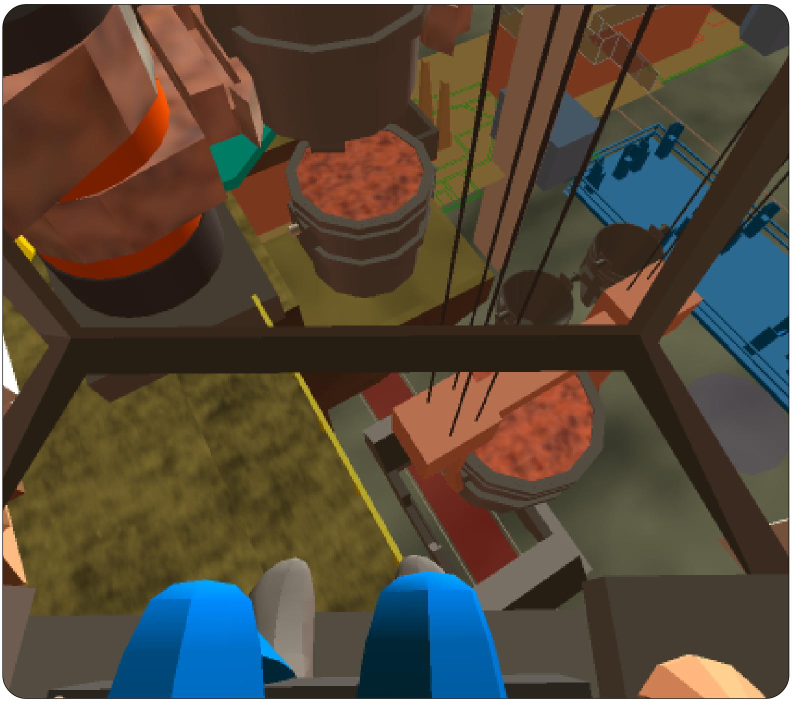

Timo Määttä

Virtual environments in machinery safety analysis

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Virtual environments in machinery safety analysis

Timo Määttä

VTT Industrial Systems

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Abstract

Safety is a feature that someone or some ones have planned for a product. To ensure that safety issues have been properly considered in the design phase of a product or production system different methods and procedures and tools have been developed. Safety analyses already in design phase have been basics for ensuring product or production system safety features. To engage all possible knowledge in the safety design participatory approach and different tools have been developed and implemented.

The rapid development of computers and software has made it possible to investigate systems in virtual environments (VEs), which are potential tools for safety analyses in design phases. The use of virtual environments in safety analysis for production evaluation purposes have remained minimal, reasons being lack of methods and knowledge of their applicability in safety analysis. The objective of this work was to evaluate the impacts of VEs on safety analysis.

A new method (SAVE) of applying VEs for safety analysis was developed and tested in the work settings. The method involves a procedure, based on Participatory Approach (PA), Task Analysis (TA), Work Safety Analysis (WSA), standard EN 1050 and three-dimensional (3-D) modelling of the objects being analysed.

The materials of this thesis comprised machinery systems of five plants in a steel factory, implementing ongoing modernisation projects. The plants were hot steel storage plant, steel converter plant, secondary metallurgy station, continuous casting plant and strip production plant. The machinery systems were cranes, mixers, desulphurisation station, remote-handled cars, steel converters, ladle turrets, continuous casting machines, coilbox machine and coil conveyer.

The results indicate that the SAVE method was applicable for safety analysis in machinery layout design phase. Safety analysis will clearly benefit from the use of VEs. According to the results 58% of all identified hazards in a steel factory could be identified with VEs. Simulation with a virtual environment was assisting the identification of hazards in 25% and digital human models in 10% of all identified hazards. A common understanding of designs, possibilities of evaluating and developing the system by the workers and of providing training for operators and maintenance persons were the major contribution when using VEs in safety analysis and applying participatory approach. VEs with an analysis group improved the identification of critical safety situations during the analysis.

Once equipment and software for VEs have become more versatile and less expensive the usage of VEs in plant design and development work will increase. This, however, calls for further investigation of more effective implementation procedures and cost management. The use of VEs in plant design will enhance the development and analysis of different design variations from several points of view, including safety.

Preface

This study was carried out at the VTT Technical Research Centre of Finland. The thesis presents a method for safety analysis which uses virtual environments.

I would like to express my sincere thanks to my thesis advisers Research Professor Risto Kuivanen and Professor Kaija Leena Saarela for all the guidance, valuable comments and support during my work. I am also grateful to all my colleagues who gave support for this work. In particular, I am grateful to Senior Research Scientist Juhani Viitaniemi, Research Scientist Kaj Helin, Research Scientist Simo-Pekka Leino, and Assistant Research Scientist Timo Rantala, who actively participated in most of the projects this thesis is based on. I would also like to thank Mrs Tiina Työppönen for all the help and guidance in practical matters. The work with the inspirational and innovative team has made this undertaking possible and is highly appreciated. I would also like to thank Professor Jouko Suokas for valuable discussions and comments during the writing of the thesis.

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Tampere, December 11, 2003

Timo Määttä

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List of symbols

3-D	Three-dimensional
AR	Augmented reality
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CAVE	Cave Automatic Virtual Environment (CAVE™)
CPU	Central processing unit
CRT	Cathode ray tube
EN	European standard
HCI	Human computer interaction
HMD	Head-mounted display
ISO	International organization for standardisation
LCD	Liquid crystal display
LED	Light-emitted diode
LOD	Level of detail
PC	Personal computer
WSA	Work safety analysis
VR	Virtual reality
VE	Virtual environment
VRML	Virtual reality modelling language

Definitions

Accident	An unplanned sequence of events leading to actual adverse consequences (death, injury, damage to or loss of equipment or property, damage to the environment) (Guidelines … 1992, van der Schaaf 1992).
Animation model	A computer-based three-dimensional (3D) model, in which machines and peripheral devices can move according to the computer program.
Design process	Totality of the activities with which all the information necessary for producing and operating a technical system or a product is processed in accordance with the task (VDI 2221, 1987).
Desktop VR	Animated computer-aided design (CAD). This can be virtual reality or simply a more sophisticated version of CAD.
Human-machine system	A combination of one or more human beings and physical components interacting to shape given inputs into some desired outputs (Sanders and McCormick 1987).
Machinery	Assembly of linked parts or compoments, at least one of which moves, with the appropriate machine actuators, control and power circtcuits, joined together for a specific application, in particular for the processing, treatment, moving or packing of material (ISO 12100-1:2003; 3.1).

Manufacturing system	A system created to manufacture certain products or to carry out phases of product manufacturing.
Model	A simplified or idealized description of a system, situation, or process, often in mathematical terms, devised to facilitate calculations and predictions (Shorter Oxford English Dictionary).
Participation	A procedure where some or all of the users of a product or production acts as specialist in a design or development team.
Perception	The awareness of external objects, qualities, or relations, which ensures directly upon sensory processes (Kalawsky 1993a).
Risk	A combination of the probability and the degree of the possible injury or damage to health in hazardous situation (EN 292-1, 1991).
Risk assessment	A comprehensive estimation of the probability and the degree of the possible injury or damage to health in hazardous situations, determined in order to select appropriate safety measures (EN 292-1, 1991).
Risk estimation	Defining likely severity of harm and probability of its occurrence (ISO 12100-1; 2003, 3.15).
Safety	Safety is a machine’s ability to perform its function without causing injury or damage to health (EN 292-1, 1992).

Safety analysis	A systematic approach for the identification of hazards (Kuivanen 1995).
Safety measure	Means that eliminates a hazard or reduces a risk (ISO 14121:1999; 3.3).
Sensation	Subjective response or any experience aroused by stimulation of a sense organ (Kalawsky 1993a).
Simulation	The technique of imitating the behaviour of some situation or system by means of an analogous situation, model or apparatus, either to gain information more conveniently or to train personnel (Shorter Oxford English Dictionary).
Simulator	Any machine or apparatus that simulates a desired condition or set of conditions, such as a flight simulator (Kalawsky 1993a).
Simultaneous, (concurrent) design	An approach whereby products and their related manufacturing and support processes are developed concurrently (Sohlenius 1992).
Task	A generic term for associated series of actions which are normally performed in the prescribed sequence and place demands on the worker (Landau et al. 1998).
Task analysis	A systematic approach to describe and evaluate tasks and its relationships in a certain process in order to compare features to demands.

Virtual environment (VE)	Virtual environment is a synthetic computer-generated representation of a physical system; a representation that allows a user to interact with the synthetic environment as if it were real (Kalawsky 1993a).
Virtual reality (VR)	A phrase coined by Jaron Lanier and the same as VE, but more familiar to the public (Kalawsky 1993a). VR can be seen also as pinnacle of what is ultimately sought to achieve when implementing VE systems. In VR the three components, autonomy, presence, interaction, are all at their maximum value in the Zeltzer cube (Zeltzer, 1992).

1. Introduction

Industrial companies are constantly improving their capacity to maintain the successful life of the company. Improvements may comprise small or substantial changes in production systems, depending on particular needs. Sometimes there is a need to modernise the whole production system, and this could be done at the same time or sequentially. When changes are planned in a production system, safety aspects should also be considered in the light of relevant regulations.

Safety should be reckoned with preferably in all design stages. Initially a design process will involve unknown factors, and decisions must be made under uncertainty of possible unintended consequences (Behesti 1993). Project risk management and management of safety and health risks are basic parts of a company's risk management (Wideman 1992). Deficiencies in design processes have caused unacceptable failures and disasters, many of which could have been avoided by systematic approaches to the management of engineering design (Hales 1995).

Hazard analysis and risk assessments are widely accepted in product and process design (Van Aken 1997). Many manufacturing system design processes have nonetheless shown little evidence of systematic safety analysis (Mattila et al. 1995). Today manufacturers or their representative must carry out a risk assessment and take the results into account in machine design (Directive 98/37/EC). In the European Union the essential health and safety requirements formulated in the machinery safety directive have become an important project management task in machine design and manufacturing.

In the case of a system where a company implements a totally new installation the manufacturer signs the declaration of conformity and fastens the CE mark to the machine. In cases, however, where a company itself installs different parts of a machinery system, the company is responsible for all measures required in the Directive, including risk assessment, design and realisation of the necessary safety measures, and complement to the documentation. During this task the company may implement a participatory design method in order to gather all possible knowledge of the company for risk assessment and design of safety measures.

A participatory design could have greater potential if the drafts for risk assessment are understandable and the instructions for work tasks are clear. Fallon and Dillon (1988) presented a CAD system which brought out the role of ergonomics in design process. Bengtsson and associates (1996, 1997) concluded in their study that computer modelling and simulation combined with drawings were more informative than ordinary drawings. Örtengren (1992) concluded that graphic simulation is a beneficial tool in evaluation of the ergonomics of a work in the design phase.

There are other, more advanced means – e.g. animated demonstrations – of presenting the information required for the proper use of a product. In some cases, these means may be superior to the traditional ones (Kieras 1992). Kuorinka (1997) argues that conventional tools, tables, drawings, CAD etc. are too complex and may not be applicable in a participatory context. Instead, he suggests that a hands-on approach is needed, as abstract and conceptual issues are difficult for some participants to understand, especially at the beginning of the process.

In this present work an attempt is made to overcome these deficiencies and to enhance the quality of safety analysis, implementing simulation and visualisation with a novel technology. The basic procedures of most safety analysis together with the most fundamental knowledge of the system also constitute the basics for this undertaking. A new means of identifying potential hazards and hazardous situations with computerised visualisation is presented. This work will in one way improve the situation with safety analysis when the participative approach is implemented. The use of VEs as tools is a step forwards to enhance understanding of the functions of a system in hand for participants in design or evaluation procedures.

In this work the Virtual Environment (VE) and Participative Ergonomics (PE) approach and the Work Safety Analysis (WSA) method with Task analysis are utilised in safety analysis of new designs for different plants in a steel factory. Altogether seven cases were studied using the new method in analysis of hazards during modernisation projects.

2. Review of the literature

2.1 Design process and methods

2.1.1 Product design

In the development of design processes a great number of works has been published especially describing systematic approaches to design (e.g. Pahl and Beitz 1977, 1996, Hales and Wallace 1991, Roozenburg and Cross 1991). These approaches are included in VDI recommendations (VDI 2222 1977, VDI 2221 1987). Figure 1 illustrates the life-cycle of a product including the design of a product. The recommendation is directed more to product design than to system design.

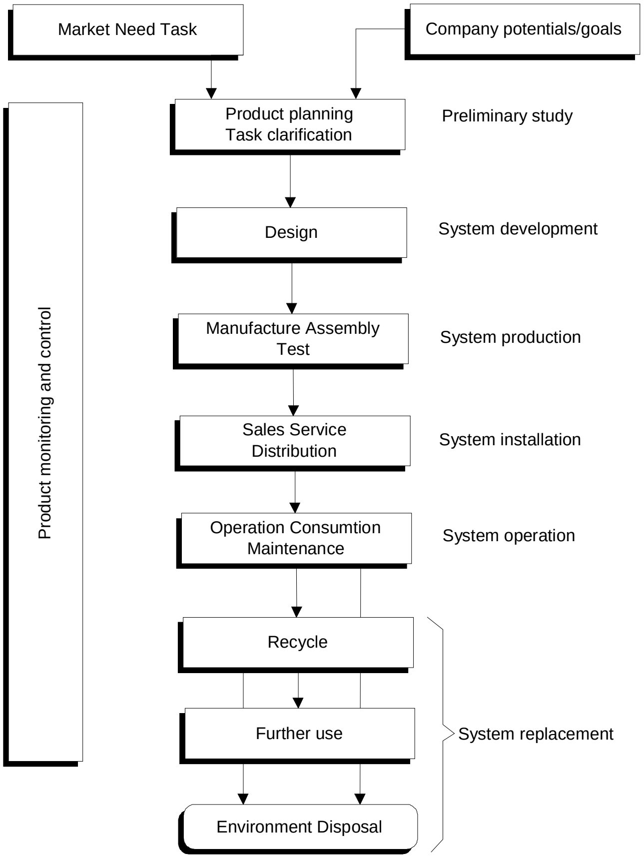


Figure 1. A model for the life-cycle of a product (VDI 2221 1987).

The systematic approaches are structured in two dimensions, the vertical, dividing the life-cycle of a product into life phases (Roozenburg and Cross 1991, Roozenburg and Eekels 1995), and the horizontal, based on a cycle of problem-solving which takes place in every phase of the vertical structure (Roozenburg and Cross 1991). Figure 2 presents the vertical dimension of design phase.

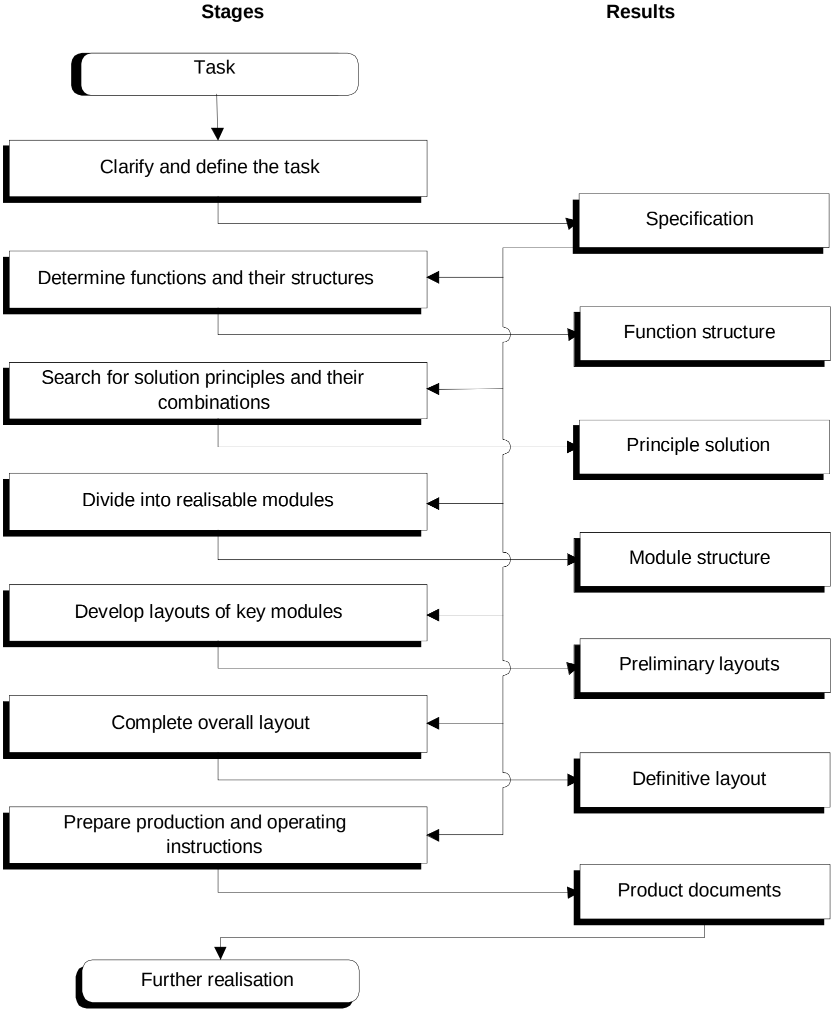


Figure 2. The vertical dimension of the general approach to design (VDI 2221 1987).

The horizontal dimension of design phase is a problem-solving cycle and includes analysing and defining problems, synthesising and analysing solutions, and arriving, by means of an evaluation process, at a decision on whether to develop the preferred solution or discontinue development (Figure 3).

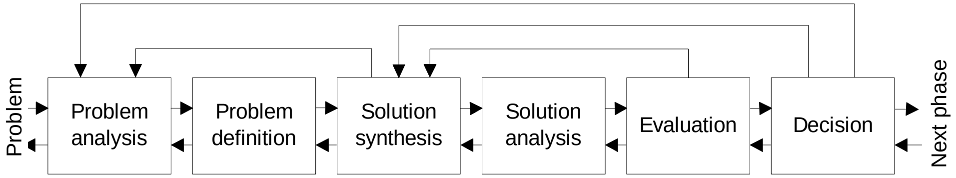


Figure 3. The horizontal dimension based on a common problem-solving cycle (Roozenburg and Cross 1991).

The systematic design approach involves breaking the problem-solving process down into parallel paths. Another strategy in this approach includes proceeding from general and abstract to particular and concrete. This is to keep the solution space as wide as possible during the initial phases of the design process (Reunanen 1993).

The design phase can be further divided into various design phases, namely clarification of task, conceptual design, embodiment design and detail design (Pahl and Beitz 1977, 1996). Collecting information on the requirements of the task serves to clarify the design task, the aim in this phase being to structure the task from the designer’s point of view. The requirement or specification list can be established independently of any solution, and constantly reviewed during the design process (Reunanen 1993).

Brunetti and Golob (2000) have introduced a feature-based approach which emphasises integrated product model with conceptual design information. The conceptual design phase involves determinations of functions to be fulfilled by the product, and establishment of the function structures. The results are functional structures and principal solutions which represent the best combination of physical effects and preliminary embodiment features to fulfil the function structure. At this stage the principle solution may be documented as a sketch, a diagram, a circuit or a description.

The embodiment design phase involves development of the product or system by the designer from the concept taking account of technical and economic considerations (Helander and Nagamachi 1992, Eversheim et al. 2000). This phase also includes safety design (Table 1). The definitive layout here contains all the essential configuration information necessary for the realisation of product. The main forms of representation of results are scale layout drawings, a preliminary parts list, instrumentation flow charts, etc.

The detail design phase involves the arrangement, form and dimensions and surface properties of all individual components, material specifications and technical and economical rechecking. The safety design task in this phase can be divided into four subtasks (Kivistö-Rahnasto 2000). Layout design includes the layouts and critical dimensions of the most important safety measures. The design of interfaces includes design of usability. The design of ergonomics includes design of main work tasks. The design of the key modules includes the safety design for the risks caused by the layouts modules.

The result is a set of product documents, in the form of detail and assembly drawings, part lists, and production, assembly, testing, transporting, and operating and maintenance instructions. In the detail design phase safety design is also conducted and the results are detailed designs of safety measures, interfaces, tasks and machines.

The integration of the essential health and safety requirements into the different design stages should be studied and practical methods developed for assessment of the acceptability of risks. Safety issues are to be considered in every stage of design, since decisions will often have an impact on the safety of a product or production.

Table 1. Safety design in the embodiment design phase (cf. Kivistö-Rahnasto 2000).

Process phase	Safety design task			
	Design of layout	Design of interfaces	Design of ergonomics	Design of the key modules
System synthesis	**Design of layouts and most critical dimensions of the main safety measures** (incl. e.g. risk reduction, safety devises, personal safety equipment, warnings, instructions)	**Usability design of the main user interfaces**	**Ergonomic design of the main work tasks**	Design of the layouts of the key modules **Safety design for the risks caused by the layouts of the key modules**
System analysis and evaluation	Conformance with the legal requirements and standards Analysis and evaluation of the risk reduction and residual risk	Analysis and evaluation of the usability of the user interfaces	Analysis and evaluation of the ergonomics of the most important work tasks	Analysis and evaluation of the remaining risks caused by the layouts of the key modules
Decision - making	Decisions on the layouts of the most important safety measures	Decisions on the most important user interfaces	Decisions on the most important work tasks	Decisions on the layouts of the key modules
Result	The layouts of the most important safety measures	The layouts of the most important parts of user interfaces	The layouts of the most important work tasks	The layouts of the key modules

2.1.2 System design

System design can be divided into eight phases (Franke 1984):

1. Planning
2. Preliminary study
3. System development
4. System creation
5. System installation
6. System implementation
7. System operation, and
8. System replacement.

In the *planning phase* a framework fulfilling the set of demands of the system is created and gives general guidelines for designing the production system.

In the *preliminary study phase* the technical possibility of the indented system is evaluated e.g. with simulations, mock-up models or a small-scale experimental system. This phase may include evaluation of old constructions, selection and modification of solutions providing a basis for design, and decision on the novelty and complexity of the object.

In the *system development phase* the chosen technology will be further developed to meet the relevant demands, e.g. capacity, performance, quality, schedule, products, costs, reliability, usability, maintainability, safety, interfaces, competition and regulation. Also the material flow, layouts and equipment will be chosen, the organisation designed and personnel selected and training level specified.

In the *system creation phase* the tenders, their evaluation and testing, manufacture of self-made components and technical preliminaries will be completed. Also basic training of personnel and testing of internal system functions will be organised.

In the *system installation phase* all the components of the system will be installed and tested in their final places. The system will be ready to for the implementation and production.

In the *implementing phase* the manufacturability, subsystems, resources, organisation, usability and working methods are designed and evaluated.

In the *system operation phase* the system operates in the manner envisaged. Also the programming, disturbance control, maintenance, and the function of organisation are designed and under continuous development in this phase.

In the *system replacement phase* modules of the system are under modernisation or alteration. Also dismantling, reuses, forwarding, storage and recycling of modules of the system are included in this phase.

2.1.3 Manufacturing system design

According to Nicolaisen and associates (1992) there are three philosophies in the creation of a manufacturing system:

- Device-oriented,
- Automation-oriented, and
- Problem-oriented design.

The device-oriented mode is based on the concept that a new device or equipment will solve a certain type of problem. The design task is to find proper places for existing apparatus or device.

The automation-oriented design sets out from the assumption that the automated work is more effective, more desirable and somehow superior to manual work. The goal of the task is to find solutions which involve a higher level of automation than the previous system.

The problem-oriented design assumes that by problem analysis the relevant solution can be sought, and all the factors included in the specific design are taken into consideration.

Pylkkänen (1984) adopted a wider perspective and introduced system-oriented and vision-oriented design philosophies. The first mentioned is based on the flexibility of production, short throughput times, high quality of product, high reliability of production, one piece flow and larger entities of workflow, high integration of different tasks, and modularity. The work may involve tasks, requiring of the operator high skills as well as a detailed understanding of the whole manufacturing process (Kuivanen 1995). The main goal in this approach is to produce a given number of certain products in an effective way.

The vision-oriented design, on the other hand, is based on the idea that usability of a system must remain constant even during sweeping changes in limiting conditions. This design philosophy takes into account the needs of the future, i.e. new products, new production varieties and new volume of production.

These technically oriented design approaches have been criticised as tending to ignore the human role in manufacturing systems (e.g., Bainbridge 1983, Hyötyläinen 1998, Kidd 1994). The technical solutions are designed separately from production, operators and the design of working organisations (Hyötyläinen 1998). Control of a manufacturing system is constructed from the point of view of both software and hardware technology. The operators are placed in the system only to control manufacturing. The technology itself cannot solve productivity problems if a human presence is needed to keep production going (Kuivanen 1995). The system must be considered as a larger socio-technical system.

The socio-technical approach to design has been an alternative to the purely technical one (Daniellou and Garrigou 1992). Socio-technical design is based on the idea that a production system comprises two subsystems, technical and social. They complement each other and are equally important for the system. The production system is effective only if both of these subsystems are functioning and well co-ordinated. The goal in this approach is to find the best possible solution suiting both the technical and human aspects. The practical task is to design the allocation of humans and machines and to design the human-machine interface. One example of a specific socio-technical design approach is the lean production concept, whose goal is to eliminate all wasteful work e.g. by job improvement and human aspect consideration. This also includes self-made improvements, which benefits both job satisfaction and the production system. From this point of view a new human-centred approach has been introduced (Rosenbrock 1980, Brödner 1985, Corbett et al. 1991).

The human-centred design approach is based on the conception that technology should be designed to support wide human skills, not to replace them. Human issues are taken into consideration in the early design phase and the process applies simultaneously to human, technical and economic aspects (Kidd 1994). Essential to human-centred design is that it is a development process in which the whole organisation participates.

When implementing human-centred design approach some deficiencies have been brought out (Corbett et al. 1991):

1. There is a wide gap between theory and practice. The theoretical knowledge is difficult to connect to the experiences and knowledge of the technical design.

2. Human-centred design has concentrated on individuals and the work group while wider perspectives have received less attention.

3. The operator’s minimal participation in the design process. There can be communication problems between operators and designers. The operator’s possibility to have a real effect on the design is also limited in that the time for familiarisation with the concepts involved is often too short. There is a lack of an understandable and mutual language.

4. Difficulties in defining human-centred technical solutions. It is felt that the methodology adjusting the social system to the demands of technology should be so altered that technology meets the demands of human.

The technical-based design approach introduced in VDI 2221 is widely accepted, but is directed more to product design than to system design. There is a lack of wider implication of the socio-centred and human-centred design approaches.

2.2 Participatory design

Participatory design is a procedure where persons working with the same production process or machine have the opportunity to take part of the design process and can influence the design and development of the target. In participatory design some or all of the workers who will work e.g. at the forthcoming plant take part in a number of design sessions during the different design phase (Mumford 1989).

The particular organisation capabilities will determine the form which could be implemented in participative functions. In addition participation includes common requirements such as motivation, competence, good information exchange, voluntarily and uniformity of the goals (Kallela 1996).

Participation can be divided into three levels (Table 2). The participation level increases towards user-oriented design when implementing the participation-oriented approach (Leppänen et al. 1991). At the highest level of participatory design the users will design with the support of experts. This level obviously calls for more knowledge and comprehension of procedures in the design than other levels. A change towards participatory design requires training for the participants and the designers.

Table 2. The levels of participation in design (Leppänen et al. 1991).

Levels of participation				
Designer-oriented	→	Participation of the users increases	→	User-oriented
The users will not participate	Information, consultation, training	A representative in the design group	Participatory design	The users will design themselves with the support of experts

Participation can be supported and encouraged in different ways (Table 3). The tools can be divided into four categories such as common ways of thinking, modelling the object, communication equipment and knowledge of handling equipment (Leppänen et al. 1991). All of these tools can be used in a participatory design process.

Table 3. Tools for participatory design (Leppänen et al. 1991).

Common ways of thinking	Modelling the object	Communication equipment	Knowledge handling equipment
▪ Production process ▪ Organisation ▪ Operation ▪ Strain ▪ Learning ▪ Development	▪ Explanations in words ▪ Diagrams ▪ Drawings ▪ Models of workplaces ▪ Tests, examinations ▪ Simulation ▪ Scale models ▪ Computer aided design (CAD)	▪ Discussion techniques ▪ Group work techniques ▪ Innovation techniques ▪ Screen techniques	▪ Manuals, instructions ▪ Work analysis methods ▪ Check lists ▪ Examples ▪ Computer programs

In the process industry the objectives of designs are usually extensive, complex and difficult to comprehend, so drawings will not be suffice for visualisation of the objects. Scale models and simulators suit perfectly, but are also more expensive to implement (Kallela 1996).

Participatory design in complicated systems demands that the internal model of production and operation process is good (Kallela 1996). The internal model is a person's internal reflection of the external environment (Leppänen 1993).

In implementing participatory design in a large-scale system, the mode of modelling is actually a tool both to create the internal model of work and to gain a perception of the production process (Leppänen et al. 1991). Modelling in this context is a description of a work process or part of the process in such a way that a person will have a picture of what the system is and what happens in it. Leppänen and associates (1991) suggest that at least four models should be developed when modelling a large-scale system. The first model is product-oriented and is based on the specification of manufacturing stages of the product. The second is machine-oriented and based on a description of the material flow. The first two models give an overview of the production system. The third model includes descriptions of stages where the human agent is involved in the process, while the fourth describes the human functions which change the target from the original stage in the desired direction. This needs information from the human psychological and physiological control system. The division of labour among workers is also included in this model.

According to Hirchheim (1989) the advantages of participation are,

- *Better result of design*: As the users themselves can influence their working environment, it will become more suitable and practicable to work than without participation

- *Commitment*: Users will experience the new system more as their own and will implement it more easily when they have been heard during its design

- *Work satisfaction*: Operators will be more satisfied with their job when they have influenced their working environment

- *Training*: Participation constitutes effective training for the operation of the new system and knowledge of the work and processes will in general increase

- *Efficiency*: Increased knowledge together with the new suitable tools will lead to more effective production

- *Participation as a value itself*: Participation is a feature of democracy and is, as a form of it, a value itself.

Participation is not a simple task to implement in industrial systems. Obstacles to participation, according to Mumford (1989), are:

- Techniques may be so rigid, that it is not possible to alter them
- Releasing workers from their normal duties is difficult
- Conflicts may arise between management and unions
- Conflicts may arise at the personal level
- Fear of change, especially appreciation, skills and loss of employment may jeopardise even a good project
- Many forms of reaction such as aggressiveness, evasion and projection, could interfere with participation
- Old workers and rigid organisation could hinder the process.

Participation also involves problems in implementing the method. These may be social, personal, organisational or technological (Mumford 1989):

- *Trust.* Workers do not always trust the good intentions of the management when the management suddenly gives an opportunity to make decisions.

- *Choosing delegates or representatives.* The representative of the users should be chosen by election, but this can lead to over-representation.

- *Conflict of interest.* There may be conflicting goals between users and participation will bring them out.

- *Stress.* The amount of work will increase. At the same time workers must discuss the design project during the work tasks.

- *Communication and negotiation skills.* Participation calls for these skills, which are usually difficult to learn.

- *Role changes.* In participation the role of directors and managers will change from decision-makers and commanders to coaches and consultants.

- *Changes in technology.* Even though users may come familiar with the possibilities and limitations of the technology during the design process the rapidly changing technology will make this knowledge old.

There are in addition restricting factors in participation which are connected to technology, production and organisation, for example the nature of the technology implemented, production philosophy and the mode of organisation of the company. Implemented technology may be such that there are no possibilities to implement participatory design. Typically such situations arise when the changes are expensive and demanding and development in small steps is not economically realistic. When designing a new system the phase of specification needs users' knowledge to yield as practicable a solution as possible. Suitable and professionally qualified workers for the participatory design are not easy to find (Kallela 1996).

According to Kallela (1996), participatory design is not necessary when the production system implemented involves standardised products, the production system is easily controlled, variance in products are few, customisation is at a low level and orders are extensive. The development of such a system will need only adjusting, optimisation, differentiation and simplification and co-ordination of the management.

An evaluation of the implementation of participation in the development of production can be accomplished through to the operation environment (Table 4). When the system environment is more dynamic and complex the participatory design will impact the more on the development process (Feeney 1996).

Table 4. Classification of the system environment (Hendrick 1987).

Complexity	Dynamic	
	Stable	Changing
Simple	– Stable, reliable environment – Few products and services – Restricted clientele and competitors – Minimised need of expertise	– Dynamic, unexpected environment – Few products and services – Restricted clientele and competitors – Minimised need of expertise
Complex	– Stable, predictable environment – Abundant products and services – Abundant customers, suppliers and competitors – Need for expertise	– Dynamic, unexpected environment – Abundant products and services – Abundant customers, suppliers and competitors – Need for expertise

Automatisation can affect on the demand for expertise at work on three levels (Alasoini 1990). The need for expertise will rise, will be kept at the same level or will be diminished (Figure 4). A need will rise when work phases in the middle or aside of the automated production stages are bound together into a greater integrated system. The need will remain at the same level when an enhanced system or minimisation of personnel does not incur to changes in job demands. The need for expertise diminishes when automatisation minimises the need for experience-oriented knowledge but brings no new demands for the job.

Automation moves workers into new strategic positions and gives rise to a need for new kinds of knowledge. Especially skills are needed in handling disturbances and unexpected situations (Brödner 1985, Julkunen 1987).

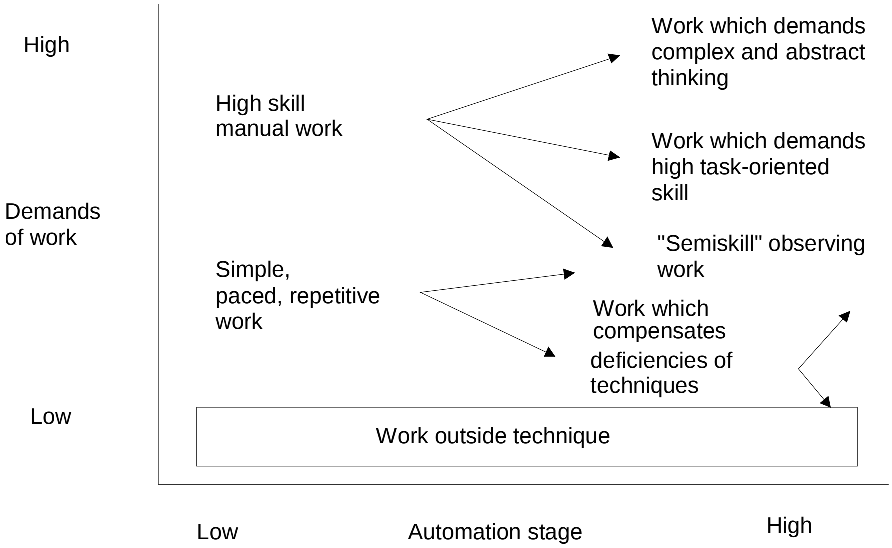


Figure 4. Automatisation changes the needs for expertise (Alasoini 1990). (Translations by the author)

Participation is a logical result of the pressures to change and implement new technology. The design and development of complex and flexible production systems will have more success with participatory design than without, because by implementing participatory design unexpected situations will be more under control (Kallela 1996).

Previous studies have shown that the participative ergonomics strategy can be an effective and feasible method for reducing workloads and increasing job satisfaction (Pohjonen et al. 1998). The costs for improved working condition are lowest at the beginning of the project and increase rapidly with time (Eklund and Daniellou 1991). This indicates that it has value implementing participatory ergonomics at the early stage of a development project.

The video-computer interaction method can be used to strengthen a participative approach to work (Kadefors and Forsman 2000, Hanse and Forsman 2001). The workers can be intensely and directly involved in the participatory ergonomics strategy, especially at the stage of taking an active role in the identification of psychosocial problems and specific risk indicators as regards work-related musculoskeletal symptoms (Hanse and Forsman 2001).

According to Noro (1991) the greatest impact of participatory ergonomics is in production. The production manager is the key player in the participatory ergonomics team.

2.3 Ergonomics design procedures

The implementation of ergonomics into the design procedure can be descried in two ways, which are not exclusionary: according to the system approach (Saari 1981) and according to the participatory approach (Wilson 1999a, 1999b). In the system approach a systematic and broad view is emphasised (Figure 5). In addition, the relationships between different phases are taken into consideration.

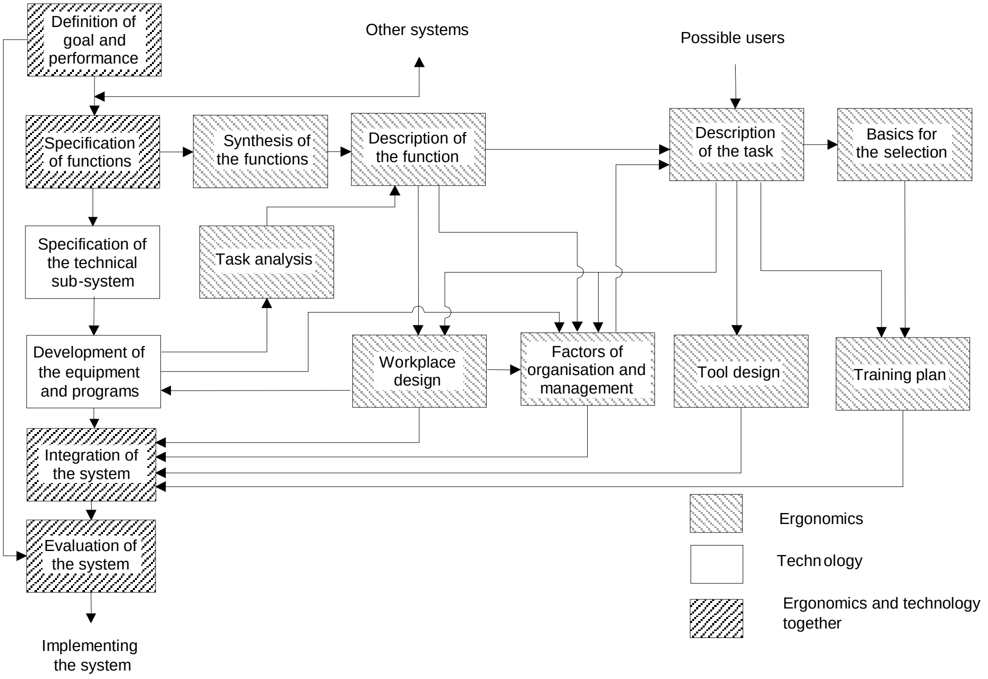


Figure 5. Ergonomics in design according to the system approach (Saari 1981). (Translations by the author)

In system approach the ergonomics is considered as a part of the design process, which is divided in sub processes. These sub processes include ergonomics issues to be considered during the design.

In participatory design the knowledge of different persons in a development group is highly appreciated (Figure 6). The right size and the structure of the group are emphasised.

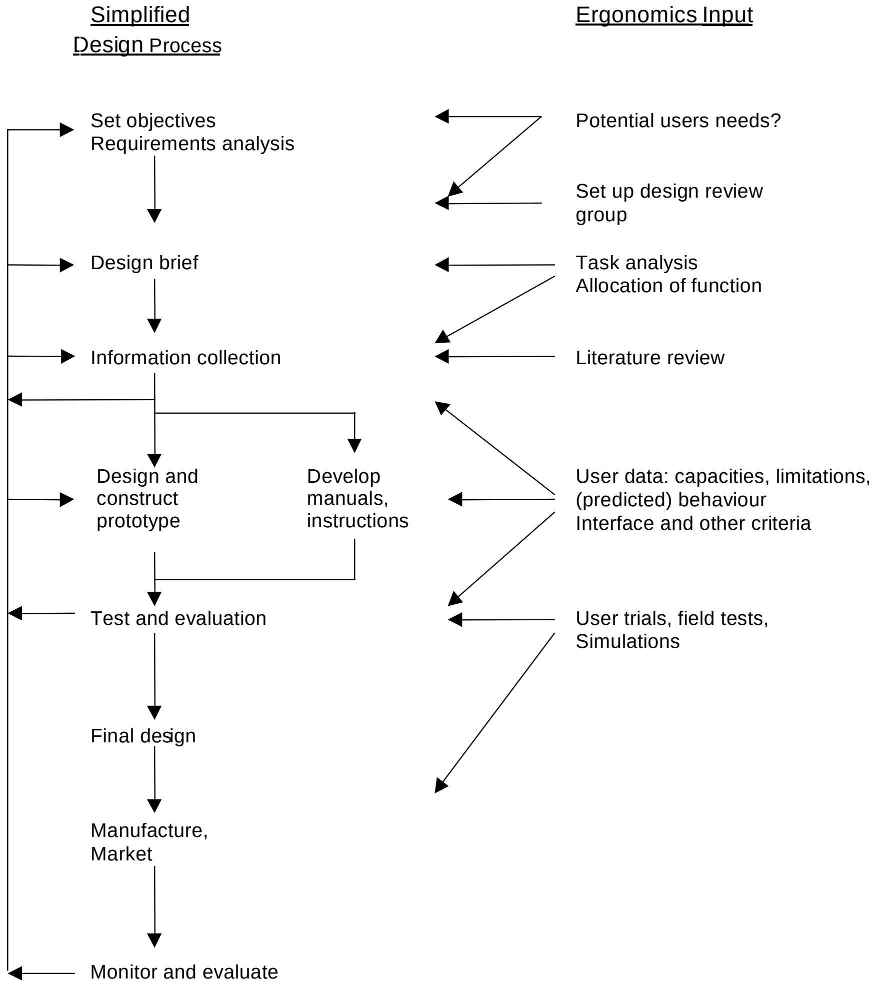


Figure 6. Ergonomics in design according to the participatory approach (Wilson 1999a).

Ergonomics input are taken into consideration in every step of the design procedure. Participation is the key element of sharing the knowledge between the designers and users. User trials and evaluations are essential parts of the design process.

2.4 Participatory ergonomics

Participatory ergonomics is one perspective in system ergonomics, which requires end-users as the beneficiaries of ergonomics to be involved in developing and implementing the technology (Imada 1991). In participatory ergonomics the aim is to develop methods and principles whereby to involve employees in the design of work and workplaces (Örtengren 1997). Participatory ergonomics is practical ergonomics with participation by necessary actors in problem-solving, inviting the participation of those who may have first-hand experience (Kuorinka 1997).

According to Wilson and Haines (1997a) participatory ergonomics consists in the involvement of people in planning and controlling a significant proportion of their own activities, with sufficient knowledge and power to influence both processes and outcomes in order to achieve desirable goals. According to Nagamachi (1995) participatory ergonomics is the active involvement of workers in complementary ergonomics knowledge and procedures in their workplace design supported by their supervisors and managers in order to improve working conditions and product quality.

The participatory ergonomics approach is actually a new way of improving the final result in workplace or product design by involving people who are familiar with the work process or who use the workplace or the product (Shipley 1990, Sundin 2001). One reason for the use of participatory ergonomics is to take advantage of the knowledge and experiences of workers in the design in order to enhance the results (Wilson and Haines 1997a, 1997b). Furthermore, participatory ergonomics can also be used for learning purposes, both for workers and designers (Wilson 1997, Garmer et al. 1995). Participatory ergonomics is being used not only to solve existing problems but also in the design and planning of new installations (Kuorinka 1997).

This approach needs tools for a successful process (Snow et al. 1996, Held and Krueger 2000, Väyrynen et al.1999/2000, Wells et al. 2000). Some of these tools can be connected to different activities of the approach, e.g. organisation, preparation and control of activity, analysis of problems, evaluation of different situations, enhancement of creativeness, producing ideas, and evaluation and development of ideas (Imada 1991, Wilson 1996, Wilson 1999b).

Participatory ergonomics would not prove appropriate in all cases. There is some doubt as to whether the approach will produce real changes in work; workers cannot or will not really develop their work, the approach will not provide functional results, and a consensus is not always reachable.

When developing the design process from design-oriented to user-oriented, the learning process is essential. In this respect the participatory ergonomics approach has some benefits. Understanding of work, work place and work environment, practical knowledge of processes and functions, identification of problems, and the value of enhancing and evaluating ideas processed by working together will be enhanced when utilising this approach (Wilson 1999b, Engeström et al. 1996).

The fundamental condition for successful participatory ergonomics is the participants' capability to communicate and interact with each other. According to Eklund (1999) the basic elements are:

- All those concerned must be able to participate.
- The participants should be active, present their ideas and encourage others to present their own.
- The participants are equal.
- Discussion should be understandable to all participants.
- Any relevant arguments may be presented.
- Participants should approve justified arguments presented by others.
- Participation should be based on physical presence.

- The role and authority of the participants should be discussable.
- Differences of opinion should be tolerated.
- During discussion a consensus on taking actions should be reached.

Sundin (2001) has introduced the concept of participatory ergonomics design (PED), which is based on the idea that measures taken in the design phase have a larger impact on the final production situation than measures taken in later stages (Figure 7). The benefit of this approach is to detect possible problems arising in the production phase already in the design phase by working with multidisciplinary teams. This approach will collate together the knowledge of product and production by implementing simultaneous engineering procedures.

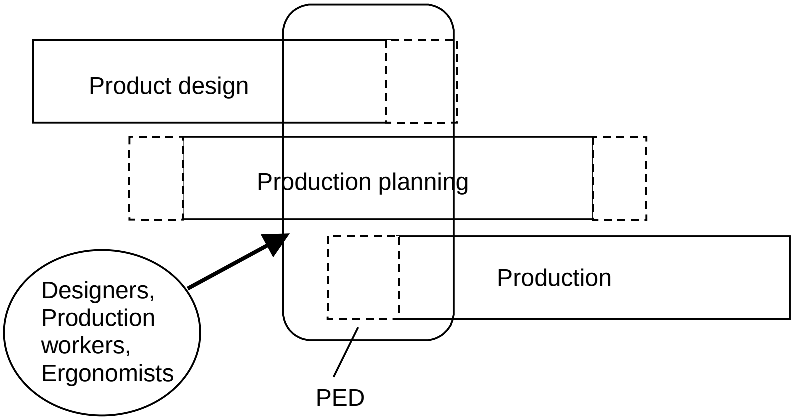


Figure 7. Participatory Ergonomics Design (PED) according to Sundin (2001).

The present work is based partly on the PED concept and will continue to implement such an approach, which is also focused on assessing the knowledge of workers in development undertakings.

2.5 Three-dimensional computer modelling and visualisation

The rapid development of computer graphics and software has made it possible to create digital pictures, which are near-realistic visualisations. This development has changed designing with computers from two-dimensional (2-D) to three-dimensional (3-D). The level of visualisation has thus increased towards more realism. The information in 3-D pictures is more substantial than in 2-D pictures. In reality the pictures on the screen are only 2-D+ without a stereo picture and stereo glasses. Computer visualisation is a means to visualise the object in digital mode and 3-dimensional with computer software and hardware (Sundin 2001).

Computerised visualisation supports participatory ergonomics (Laring et al. 1996, Sundin 2001). Results show that computerised visualisations enhance the understanding of ideas and solutions and make it easier for participants in a group to present their ideas, in turn facilitating the participatory ergonomics process. Understanding of how a workplace should function was difficult using the CAD software. According to Sundin (2001) this was mainly due to the difficulties in understanding how equipment and other objects would move, as they appeared too static in CAD pictures.

A digital human model (i.e. computer manikin) would seem to offer a viable means of improving the understanding of solutions, especially those related to ergonomics (Bonney et al. 1999, Sundin et al. 2000). Advanced tools with colours, digital human models and animations further understanding and could offer a way of improving the results of design or analysis. With the help of these visualisation techniques it is expected that less time will be needed to explain the solution to other workers on a team, as the solution is thereby made easier to understand (Sundin 2001).

The use of the most advanced computerised visualisation tools, e.g. different forms of VR, may possibly contribute to even greater understanding in that with their virtual environments they give the user a sense of immersion. More sophisticated analysis tools may mean heavier reliance on outside experts as well as reduced possibilities for sustained, broad use of participation which is technically self-sufficient (Sundin 2001). The complexity of tools has increased and new tools have been introduced during the years of implementing participatory ergonomics (Figure 8).

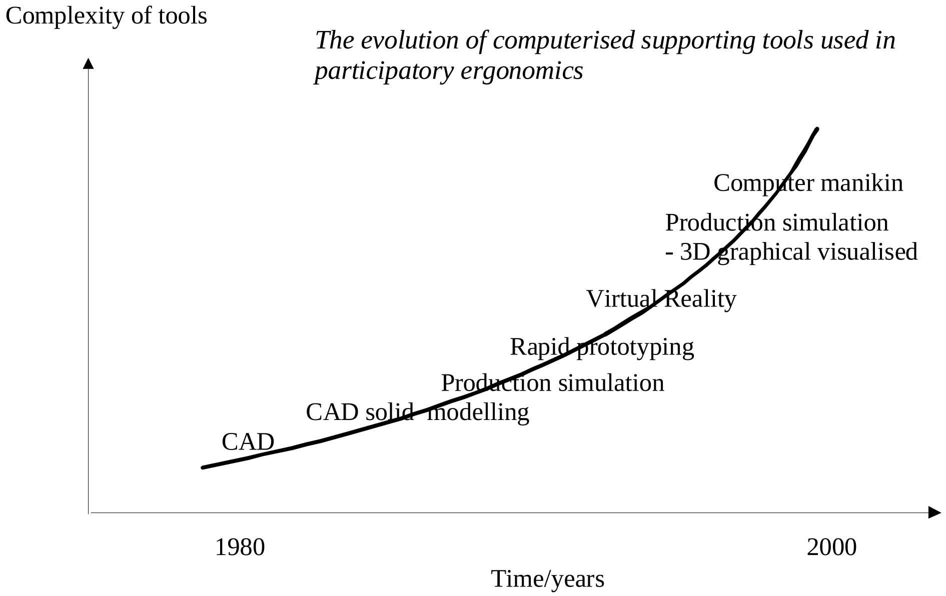


Figure 8. The complexity of computerised tools (Sundin 2001).

Sundin (2001) suggests, on the basis of the results of his work, that the use of the digital human models further improves the understanding of issues related to the product and production. Some efforts have been accomplished to study human models in work place design (e.g. Grobelny and Karwowski 2000, Sundin 2001).

According to Väyrynen (1988) computer modelling and simulation can be used to evaluate safety in getting into and out of a cabin in a working machine. According to Leskinen and Haijanen (1997) implementing digital human models is a developing area of computer simulation, and digital human models can be used in the evaluation of the ergonomics of workplaces.

2.6 Simulation

Simulation is the technique of imitating the behaviour of some situation or system by means of an analogous situation, model or apparatus, either to gain information more conveniently or to train personnel (The Oxford English Dictionary 1989). Carrie (1992) defines simulation as the technique of building an abstract and logical model of a system, which describes the internal behaviour of its components and their interactions, including stochastic variability. Simulation is a technique whereby computers can be used to imitate the operations of various kinds of real-world facilities or processes (Law and Kelton 1991). The facility or process of interest is called a system. In order to study the system a set of assumptions regarding the way how it works have to be made. These assumptions with mathematical or logical relationships constitute a model, which is used to gain insight into how the corresponding system behaves.

Wallace and Dougherty (1991) have specified simulation in the field of manufacturing as a technique of utilising representative or artificial data to reproduce in a model various conditions which are likely to occur in the performance of a system. The European Logistics Association (1990) defines simulation as the imitation of reality for studying the effects of changing parameters in a model. Greenblat (1988) summarised simulation as an operating model of central features or elements of a real or proposed system. Greenblat (1988) also pointed out the active and dynamic roles of participants during simulation sessions.

A system is defined as a collection of entities which act and interact toward the accomplishment of some logical end (Schmidt and Taylor 1970). In simulation a system can be of two kinds: discrete or continuous. A discrete system is one for which the state variables change only at a countable or finite number of points in time. A continuous system is one for which state variables change continuously with respect to time. In practice few systems are wholly discrete or continuous, but when one type of change is predominant for most systems, it will usually be possible to classify a system as being either discrete or continuous (Law and Kelton 1991).

A model is a representation of a system developed for the purpose of studying that system (Law and Kelton 1991). A simulation model is a particular type of mathematical model. The model can be static or dynamic, deterministic or stochastic and discrete or continuous. A static simulation model is a representation of a system at a particular time. A dynamic simulation system model is a representation of a system as it evolves over time. A deterministic simulation model contains no random variables, while a stochastic simulation model contains one or more random variables. A discrete (event) simulation model is a representation in which the state variables change at a countable number of points in time, whereas continuous simulation model is a representation of a system in which the state variables change continuously with respect to time.

Some possible reasons for the widespread popularity of discrete-event simulation are (Law and Kelton 1991):

1. Most complex, real-world systems with stochastic elements cannot be accurately described by a mathematical model, amenable to analytical evaluation. Thus a simulation is often the only type of investigation possible.

2. Simulation allows one to estimate the performance of an existing system under some projected set of operating conditions.

3. Alternative proposed system designs (or alternative operation policies for a single system) can be compared via simulation to establish which best meets a specified requirement.

4. In a simulation we can maintain much better control over experimental conditions than would generally be possible when experimenting with the system itself.

5. Simulation allows us to study a system with a long time-frame, e.g., an economic system, in compressed time, or alternatively to study the detailed working of a system over expanded time.

Also some drawbacks may be encountered with simulation (Law and Kelton 1991):

1. The development of simulation models is often expensive and time-consuming.

2. On each run a stochastic simulation model produces only estimates of a model's true characteristics for a particular set of input parameters. Thus, several independent runs of the model will probably be required for each set of input parameters to be studied. For this reason, simulation models are generally not as good at optimisation as they are at comparing a fixed number of specified alternative system designs.

3. The large volume of numbers produced by a simulation study often creates a tendency to place greater confidence in results than is justified.

Simulation is one of the most widely used techniques in operations research and management science (Law and Kelton 1991). Some impediments to its even wider acceptance and usefulness observed in the 1980s have since the 1990s been solved, e.g. the arduous task of writing computer programs and the large amount of computing time with complex systems by special purpose computer software and effective and lower price computer processors.

Mikkola (1997) studied fatigue damage in a hydraulically driven boom system using virtual prototype simulations. He concluded that it was possible to create a simulation model which can be used to determine realistic loads for fatigue analysis and the properties of modern software and hardware enables simulation models to be applied to problems which involve various fields of engineering. Simulation can serve as a medium of communication between different engineering teams and thereby supports modern design methods such as concurrent engineering. To obtain the best results from simulation, different engineering teams must co-operate with each other. Virtual prototypes make it possible to produce large amounts of information on the effects of design parameters. This information can be used to facilitate design work while a new product is still in the design phase.

2.7 Virtual Environments

2.7.1 Definitions

The virtual environment (VE) is a synthetic computer-generated representation of a physical system; a representation which allows a user to interact with the synthetic environment as if it were real (Kalawsky 1993a). According to Kalawsky (1993a) virtual reality (VR) is a phrase coined by Jaron Lanier and is the same as VE, but more familiar to the public. VR can also be seen as a pinnacle of what is ultimately sought when implementing VE systems. In VR the three components, autonomy, presence, interaction, are all at their maximum value in the Zeltzer cube (Zeltzer 1992). Figure 9 illustrates the dimensions of virtual reality.

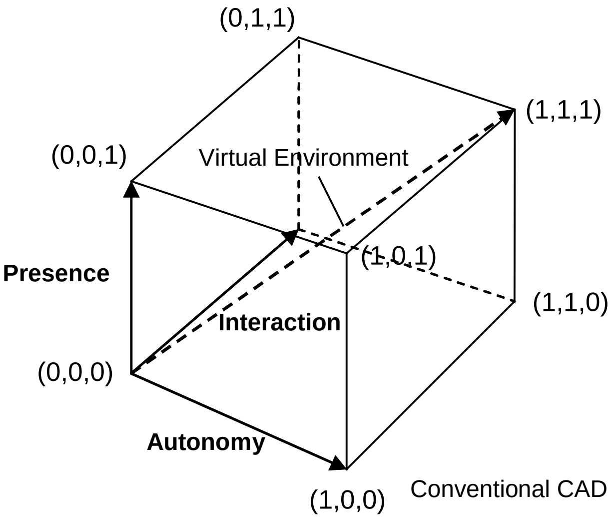


Figure 9. The Zeltzer cube for the Virtual Reality concept (cf. Kalawsky 1993a).

According to Zeltzer (1992):

- *Autonomy* (A) refers to a qualitative measure of the virtual object's ability to react to events and stimuli. A rating 0 applies when no reaction occurs and a value of 1 applies when autonomy is at its maximum.

- *Interaction* (I) refers to the degree of access to the parameters or variables of an object. A rating of 0 applies to non-real-time control of variables. A value of 1 is assigned for variables which can be manipulated in real time during program execution.

- *Presence* (P) refers to the degree of presence with a measure of the fidelity of the sensory input and output channels. The degree of presence is highly dependent on the task requirements.

In virtual reality, point (1,1,1) as (A,I,P) in the Zeltzer cube, the sensory simulation would be so complete that one would not be able to distinguish the virtual environment from the real world (Kalawsky 1993b). The point (0,1,0) indicates that the user can control essentially all the variables of an object or model during program execution in real time. The point (0,1,1) represents the status of virtual environments where one can experience a high degree of interactivity with a reasonable degree of presence. The point (1,0,1) represents a situation where there is a high degree of autonomy and presence but a low degree of interaction. In this world a human could be a passive observer with freedom only of control of his or her viewpoint but possibly fully immersed in the virtual environment.

According to Sheridan (1992) the sense of presence can be divided into three determinants. Kalawsky (1993b) has added a fourth. These determinants are:

- Extent of sensory information

- Ability of observers to modify their viewpoint for visual parallax or visual field

- The ability to modify the spatial relationships of objects in a virtual environment

- The closed loop performance due to an operator-induced motor movement. This includes the dynamic behaviour of movable objects in the virtual environment.

Kalawsky (1993a) introduced the fourth determinant of the sense of presence to include the important motion effect of objects in a virtual environment. The meaning of lags and delays in tracking or computer graphics systems is important to the sense of presence.

The term virtual reality has been used by many researchers and attributed a number of different interpretations. One of the broadest definitions for this technology is that whereby VR is identified as a way for humans to visualise, manipulate and interact with computers and extremely complex data (Aukstakalnis and Blatner 1992). VR is thus an innovative interface between humans and computers. The technology has interesting potentials to depart from the traditional methods of interacting with the computer perhaps to a higher level. Coldfarb (1991) defines VR as an interactive computer system so fast and intuitive that the computer disappears from the mind of the user, leaving the computer-generated environment as the reality.

The first immersive virtual reality system was that demonstrated in 1961, called Sensorama. This was not however a computer-assisted system but a system with camera film solution. The first computer-assisted system can be seen in that presented by Sutherland (1968). This system was actually also the first augmented reality (AR) system in possessing a see-through function with semi-transparent display.

The term virtual reality describes something which is real in effect although not in fact and which can be considered open to acceptance as fact for some purposes (Wilson 1997). A virtual environment is an artificial world created with a computer and used in real time. This world could be a three-dimensional model and the display could include a set of complex data. The users of the VR system can have a sense of immersion in the virtual environment with quasi-real interaction with it. The VR interface includes displays for the eyes, gloves for the hands, headphones for the ears and tactile feedback devices for the body.

The experience in the virtual environment should enable participants to feel transposed to a new location, to interact with objects and the environment, and to feel that the objects they are manipulating or observing are behaving appropriately (Wilson 1999c). Participants should be able to perceive some equivalence between the virtual and the real environments in terms of interactions with objects and objects' interactions with each other.

According to Gigante (1993) virtual reality is the illusion of participation in a synthetic environment rather than external observation of such an environment. Milgram and Tagemura (1994) have presented a Virtuality-Reality Continuum concept, which describes a taxonomy which identifies how an augmented reality and virtual environment are related. The reality-virtuality continuum relationship is shown in Figure 10.

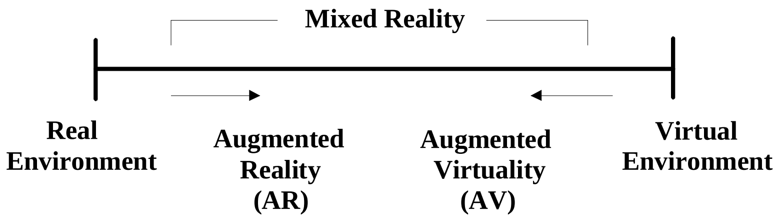


Figure 10. Mixed Reality in the Real Environment and Virtual Environment diagram (Milgram and Tagemura 1994).

According to Milgram and Tagemura (1994) the mixed reality is a combination of real environment and virtual environment. In mixed reality an operation or function in reality could be performed with the aid of augmented virtuality, and accordingly operation in a virtual environment can be performed with augmented reality. In addition, augmented reality could enhance information for the operation in reality. This could be e.g. camera images from a point one can not see during an inspection tour of a machine. When augmented virtuality is used the image coming from some section of a machine could be created with virtual environment. Some technical equipment which actually implements this concept, is already been developed, for example transparent HMD for fighter pilots, and extra displays for maintenance work.

The definitions of virtual reality and virtual environments are somewhat different. Some of the definitions are presented in Table 5.

Table 5. Some definitions for virtual reality and co-concepts.

Definitions	Coldfarb, 1991	Nugent, 1991	Aukstakalnis and Blatner, 1992	Kalawsky, 1993a	Larijani, 1993	Gigante, 1993	Wilson, 1996	Isdale, 2000
Virtual Reality	is an interactive computer system so fast and intuitive that the computer disappears from the mind of the user, leaving the computer-generated environment as the reality.	is a computer-synthesised, three-dimensional environment in which a plurality of human participants, appropriately interfaced, may engage and manipulate simulated physical elements in the environment and, in some forms, may engage and interact with representations of humans, past, present or fictional, or with invented creatures	is identified as a way for humans to visualise, manipulate and interact with computers and extremely complex data	is a phrase coined by Mr Jaron Lanier and is the same as VE, but is more familiar to the public.	is a digital model of an environment; the convergence of computer simulation and visualisation that attempts to eliminate separation between a user and a machine	is the illusion of participation in a synthetic environment	describes something that is real in effect although not in fact and that can be considered capable of being considered fact for some purposes	is a computer mediated 3D environment with viewer control over viewpoint, presentation is primarily visual, possibly augmented with audio, haptics, etc with some degree of interaction with the environment
Virtual Environment				is a synthetic computer generated representation of a physical system; a representation that allows a user to interact with the synthetic environment as if it were real				
Augmented Reality					is enhanced perception, when a person chooses to rely on the real world as a frame of reference but uses a transparent display or other no			

Virtual environments have the following attributes (Wilson et al. 1995);

- Environments are generated by a computer
- Environments or participants' experience of them are three-dimensional
- Participants have a sense of presence in VEs
- Participants can navigate around VEs
- Behaviour of objects in VEs can match their behaviour in real life
- Participants can interact with VEs in real time.

Virtual environment is created with different system elements: software to produce visual and other images and to interface with input devices; interface systems comprising sensors and effectors; and communications systems for networking. Depending upon which elements of the available technology they use, VE systems may be classified from full simulators to those using head mounted-displays (HMDs), gloves, body suits, etc, to desktop systems. Desktop systems provide a lower level of presence, but they have the advantages in terms of graphics quality, user comfort and convenience, suitability for existing work patterns, lengths of time the participant can be working and cost (Wilson 1996). When using VEs in industrial applications, it is valuable to place participants in environments they cannot normally, or easily experience. This is to allow them to perform in ways not normally or easily possible, to enhance visualisation of and communication about a situation, and to allow exploration and different viewpoints for an environment (Wilson 1996).

Generally, VE systems can be divided into Desktop VE, augmented reality and visually coupled display systems. Desktop VE is a subset of a traditional VE system with 3-D image achieved with lightweight glasses and LCD (liquid crystal display) shutters. In augmented reality, transparent head-mounted displays are used, allowing the user to simultaneously be in the virtual and the real world. With the visually coupled displays system, the displays are placed directly in front of the user's eyes, and immersion is achieved through head-mounted displays. Immersive systems can stimulate users' visual, aural and tactile senses in such a way that they feel immersed in a computer-generated experience. The concept of VR with its non-clear boundaries and trendyness has led to some-times confusing usage of the term VR (Sundin 2001).

In this study virtual environments are generated by a computer, the environment model is three-dimensional, participant in virtual environments has a sense of presence and can navigate around VEs, and the objects in VE match the behaviour in real life.

2.7.2 Virtual environments applications

The fields of applications of virtual environments are extensive. VEs are implemented e.g.:

1 In *Architecture*, used to evaluate the designs of new structures with realistic walk-through. Such applications enable the assessment of the structure's aesthetics, acoustics and physical lighting.

2 In *Education and Training,* used to enable people to experience worlds like the surface of planets, models of molecules and the interior of human or animal bodies. Applications have also been developed for the training of pilots and drivers.

3 In *Entertainment,* used by film studios, amusement parks, video games makers and toy manufacturers.

4 In *Health and Medicine,* used in radiation therapy planning and surgical simulation for training purposes.

5 In *Information Control*, used to present large and complex sets of data in forms more easily understood, such as the visualisation of complex multivariable financial and market data.

6 In the *Sciences*, used to model and study complex phenomena and data in the computer, such as visualisation of airflow fields, visualisation and interaction with complex mathematical and astronomical data.

7 In *Telepresence*, used to develop e.g. the remote control of robots or vehicles which are directly manipulated by humans immersed in the respective virtual environments (Telerobotics).

Product design and manufacturing is the most critical field for VE applications in the manufacturing industry. Angster and Jayaram (1997) have presented a framework for a virtual reality-based product development system. The researchers have carried out a state-of-the art review, and have concluded that virtual reality techniques provide engineers with the added information needed to reduce time and cost. Many VE-based softwares for design and manufacturing are, however, limited in their expandability, customisation, and usability with current CAD/CAM systems.

If compatible with current parametric CAD/CAM systems, a VE system could support techniques such as virtual design, virtual assembly, virtual manufacturing, and human integrated design (Angster and Jayaram 1997). The architecture of such a system should allow the expansion and customisation of virtual environments the better to suit more the engineer's needs. VE technologies do not however provide at the moment the necessary functionality to perform adequate processes in a virtual environment with all the realism and the intuition of the real-world process. Actually, VE system development is a matter of Human computer interactions (HCI).

Virtual environments are used for several engineering design tasks, e.g. in work place design (Järvinen et al. 1996, Määttä et al. 1999a and 1999b, and Andreotti and Perotti 2001), assembly planning (Bullinger et al. 2000, Chryssolouris et al. 1999), ergonomic planning (Christmansson et al. 2000), and in education and training of safety engineering and maintenance (Flaig 1998) and in ergonomic assessments (Gautal 1999). Kuivanen (1995) found that 3-D modelling could give a good image of the hazards and risks of a robot system in the design phase. Moreover, the VE offered a better-scaled impression of the real world solution.

2.7.3 Hardware of Immersive VE Systems

A typical VE computer configuration is shown in Figure 11. Its concept as in every human-machine interaction task lies upon bi-directional communication defined by input and output channels. The user of the system specifies the input data and the computer responds to this action by updating its output.

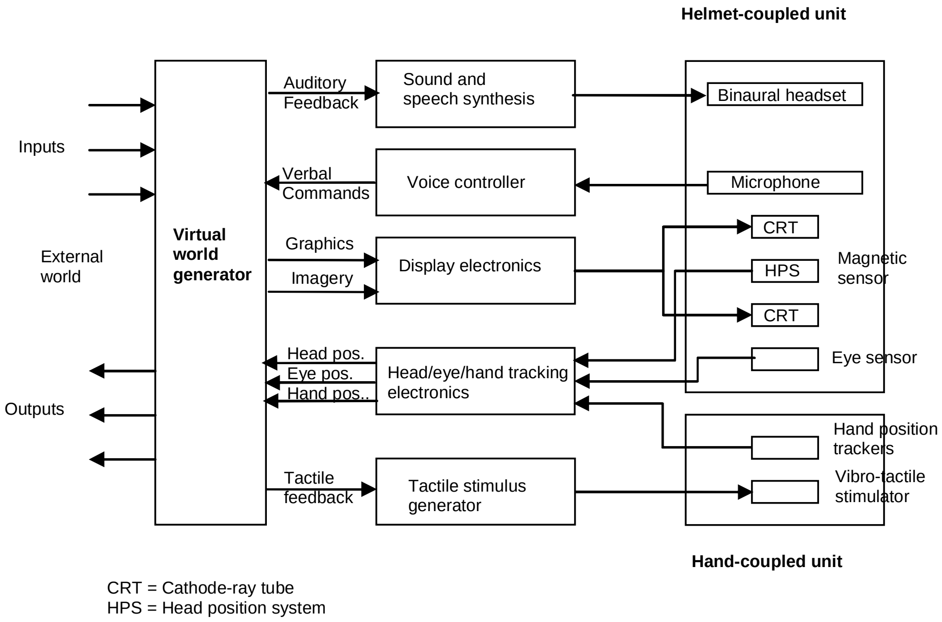


Figure 11. Virtual reality computer configuration (cf. Kalawsky 1993a, p. 322).

The input channels include the interface used by humans to communicate information and interact with the virtual environment. These actions comprise mainly locomotion and manipulation

The key element for movements in VE applications constitutes motion tracking and control. This refers to the tracking of the position and the orientation of a real world object moving within the virtual environment. Real time tracking of e.g. the head's motion is required in order to specify the viewpoint changes and update accordingly the displayed stereo images.

The basic position- and orientation-sensing technologies used in VE systems are magnetic, mechanical, optical, ultrasonic and gyroscopic. Some descriptions of the technologies are as fallows:

- *The magnetic system* uses a static source that generates low frequency magnetic fields and receivers on the moving objects to detect it. It allows a relatively large working area, has low delay times, and does not require optical contact between the receiver and the transmitters. The receivers can be also quite small devices. The system is however sensitive to electromagnetic interference of other magnetic devices in the working space. Major measuring errors are possible when metallic objects are inside the working area.

- *The mechanical system* uses movements of a mechanical arm's joints, attached to an object in order to record its motion. Such a mechanical arm is usually heavy and allows a quite small working area. Weight compensation techniques have been developed for some of those systems.

- *The optical system* uses light-emitting diodes (LEDs) and a combination of cameras and image-processing software to track the position of the LEDs. Instead of the LEDs special reflectors are also used. Weaknesses in this technology are that it requires a large amount of calculations by the host computer and that the light source and the camera must be in line of sight.

- *The ultrasonic system* uses audio sources and microphones to capture motion based on the time-of-flight principle. This method evinces little accuracy and is highly susceptible to sound noises from the environment. It is usually found in low cost systems.

- *The gyroscope system* uses miniature gyroscopes on the user's head to extract the head's orientation via double integration of the angular acceleration on each axis. These systems will not require a ground-based point of reference (transmitter or receiver) and are not expensive.

The key element for direct and realistic interaction between the human and the virtual environment is the hand orientation system. Most such devices available today are glove-like (Figure 12). Gloves are equipped with devices which sense both the position and orientation of the wrist and the flexion angles of the fingers and hand joints. A common technique for sensing the bending of the fingers uses a fibre-optic cable with an LED at one end and a photo sensor at the other, for each finger. Another technique is the placement of strain gages on the outer part of the figure joints.

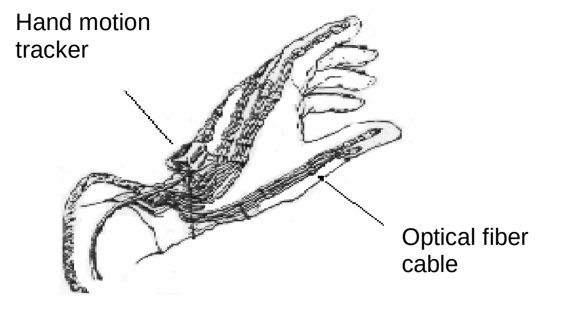


Figure 12. An example of a data glove (VPL DataGlove, VPL Inc).

The output channels include the interface used by humans to receive information from the virtual environment. The critical output channels used in VR applications today are graphical display, audio output and haptics and force feedback. The most commonly used graphical display unit called head-mounted display (HMD) comprises mainly two miniature display screens and a set of special optics (Figure 13). The screens (LCD or CRT) present to the user two images, according to his or her view on the virtual world. This view is controlled by using head motion tracking. The respective images of the virtual world are presented on the screens. Using stereo vision techniques these images create the illusion of depth.

Stereoscopic screens are either projector screens or conventional monitor of a computer. The user sees a three-dimensional image on a single screen with the use of LCD shutter glasses. Each eye view is toggled on the screen sequentially at a high refresh rate, giving the user the illusion that he or she sees a constant image, which is a slightly different for each eye, giving him or her in this way the perception of depth.

One interesting output in VE audio system is the display of three-dimensional sound. This output creates a sound providing the user with the sense of sound localisation. The illusion is created using mathematical models, which represent the various sound modifications of sound in real life.

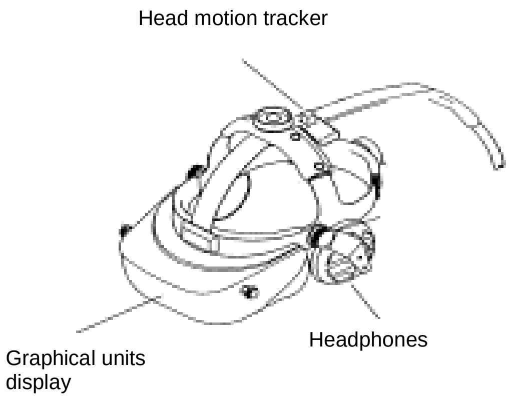


Figure 13. An example of a head-mounted display (VR 8, Virtual Research Systems Inc.).

Usually large projectors are used to provide a wide field of view, which is not usually the case with the HMDs. Such systems can provide an image usually with better quality than the head mounted displays. The user can see the virtual environment only from one selected direction with a wide view, but not from any direction according to the user's head, as in the HMDs. Another advantage of such systems is that other people can be present in the simulation within the virtual environment. A special application based on this principle is the CAVE™ (Cave Automatic Virtual Environment, trademark of Fakespace Systems Inc.). The CAVE™ comprises of a cubic room with walls, floor and ceiling which are rear-projection screens. The user inside the room sees the virtual environment wherever he/she looks, having the full field of view of the human eyes. By reason of the wide images provided on the screens the cave-type (cubic virtual room) system needs extensive computational power. The image quality is however not as good as in display or in HMD due to the large size of the projector screens. An example of a cave-type screen system is illustrated in Figure 14. The virtual room could also be other than cubic. Spheres and even 12-wall constructions are used especially in the military applications.

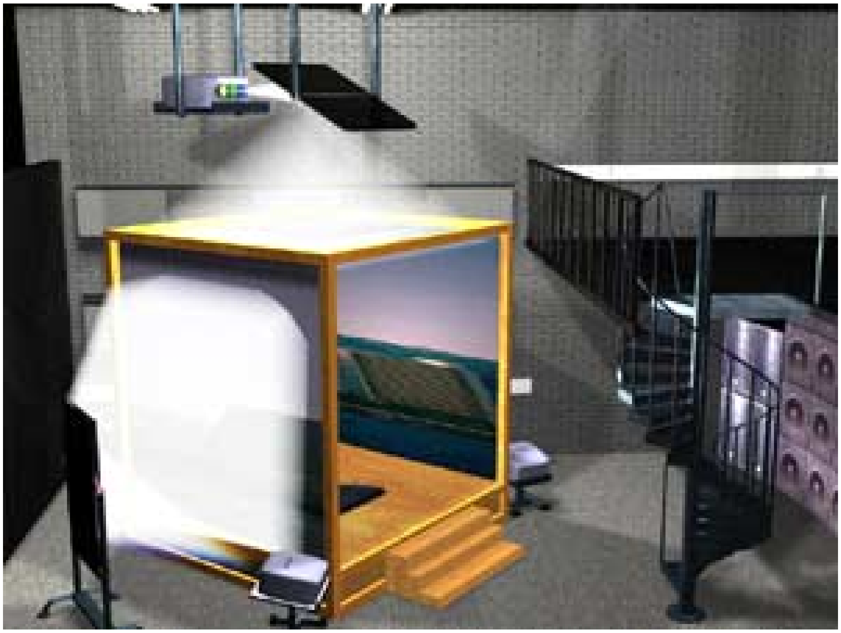


Figure 14. An example of a cave-type projector VE system (Mika Iltanen, Tampere Virtual Reality Center).

The sensation of virtual touch is also crucial to immersion and realism in VR applications. This sensation includes tactile and kinaesthetic information from interaction between the user's hand and a virtual object. The major types of haptics and force feedback interfaces currently available or being developed are:

1. *Hand controllers*; ground-based multijoint arms which provide, usually 6-DOF, force feedback to the user's hand, wrist, elbow and shoulder.

2. *Exoskeletons*; rigid link devices which fit over and move with the limbs or fingers of the user. Most of them provide force feedback using hydraulic actuators.

3. *Shape changers*; tactile displays which stimulate the skin by controlling the deformation or forces distributed on it.

4. *Vibro- or electro tactile*; tactile displays which stimulate the hand skin through an array of vibrating pins or surface electrodes.

The host computer is the core of the virtual environment system. It has to provide extremely demanding graphics as well as CPU performance. The virtual environment is a world created with real time graphics. In order to display smooth motion as the user moves in the virtual environment, the graphic images provided must be rotated and translated over 20–30 times per second. The more computational power for these features the workstation has, the more polygons can be displayed for each frame. A model of virtual environment can consist over 100 000 polygons. For the graphics power in virtual reality applications the workstations are usually equipped with special hardware for graphics acceleration. CPU performance specifications are also demanding in the case of features such as collision detection and various numerical simulations.

The technology of VE continues to develop. Some novel applications have recently been introduced. Rakkolainen (2002) presented a new kind of penetrable projection, a non-solid fog-screen, which enables high-quality walk-through virtual environments and new projection experiences, and removes the risk of screen fragility. The work also introduces a novel tracking screen, which is for tracking the user through the screen using infra-red cameras. This is, however, not as yet realised (until year 2003). Other novel technology will become available as the market for implementing virtual environments emerges.

2.7.4 Virtual Environment Software

The toolkits and the authoring systems are two major categories of software for the development of virtual environment applications. Toolkits are programming environments which provide a set of functions with which programmers can develop customised VE applications. Authoring systems are complete programs which offer graphical interfaces and tools enabling users to create virtual worlds and develop VE applications without skilled programming. Other methods used to describe a virtual environment are visual programming languages, world building within the environment and automated world building.

Some of the software components required of a virtual environment software tool are:

1. *The geometry process software*, which handles the geometry of the virtual environment and performs the rendering and projection onto the screen.

2. *The world modelling and simulation software*, which provides the tools to model the physical and behavioural aspects of the environment.

3. *The interaction software*, which provides the mechanisms to process input from the control devices and interpret them in the form of an application operation.

Virtual environment system should operate in real time to produce full immersion. This usually requires respective real-time features of the operating system upon which the software runs. Multiprocessor systems are usually required in VE applications in order to provide the necessary computational power. This means that the software architecture must support distribution of tasks to many resources for parallel execution with all the concerns for parallel execution methodologies.

In this work a virtual environment was adopted in which one can virtually move in a 3-D model wherever he or she wishes. To distinguish from conventional CAD, in virtual environment one can virtually enter into the model from any direction. Figure 15 illustrates the differences of 3-D models from 2-D models.

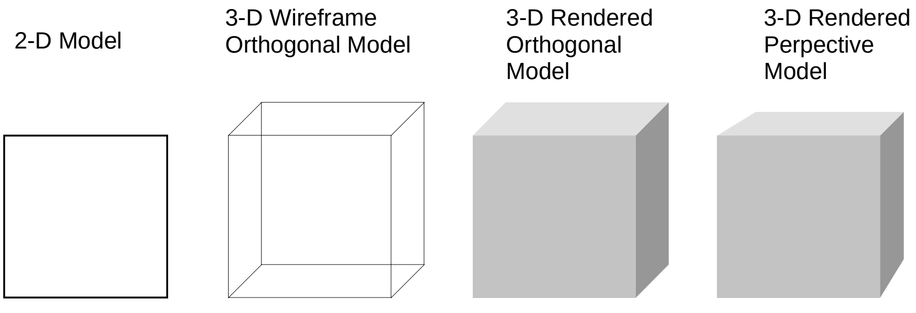
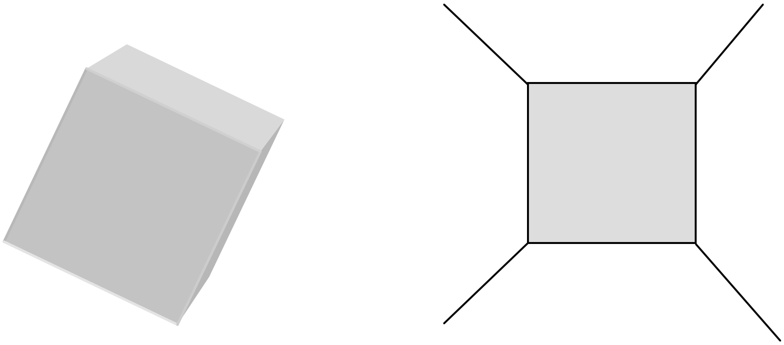


Figure 15. Examples of 2-D models and 3-D models.

Figure 16 illustrates the differences of a CAD model from a virtual environment model. A CAD model can be rotated in any angle, but not entered. In the virtual environment the model can be entered in any direction and the illusion of “being there” can be realised.



A. CAD model

B. Virtual environment

Figure 16. Two simple models to illustrate the CAD models and VE models.

In VE one can virtually move freely to a new point e.g. to be inside an object. The sensation of being inside the model, i.e. in the virtual environment, is called immersion. This could be accomplished by desktop, screen, head-mounted display or cave–type screen. The degree of immersion can be enhanced with HMD and cave-type screens from that with desktop screens. The immersion is also higher with stereoscopic view than without.

2.7.5 Health and safety issues of VE

The rapid development of virtual environment systems and their increasingly widespread application have also increased concerns for the health and safety of VE participants. In fact, there is as yet no agreement on a suitable bank of reliable, valid and robust test methods and criteria to assess any effect of VE participation or the consequences of these (Wilson 1996). There is some evidence of side effects such as disorientation, sickness and nausea when using VE, but scientific evidence is scarce (Wilson 1996). Mogal (1993) sees that delays in the VE system, giving lags of up to 250 ms, mean that the “expectation of the brain and reality move out of sync, resulting in possible significant adverse effects. There has also been some concern over behavioural change as a result of working in virtual environments. Suggested potential side effects are direct or indirect, short-or long-term, and musculoskeletal, psychological or physiological in nature. According to Wilson (1996) “it is unlikely that all virtual environments are potentially harmful by their nature, but some aspects may have greater side effects than the others, and some of these side effects may be disturbing or harmful”. Such problems should be identified and rectified by the developers, researcher and regulators (Wilson 1996).

Some visual function effects with HMD have been investigated and potential side effects have been found (Piantanida 1993, Wann & Mon-Williams 1997). Technical details such as refresh rate, latency of the tracking system, lags of sensors, and scaling and translational errors were studied in the 1990’s (Bryson and Fisher 1990, Encarnação et al. 1994, Kalawsky 1993b, Mon-Williams et al. 1993, Pimentel and Teixeira 1993, Moshell et al. 1993, Bolas 1994, Ellis 1994, Howarth and Bradbury 1994, Rushton et al. 1994, Wann and Mon-Williams 1997, Stanney and Hash 1998, Stanney et al. 1999). According to Wilson (1996) the VE systems have so many variables that it is impossible to distinguish among effects with the current state of knowledge, i.e. whether these are performance or health and safety effects. With the present or the future generations of technology there is no evidence that the consequences of any effects will be serious or long-lasting (Wilson 1996). In the literature suggested potential human factor issues resulting from VE use are presented in Table 6.

Table 6. Potential human factor issues resulting from VE use (Nichols and Patel 2002).

Addiction
Biochemical change
Blurred vision
Cardiovascular change
Changes in motor performance
Changes in perceptual judgement
Enjoyment
Equipment fit
Eyestrain
Frustration
Gastrointestinal change
Hallucinations and visual flashbacks
Isolation
Musculoskeletal discomfort
Participant attitudes
Perceptual shifts and disorientation
Postural instability
Posture demands
Presence
Respiratory change
Stress and mood change
Transfer of training
Visual changes
VR-induced sickness

The positive sense of operational use of virtual environments may be however of value for health and safety, e.g. (Wilson et al. 1995)

- ergonomic assessments of workplaces, interfaces and task, such as those in design for assembly or in workspace layout;
- training of maintenance engineers, for instance to work in hazardous environments;
- improved teleoperation planning and control;
- general training for industry, including safe procedures for material movements and use of machine guards;
- home or road safety education;
- rehearsal of error diagnosis and recovery in a process plant.

A number of social and ethical issues of utilising virtual environments have likewise interested researchers (Kallman 1993, Sheridan 1992, Whitbeck 1993). The issues concern e.g. the type of worlds provided for participants, responsibility of builders for providing the virtual world, and behavioural effects on participants such as dissociation, addictions, misplaced locus of control, hallucinations, and retreat from reality.

One task for the research community is to provide advice on appropriate VE technology for different applications. “For VEs in industry, it will be valuable to place participants in environments they cannot normally, or easily experience, to allow them to perform in ways not normally or easily possible, to enhance visualisation of and communication about a situation, and to allow exploration and different viewpoints for an environment” (Wilson 1996).

2.8 Task analysis

The better to understand work and its relationship to a process the task analysis concept has been introduced. Task analysis yields data on the demands imposed on the worker by a given job, and enables the elements of a work system to be identified and compared with those of other work systems (Landau et al. 1998). Some types of task analysis procedures are intended for use in forecasting the characteristics of and stresses likely to arise in new work systems still in the design phase.

When selecting a task analysis procedure it is necessary to distinguish between organisational items, work study and ergonomic terminology (Figure 17). The organisational definition relates to the functional actions of the industrial worker. The task represents a set of targets to be fulfilled. The work study definition adopts a variable time approach whilst the organisational classifies tasks into partial or subtasks. The ergonomic definition of a work task focuses on the man and work interface and regards the tasks as a description of behaviour, an aptitude test, a behaviour demand and a complex of stimuli (Landau et al. 1998).

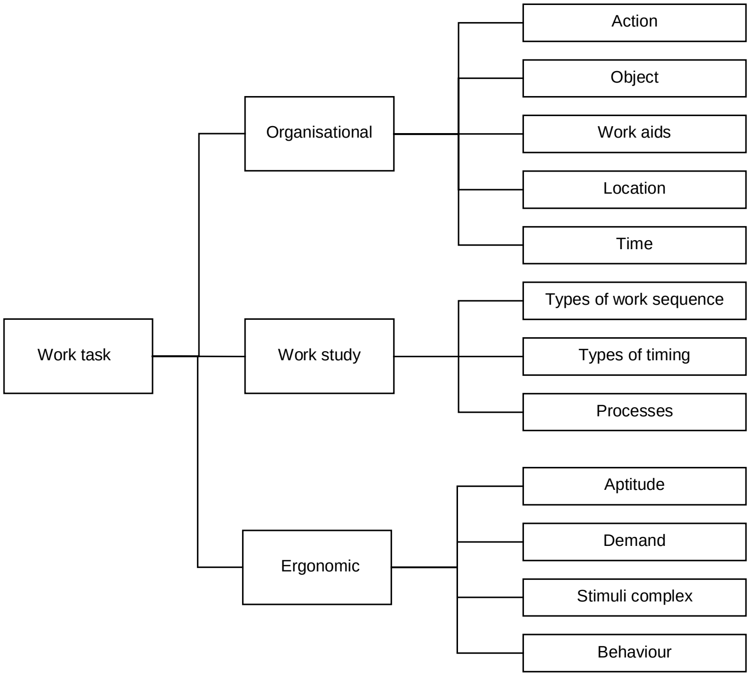


Figure 17. Definition and terminology of task analysis (Landau et al. 1998).

The concept of work consists of occupation, job, position, task and subtask or element (McCormick 1979). According to the definitions of organisational task analysis, each task (Landau et al. 1998):

- implies a given work activity, e.g. planning, analysing, preparing, assembling, etc.,
- relates to an object on which the expected activity must be performed,
- regularly involves the use of inanimate work aids employed to carry out the work process,
- can be classified in both time and space.

The organisational approach includes both task analysis and task synthesis (Figure 18). A work task is divided into partial tasks. These (or subtasks) are assembled into a bundle which can be delegated to specific persons or departments (positions).

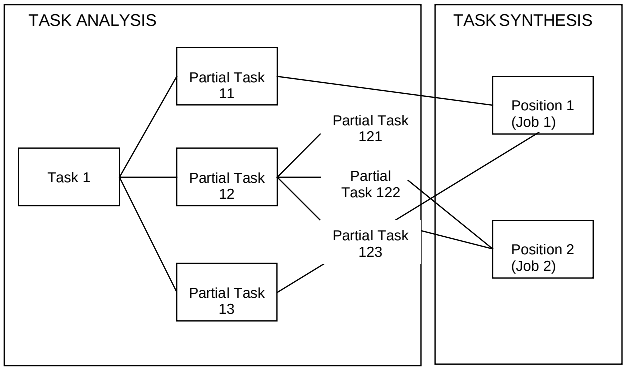


Figure 18. Task analysis and task synthesis (Landau et al. 1998).

In evaluating a work task a combination of technological, functional and information processing approaches can be used. Kirchner and Rohmert (1973) suggest that analysis of the relationship between various activities and general positioning of the job within the overall work process should be done stepwise.

The steps involved should include definition of:

- the job in general,
- the basic task involved in the job,
- the partial tasks involved in the job,
- the individual functions involved in the job,
- the special demands imposed by the individual functions,
- the special demands imposed by the overall job structure and its position in the work process.

There have been a number of different task analysis procedures. Landau and associates (1990) have collected a table of such procedures, comprising 23 different task procedures for different aims. These procedures are from the 1970’s up to the late 1980’s. Broader surveys of task analysis procedures have been published e.g. by Rohmert and colleagues (1975), Kenton (1979), Frei (1981), and Landau and Rohmert (1989).

The task analysis procedure involves classification of different jobs (McCormick et al. 1969, Frieling and Hoyos 1978), planning aid (Arent and Uhlemann 1974, Landau et al. 1975, Darmstädter and Nohl 1982, Wächter et al. 1989), identification of weak points or safety and health risks (Heinsalmi 1978, Häublein et al. 1979, Frieling et al. 1984, Bernhardt and Hoyos 1987, Elo 1989), identification of stressors (Frieling et al. 1984, Dunckel and Semmer 1987), relationships between different jobs and evaluation of technical or organisational changes (Greiner et al. 1987) and description of technical components and environmental factors with system analysis (Schmidtke 1975). Brauchler and Landau (1998) in their article on the scientific basis of task analysis concluded that a comprehensive task analysis can provide information on the undesirable components of a given job, better appreciation of the stresses arising in it and greater understanding of the tasks and requirements involved. There is not, however, no task analysis procedure satisfying all conceivable requirements of task analysis. In each individual case the user has to decide what kind of problem is to be analysed. Task analysis can and should therefore also be used with additional procedures (Brauchler and Landau 1998).

2.9 Safety analysis

Typically safety is defined as freedom from conditions which cause death, injury, occupational illness, damage to the environment, damage to or loss of equipment or property or as non-existence of risk. These definitions demand of a system absolute safety or zero risk. Safety is defined as being inversely related to risk; high safety implying low risk and low safety high risk (Thomson 1987).

It is generally recognised that reliability and safety are desirable qualities in any product and production system. They are related and mutually dependent. Failure is a key object in the context of reliability and accident in the case of safety (Shen 1986). Reliability and safety are closely related if a given function fulfils some important safety goals, i.e. failure of the specified function is capable of causing accidents. It can be roughly said that the higher risk there is in a system, the higher reliability is needed in safety measures (Reunanen 1993).

In determining risk, three essential questions may be posed (van Sciver 1990):

1. What can go wrong in terms of accident scenarios?

2. How likely is it that this will happen in terms of probability of occurrence of accident scenarios?

3. What are the consequences of this going wrong in terms of some measure of loss?

The activity of identifying relevant accident scenarios forms the qualitative element in safety analysis (Reunanen 1993). A number of models of accident phenomena have been proposed. Usually these include a chain of events which can cause accidents. A simple model of incident causation is presented in Figure 19. The chain of events is called the accident or accident scenario.

If human recovery is adequate to prevent an accident, the chain of events is called a near miss. Incident refers to a combined set of occurrences of both accidents and near misses. Sometimes only those chains of events which involve harm to people are called accidents (Kjellén 1983). According to many models and theories occupational accidents are predominantly system-type. An accident is seen as an abnormal effect of a system, the causes being defects in individual parts of the system or in the interaction between them (Kjellén 1983).

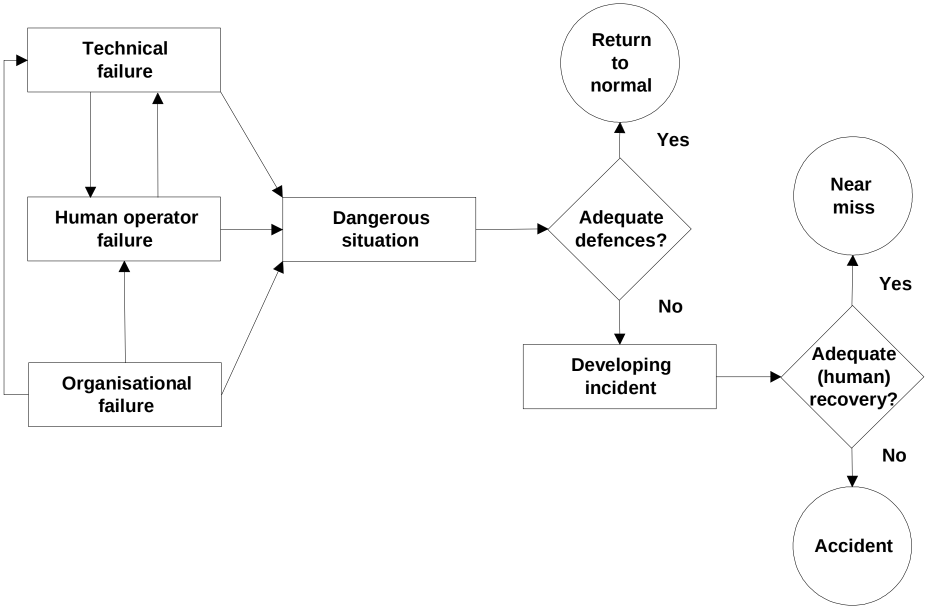


Figure 19. A model of incident causation (van der Schaaf 1992).

Shen (1986) has introduced a concept classification of safety issues based on the system approach (Table 7). According to this concept, to be useful, reference should also be made to the injurer-injured relationship speaking of the safety of something. Man, machine and environment can all be equally “injured” and “injurer”.

There are three basic models for accident phenomena, system model, process model and energy model (Kjellén 1983). The system model construes an accident as a system-based event. In the process model, again an accident is seen as a flow of events, which implies that the time factor is an important item in the description of an accident. Each particular accident scenario identified by some safety analysis method can be considered an instance of the accident model behind the particular analysis method applied (Reunanen 1993).

Table 7. Safety matrix (Shen 1986).

INJURER INJURED SAFETY	MAN	MACHINE	ENVIRONMENT
MAN	Personal safety against criminality, offence, war etc.	Personal safety against accidents, mishap, fire etc.	Personal safety against earthquake, typhoon, flood etc.
MACHINE	Equipment safety against violating instructions, sabotage	Equipment safety against potential defects etc.	Equipment safety against corrosion, deformation etc.
ENVIRONMENT	Equipment safety against nuclear tests	Equipment safety against industrial pollution etc.	Equipment safety against ecological crisis, abnormal climate

Specific safety requirements give the designer rules to apply for the design (e.g. Helander 1995). The systematic safety analyses provided, however, can not give assurance for the designer that the product to be designed is sufficiently covered by this type of requirements (Hale et al. 1990). Explicit exposure requirements give only the required level of exposure which has been arrived at the basis of epidemiological and toxicological studies. These requirements give no instruction as to the safety measures to be applied in order to reach the level required (Hale et al. 1990).

General safety requirements can be viewed as a whole set of requirements which together seek to cover all the possible threats to safety (Reunanen 1993). When this kind of approach is used, there is a need to carry out at least some form of semi-quantitative safety analysis (Hale et al. 1990). General safety requirements are introduced in order to avoid the rigidity of specified safety requirements.

Explicit safety requirements specify a numerical value of risk which must not be exceeded, and require that a quantitative safety analysis be carried out to prove that the design complies with the requirements (Hale et al. 1990). The list of requirements should be constantly reviewed and up-dated, because important findings, better understanding of solution possibilities, possible changes in emphasis etc. can lead to the modification of existing requirements and the addition of new ones (Reunanen 1993).

The type of information available during the design process is important and also has an impact on the choice of safety analysis. Table 8 gives an example of the information which becomes available through the design phases. Reunanen (1993) also introduced the human involvement problem, pointing out that this has received insufficient emphasis in systematic design methods compared to technical design problems.

Table 9 offers a tool for the selection of safety analysis for the various design phases as presented by Reunanen (1993). There are several different analysis methods suitable for each different design phase. According to Table 9 the most suitable methods in design phases are FMEA (Failure Mode and Effect Analysis) and FTA (Fault Tree Analysis), which are suitable for four design phases and for two design problems. The methods HAZOP (Hazard and Operability Study) and AEA (Action Error Analysis) are suitable for four phases and for one design problem. When human involvement is concerned AEA and WSA (Work Safety Analysis) are suitable for all phases.

These analyses are developed for safety issues. Some safety analyses such as HAZOP and WSA also include risk assessment. Risk assessment is according to the standard ISO 12100 (2003) an overall process comprising risk analysis and risk evaluation. Risk analysis for its part is defined as a combination of the specification of the limits of the machine, hazards identification and risk estimation (ISO 12100, 2003). The latter is a definition of likely severity of harm and probability of its occurrence (ISO 12100, 2003). Risk evaluation is a judgement, on the basis of risk analysis, as to whether the risk reduction objectives have been achieved. Risk assessment can be made several times during safety analysis (Figure 20).

Table 8. Available information during design phases (cf. Reunanen 1993).

DESIGN PHASE	**DESIGN PROBLEMS**					
	Working principle	Configuration	Embodiment	Material	Components	Human involvement
Clarification of the task phase	Establishing the specification					
Conceptual design phase	Selection of the working principle for the total product[1]	Selection of the principal configuration of the total product	Preliminary embodiment of the discrete parts, or the whole of the product	Preliminary selection of material for the discrete parts, or for the whole of the product	Preliminary selection of components for the discrete parts, or for the whole of the product	Preliminary allocation of tasks between product and operator
Embodiment design phase	Selection of the working principle for the discrete parts of the product	Selection of the configuration for the total product	Embodiment of the discrete parts of the product	Selection of materials for the discrete parts of the product	Selection of the components of the product	Allocation of tasks between product and operator Designing operator tasks and the equipment necessary to fulfil the tasks
Detail design phase	Completion of details of the product Evaluation of features of the product and redesign, if necessary					Establishing user instructions

[1] Production system can also be seen as a product (author's note)

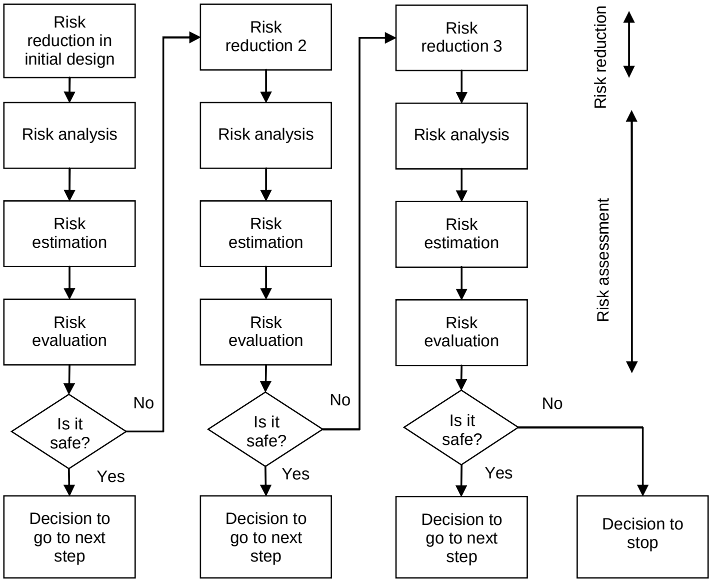


Figure 20. An illustration of risk assessment and risk reduction.

In considering human involvements in a production system Work Safety Analysis (WSA) is applicable (Table 10). WSA is a systematic investigation of working methods, machines and working environments in order to establish accident potentials and to enhance safety (Suokas & Rouhiainen 1984). In this analysis a work is divided into tasks, in which all possible hazards will be identified. Hazards are identified by observing the performance of work tasks and interviewing workers. WSA is suitable for developing work guides and, better work methods, for enhancing the safety of machines whether modifying an old machine or designing a new one. Applying the WSA method hazards in machines and equipment, and in work practices, and as well as hazards caused by the working environment can be identified.

Table 9. Chart for selecting the appropriate safety analysis method with respect to design phases and problems (Reunanen 1993).

DESIGN PHASE	DESIGN PROBLEMS		
	Working principle Configuration Embodiment Material	Components	Human involvement
Clarification of the task phase[1]	CCA ETA FMEA FMECA FTA HAZOP PHA PPA	FMEA FMECA FTA	AEA OHA WSA
Conceptual design phase	FMEA[2] FTA[3] HAZOP[2] PHA[2] PPA[2]	FMEA FTA[3]	AEA[2] OHA[2]
Embodiment design phase	AEA ETA FMEA FMECA FTA HAZOP PHA PPA	FMEA FMECA FTA	AEA MORT[4] OHA WSA
Detail design phase			

AEA = Action error analysis
CCA = Cause-consequence analysis
ETA = Event tree analysis
FMEA = Failure modes and effects analysis
FMECA = Failure mode, effects and criticality analysis
FTA = Fault tee analysis
HAZOP = Hazard and operability study
MORT = Management oversight and risk tree
PHA = Preliminary hazard analysis
PPA = Potential problem analysis
WSA = Work safety analysis

[1] Application of safety analysis methods for studying a company's existing products and competitors' products

[2] At a coarse or functional level

[3] At a qualitative level

[4] At a general level, mainly for the specification of the functions of the future organisation

According to the Guidelines (1992), Checklists, What-If method and PHA are suitable for the conceptual design phase (Table 10). Such analyses as HAZOP, FMEA, FTA, ETA, CCA and HRA are more suitable for the pilot plant operation, detailed engineering, and routine operation design phases. When expansion or modification is concerned all of the hazard evaluation techniques are appropriate. For hazard evaluation the what-if and checklist method suit at nearly all levels in a product’s life cycle. One example of a checklist procedure is given in Figure 21.

Table 10. Typical uses of Hazard Evaluation techniques (Guidelines … 1992) (HRA refers to Human Reliability Analysis, other abbreviations see Table 9).

	Safety review	Checklist	Relative	PHA	What-If	What-	HAZOP	FMEA	Fault tree	Event tree	CCA	HRA
Research and development	○	○	●	●	●	○	○	○	○	○	○	○
Conceptual design	○	●	●	●	●	●	○	○	○	○	○	○
Pilot plant operation	○	●	○	●	●	●	●	●	●	●	●	●
Detailed engineering	○	●	○	●	●	●	●	●	●	●	●	●
Construction/Start-up	●	●	○	○	●	●	○	○	○	○	○	●
Routine operation	●	●	○	○	●	●	●	●	●	●	●	●
Expansion or modification	●	●	●	●	●	●	●	●	●	●	●	●
Incident investigation	○	○	○	○	●	○	●	●	●	●	●	●
Decommissioning	●	●	○	○	●	●	○	○	○	○	○	○

○ Rarely used or inappropriate
● Commonly used

A new systematic safety analysis method called Safety Function Analysis (SFA) has also been developed and implemented for analysing systems to identify and evaluate hazards and safety characteristics (Harms-Ringdahl 2001). The method will improve the understanding of the system by a model of its safety features and will thus provide a basis for estimations and ideas for improvements.

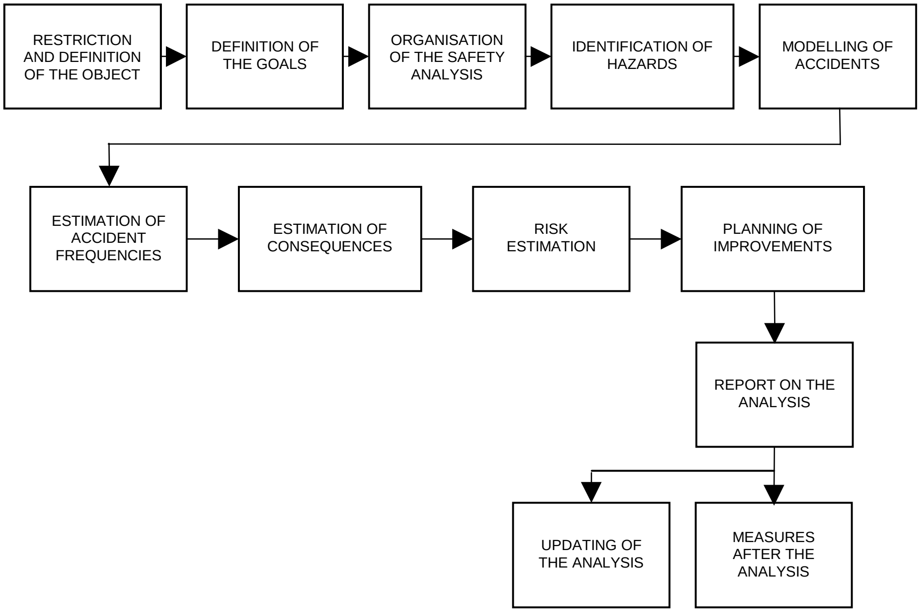


Figure 21. The checklist procedure in accordance with the phases of safety analysis (Rouhiainen 1990).

Safety analysis can be of benefit during the whole design process. The majority of safety analysis methods can only be used as analysis tools, i.e. that before their application something must already have been synthesised by the designers. Safety analysis methods have been developed to provide for systematic examination of new products and processes and old ones when modifications are planned beyond the experience base. However, experience has generally shown that analysis does not prove safety or guarantee reliability; it provides supporting evidence and assurance (Watson 1992).

3. Scope and objectives

The field involved in this work is on safety engineering. The work also has impacts to mechanical engineering, production engineering, information technology, design methodology and work group methodology. It comprises part of research activities on production systems and its implications. The work is focused on machinery system design and especially on the phase of evaluation designs prior to installation.

The main objective was to study means of enhancing the safety analysis procedure in the design phase of a machine system with virtual environments. The purpose was to establish how virtual environments impact on the analysis process and how visualisation by computer modelling can be effectively used.

A study was made of the implementation of virtual environments (VEs) in safety analysis during investment projects in the steel industry. The main interest focused on an evaluation of the impact of the Virtual Environments (VEs) and Participatory Ergonomics (PE) approach on safety analysis during the design phase. Virtual environments were applied in three modes, i.e. using only 3-D models, using additional simulation and using digital human models in VEs. Three modes for visualising virtual environments were selected to study their implementation in safety analysis, namely screen, simulator with head mounted display and laptop screen with stereoscopic view with special lenses. These applications were selected according to the author’s previous experiences and knowledge of the use of VEs in industrial applications.

The specific objectives were as follows:

1 To provide a new procedure for machinery safety analysis, adopted by users in order to train them to identify hazards and to use the new manufacturing system safely.

2 To provide new knowledge of the use of a participatory approach when computerised visualisation is employed in safety analysis.

3 To provide new knowledge of the role of computerised visualisation in the safety analysis process.

4 To provide new knowledge of the role of the digital human model in safety analysis.

4. Theoretical framework

The framework of this thesis comprises a product and production design operation, which follows the human-centred design approach. The approach includes participation of the workers in the design procedures. This study concentrated on developing methods for safety analysis during the design phase of a product or production.

This work has received impulses from engineering, social science, safety engineering, safety management, safety culture and information technology research. The basic is the system theory. The target system should be divided into subsystem elements and also evaluated in respect to factors outside the systems. This work applies a systematic design principle, a socio-technical design approach and a participatory approach.

The design procedure theory based on the work of Pahl and Beitz (1977) includes a systematic approach to design and features in the recommendation VDI 2222. This recommendation is widely accepted in the engineering field and describes the general design procedure of a product. It is also applicable in system design.

The study applied the socio-technological approach to design. This is based on the idea that the system comprises two subsystems, namely technological and social systems, which complement each other. The people in the social system have social and psychological needs such as the possibility to participate in decisions, to learn, to vary work tasks, to see the importance of the work and to see envisage future prospects (van Beinum 1988).

The participatory design is a procedure where persons working with the same production process or machine or use of a product or a similar one which is in the design phase, have the opportunity to take part of the design process and can influence the design and development of the target. The participatory approach calls for further development and tools for application in industry. This work is an attempt to enhance the usefulness of this approach to safety analysis by applying new procedures and new visualisation tools. Visualisation can have a major role in enhancing mutual understanding in a work group. As a visualisation tool in safety analysis with the participatory approach virtual environments were applied.

Figure 22 indicates the framework of this thesis. The shaded boxes present the focus of the work.

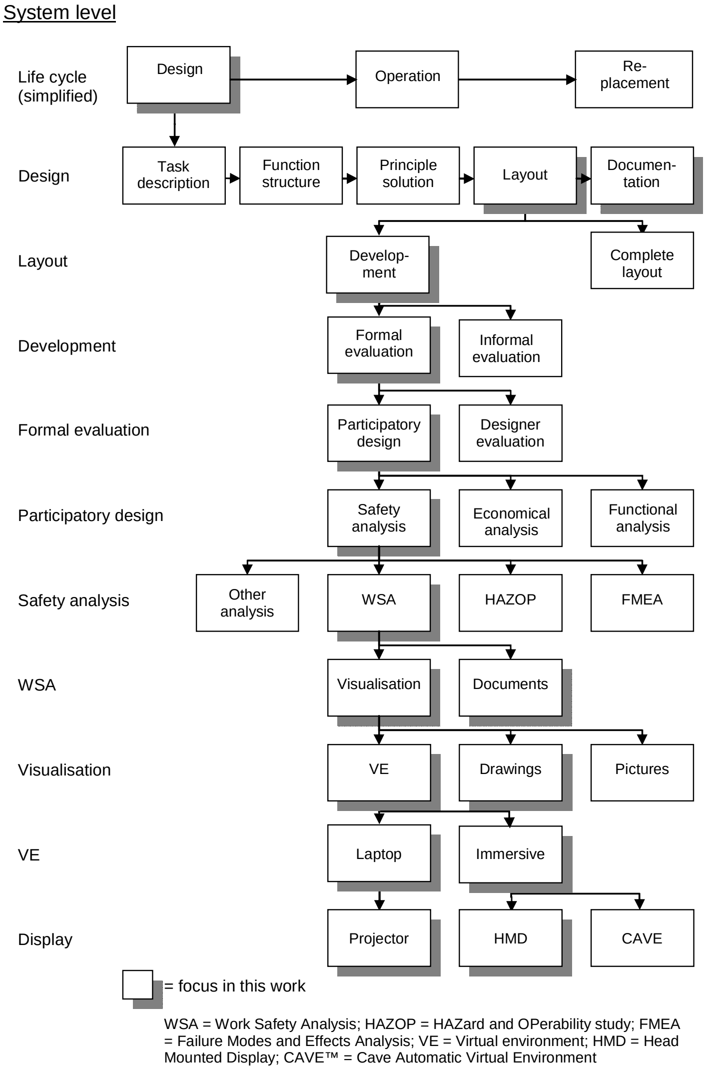


Figure 22. The focus and system levels in this work regarding the design process.

This work focuses on the design phase of a system life-cycle. The focus in design was on the system development phase, where the layouts of key modules will be developed. The plans were evaluated by a formal evaluation procedure and participatory design approach. Evaluation included safety analysis by Work Safety Analysis method, which was complemented by visualisation tools and documents. As visualisation tools virtual environments and drawings were used. The focus in using VEs was intended to implement both desktop and immersive virtual environment technology. Projector screen and head-mounted display (HMD) were used as display technology.

The case study arrangements included three different situations (Figure 23). In safety analysis two methods were applied in the case studies. In the first two cases the hazard identification method based on the EN 1050 hazard list was employed. In other case studies the work safety analysis method (WSA) was applied.

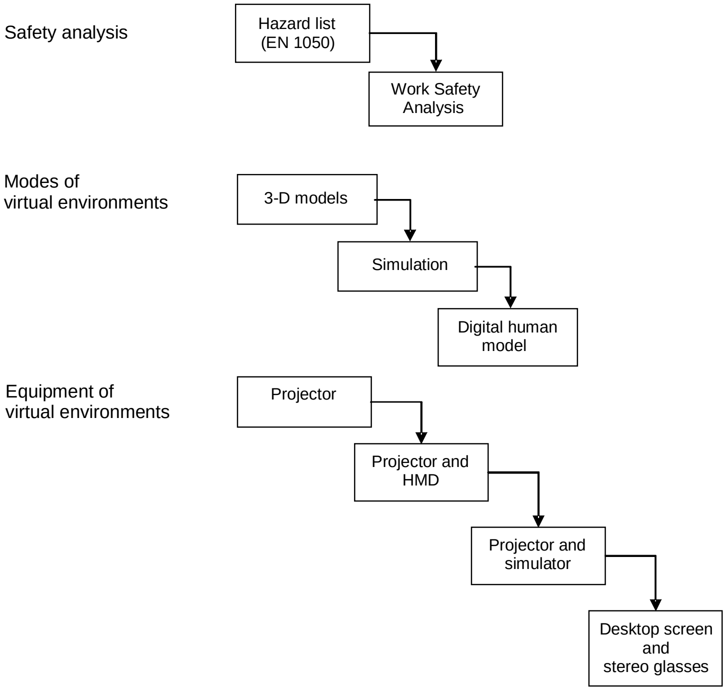


Figure 23. Case study arrangements (see text).

The modes of the virtual environments were 3-D models, simulation and digital human models. This means that when applying VEs at least 3-D models were used in all cases. In addition, simulation or digital human model could be applied in all cases with 3-D models. Desktop, projector screen and HMD modes of displays were used to create the immersion, i.e. illusion of being inside the model. Stereoscopic view was also applied in some cases as demonstration when using desktop display and HMD. In most cases screen and projector were applied.

5. Materials and methods

5.1 Materials

The materials for this work are the seven case studies performed with the company during the years 1995 to 2000 at a steel factory (Table 11). All the cases were interconnected to modernisation projects in the company.

The aims of these projects were to improve production efficiency and occupational safety. The modernisation projects contained the basic planning, planning of the equipment, manufacture, delivery and construction supervision, and introduction of a new plant and training. This work was included in the evaluation stages of planning and concentrated solely on safety issues in the new systems. The goal of the case studies was to obtain a thorough evaluation of safety when working with the new machinery systems, identifying all the possible hazards connected to its operation and maintenance. In addition the aim was to collect the main identified hazards and a list of necessary measures by which the hazards could be removed or the effects minimised. The analysis concentrated solely on the main hazards, but all possible risks were to be identified. The main hazard was defined as risk level two or higher according to the analysis.

The case studies are here presented in the order, where the development projects were activated. The first case was a steel converter case, which concentrated on improvement of the safety of operations during processes. High potentials for hazardous situations were initially identified and further actions were to be designed. The company had decided to invest in a new control room. A change in operation of the cranes was also planned in the case.

The second case included analysis of safety during critical lifts in the converter plant and continuous casting plant. The company had decided to invest in up-dating two overhead cranes. The third case included a safety analysis of a new turntable in the continuous casting plant. The table would be larger and function differently than its predecessor. There was also new additional equipment to be designed for the casting process and evaluated during the safety plan. The fourth case comprised a new machinery system for steel degassing to be installed between two plants already in production. The case also included evaluation of the change in crane operation. The fifth case constituted a situation where a new coilbox machine would be installed between the rolling processes. The sixth case involved a new coil conveyer system to be installed in place of the former conveyer. In the seventh case the process was planned to be modernised with new machines and a new additional process. The controlling system of the cranes was also to be changed during the project.

Table 11. Description of the case studies in this work.

Cases	**Plant**	**Description**
Case 1	Steel Converter	The steel converter process hot metal and steel scrap into molten steel by oxygen blowing
Case 2	Critical Lifts in Casting Plant	The molten steel is conveyed in steel ladles which are lifted by cranes from ladle cars to casting machines
Case 3	Continuous Casting Machine	Molten steel is cast by a continuous casting method into strip form (slab) with a specific casting machine
Case 4	Vacuum Degassing	The hydrogen and/or carbon in the molten steel is removed by vacuum handling method and exact amount of alloys is added
Case 5	Coilbox	The steel strips are rolled into coil with a coilbox machine. The same machine opens the coil and feeds the strips to the strip rolling machine
Case 6	Coil Conveyer	The coils are moved from down coiler to storage
Case 7	Hot steel storage	The raw steel from the blast furnace is mixed to the required iron alloy and stored in mixers, in the same plant is a sulphur replacement unit, which removes as much sulphur from the iron as possible

The cases included about half of the steel manufacturing processes. The steel manufacturing processes and the processes included in this work are presented in Figure 24.

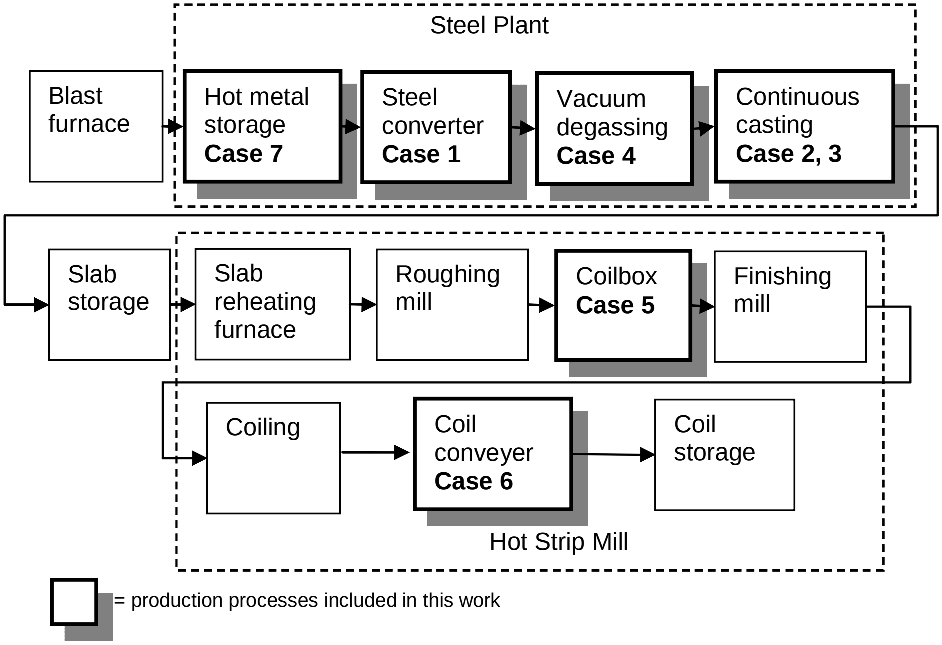


Figure 24. A schematic description of the basic process in the steel works.

The cases in this work are carried out according to the schedule of the factory investment projects and are so carried out in separate order than in the manufacturing process. This is to illustrate the possible development when implementing SAVE method in cases.

5.1.1 Case 1: Steel converter plant

The converter plant consisted of three converters and a material handling system to feed the converters with raw iron material and scrap. The operations of the converters were controlled from cabins situated at mid level and across the converters. The operations of the cranes were arranged in the cranes above the converters. These arrangements involved a high explosion hazard with the converters if scrap-iron with water and high humidly were unintentionally used.

There was a need to improve the safety of the operation in the cabins as well as on the plane of converter handling, which included work with alloys and temperature measurements. The solution to improve safety was to situate the operation rooms in safer places. There was uncertainty as to whether this new location carried new safety hazards and how operations could be safely performed.

The goal of the safety analysis was to identify all hazards with the old installation of the operation rooms for converters and cranes, to plan a new operation room for the converters and cranes, train the operators in a new mode of handling converters and cranes with the new operation rooms, and to improve knowledge of identifying hazards in the plant.

Drawings, photos and video-recorded images from the previous plan situation were used as materials for the modelling. A view to the converter plant is presented in Figure 25.

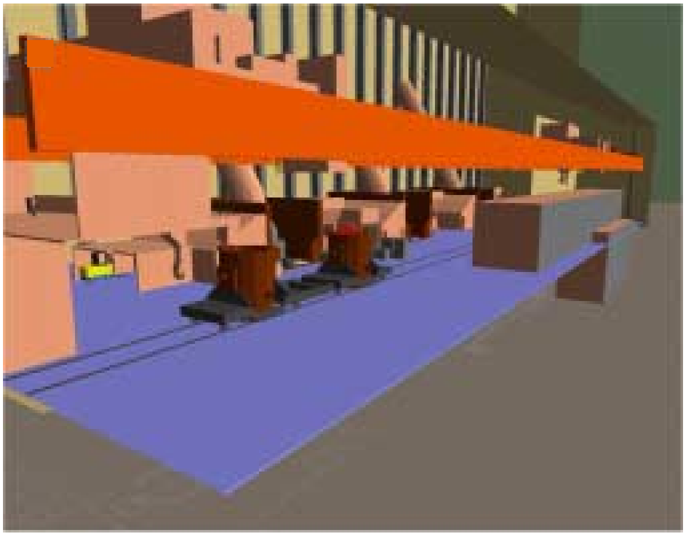


Figure 25. A view of the steel converter plant in a 3-D model used for safety analysis.

This case was the first of the series conducting safety analysis with virtual environments. In the Case 1 the specific emphasise was to study the influence of visualising the functions of the machinery for the analysis group. The views from the cranes and from the operation room in different solutions were also of interest.

5.1.2 Case 2: Critical lifts in continuous casting plant

The casting plant included several casting machines. The process with the casting machine was continuous by changing the steel ladle in turntable so that molten steel was conveyed through tundish to the casting machine continuously. These turntables were to be changed and the overhead cranes of the plant modernised with new motors, electrical systems and operation cabins. The crane operations with new tables and new schedules were to be checked for safety. Figure 26 presents an example of the views from the casting plant 3-D models.

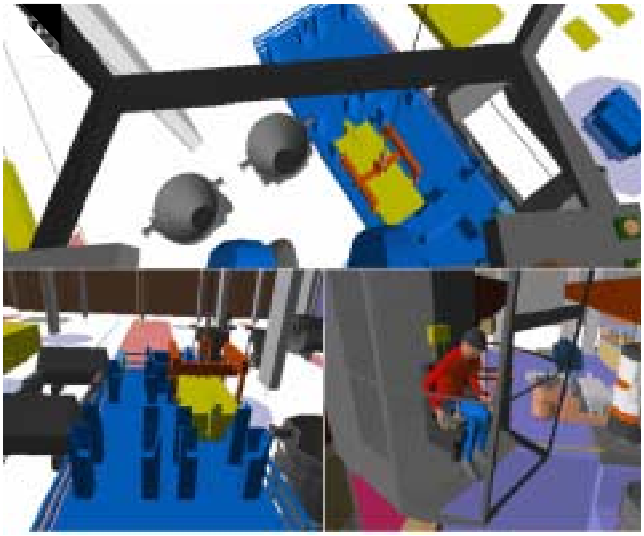


Figure 26. Examples of operator's views with the crane simulator used for safety analysis.

In the Case 2 special emphasise was to study how simulator type VEs can be implemented in safety analysis and how the participants response to simulator type analysis. All participants, including the project manager and safety specialist, used the simulator. The crane operators operated the crane simulator during the safety analysis sessions. The critical phases of work tasks were analysed with several virtual operations in the simulator

5.1.3 Case 3: Continuous casting machine

There were two types of casting machines in the continuous casting plant, differences lying in the turntables, i.e. ladle turrets, and capacity. During the project a new casting machine with higher capacity was to be installed in the same place as the previous machine. The new machine was the most modern continuous casting machine in the world at the time. The machine was larger than the former and had a new kind of ladle turrets with two different arms on the same shaft. Also the ladles had higher capacity and thus new dimensions.

With this machine the steel strand was cast by the so-called constant method. After casting the strand was cut into the slabs for follow-up processing. In this process the steel is cast through a mould from a tundish. To insure a continuous casting process one two arm ladle turrets for the ladles was used. When one ladle arm has a full ladle the other ladle can be removed without disturbing the casting operation. All ladles were removed in the same way. Figure 27 illustrates with a 3-D model the continuous casting machine from the top side where the ladle turret was situated.

The functions connected to the casting process, preliminary tasks, follow-up procedures and maintenance were performed in four levels or areas. At the first level the ladles were removed by crane lifts to their lifting and removing places. From this level the ladles were lifted by crane lifts onto the ladle turrets on the second level. On the third level of the process the steel blanks were cut down to sample pieces and for the follow-up manufacturing process. At the fourth level maintenance tasks were performed. The plant was operated in three shifts.

Figure 27. A view to the continuous casting machine with the 3-D model used in the safety analysis.

The company had decided to invest in increased production, advanced procedures and enhanced quality and safety. The manufacturer of the machines provided an EC declaration of conformity and safety instructions. To ensure the safety of the new installation the company has decided to make its own safety analysis of tasks connected to the new machines.

The analysis concentrated on lifts, casting tasks and the cutting and handling of samples from the strip. The lifts consisted of those lifting and moving the tanks from the carriage to the winding table or heating place and back, lifts connected to the replacements of the segments, lifting and moving suppliers and other lifts connected to the maintenance. The installation of the machine was defined as out of the scope of the analysis.

5.1.4 Case 4: Vacuum degassing plant

To obtain the precise characteristics for steel e.g. carbon and hydrogen in it must be removed. This could be arranged by using vacuum handling for the molten steel. During the vacuum handling the hydrogen and carbon are processed away from the steel. The plant also had a ladle furnace where the molten steel was warmed to the temperature needed in the process and mixed to the right steel composition.

The process included heavy lifts of a ladle from a ladle car into the heating unit and when necessary also from heating unit to the vacuum handling unit, and back to the ladle car. The operation of the crane was planned to take place from the crane cabin, but operation on the work plate should also be possible. The whole process was managed in an operation room, where different moving, adjusting and mixing functions were controlled. Figure 28 illustrates an example from the 3-D model of the plant above the overhead crane.

The new plant unit was sited between the steel converter and the continuous casting plant area. The process was new for the company and included up-to-date control systems. The space for the plant unit was restricted by the old factory layout with its pillars and walls. The process timetable was designed to be adjusted to the cycles of the converter-casting process as little disturbing as possible.

Figure 28. A view of the vacuum degassing station in the 3-D model used for the safety analysis.

5.1.5 Case 5: Coilbox

The steel factory also had a hot strip mill. There strips from steel slabs were rolled with rolling mill facility. The company had decided to increase coil weight to 30 tons. That is why transfer bar length was increased up to 120 m and thus the need for roller table space was increased. To handle the longer transfer bar in the same space during the rolling process a coilbox machine was installed in the production line. The coilbox had two coil stations: coiling and uncoiling. The speed in the coiling station was about 5 meters per second (m/s) and in uncoiling 1 m/s. The thickness of the transfer bars could be varied from about 20 mm to 40 mm. The width was less than 1900 mm. The coilbox was so-called mandrelless machine, in which the transportation of the coil between the stations was designed to take place by movable rolls. The process was controlled by an automation system. Figure 29 illustrates with 3-D model the coilbox with one coil in coiling and the other coil in uncoiling station.

Figure 29. A view of the coilbox machine in the 3-D model used for the safety analysis.

The analysis of the coilbox machine included coiling and uncoiling processes, and the removing of a cobbled coil from the machine. The safety analysis of the maintenance included replacing work of the coil opening equipment (peeler) and different coiling and uncoiling area rolls. The basic installation of the machine was excluded from the safety analysis.

5.1.6 Case 6: Coil conveyor system

The company were increasing their annual production by about 25% e.g. by raising the coil weight from 20 to 30 tons. This change caused the replacement of the existing coil conveyor system. The company decided to raise the automation level of the system at the same time. The system consisted of handling coils from the down coiler to the coil store. Conveyor was about 200 m long and was planned to operate as automatically as possible. Figure 26 illustrates with 3-D model the coil conveyor system.

A coil lift car moved a coil from the down coiler to a waiting position, where the C-car moved coil to a chain conveyor. The chain conveyor moved the coil to a coil lift, which lifted the coil to floor level on to walking beam conveyor. Waking beam conveyor moved coil step by step from one point to another. The coil was turned, strapped and marked in four stations. The coil conveyor system consisted of coil cars, C-car, chain conveyor, coil lift, walking beam conveyor, turning machine, coil rotating machines, strapping machines, marking machine and binding machines and trucks. Operators of the system were placed in a special control cabin near the conveyor. Figure 30 illustrates with 3-D model the coil conveyer system.

The information given by the supplier and supplementary data given by the company were included in the safety analysis. Also printed forms, block diagrams and three-dimensional models were used in the procedure. The analysis included all the main work tasks during the operation and maintenance of the new coil conveyor system.

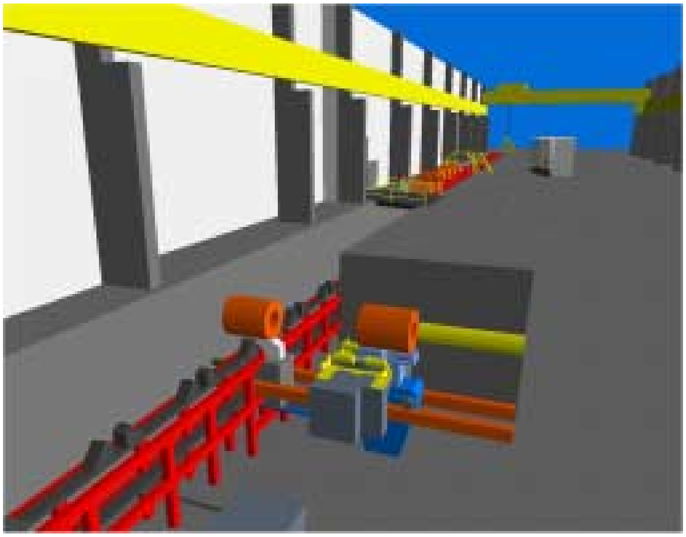


Figure 30. A view of the coil conveyor system in 3-D model used for the safety analysis. The coil car is moving a steel coil to the conveyor.

5.1.7 Case 7: Hot metal storage

The steel plant comprised two hot metal storages (mixers) (á 1300 t). There were two projects, which included modernisation of the mixer plant and installation of a new desulphurisation plant connected to the mixer. The steel plant delivers all slabs to the rolling mills for plate and strip production. The new hot metal desulphurisation plant operates in the production rhythm of the converters and casting machines.

The modernisation project involved installing new equipment such as tilting machines and slag hoe machines, and a new operation room for the operators, who operate cranes, tilting and deslagging machines at the same site. The procedures at the mixer plant included operations such as positioning a car, movements (lifting, lowering and tilting) of the hot metal ladle, deslagging, tapping to the mixer, tapping from the mixer, setting a ladle, and movements of the car into and out of the desulphurisation plant. Figure 31 illustrates with 3-D model the hot metal mixer plant.

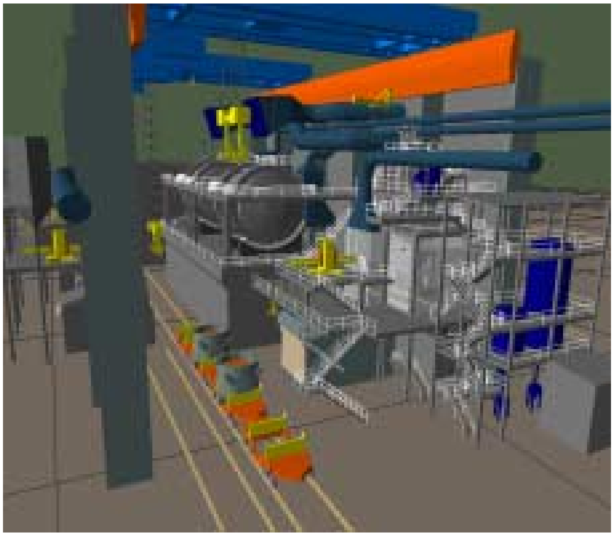


Figure 31. A view of the hot metal mixer plant with the 3-D model used in the safety analysis.

The desulphurisation unit project consisted in installing a whole new unit inside the hot metal mixer plant. The plant comprised equipment such as lance apparatus, pressure transmitter and storage bunkers, tilting mechanism, remote-controlled maintenance hoist, and sampling and temperature measuring devices. The project also included exhaust gas removal system.

5.1.8 Safety analysis groups in cases

The safety analysis groups consisted of project manager, foremen, designers, company's safety specialists, and operators. The project managers and at least three operators participated in all groups and analysis sessions. Other group members participated in most of the sessions. The participations in each case are presented in Table 12. The number of workers in the groups varied from 3 to 5, mean value 3.7, the number of foremen from 1 to 3, mean value 1.6.

Table 12. Description of the participants in the respective cases.

Case	Participant *)						
	PM	FM	WR	SE	DE	Sum	RE
Case 1	1	1	4	1		7	2
Case 2	1		3	1		5	2
Case 3	1	2	4	1	2	10	2
Case 4	1	3	5	1	3	13	2
Case 5	1	2	3		2	8	2
Case 6	1	2	3		2	8	2
Case 7	1	1	4	1	2	9	2
Sum	7	11	26	5	11	60	

*) PM = Project manager
FM = Foreman
WR = Worker
SE = Safety technician
DE = Designer
RE = Researcher

As some participants had also taken part in several cases, the sums are only the number of persons in the groups. Altogether 32 different persons participated in the cases. In addition 5 persons participated in only one or two sessions. These were deputy participants or specialists on certain issues to be handled during the session. The author took part in all cases. The person of the second researcher varied in some cases. The group sizes were from 5 to 13 persons, average age 41 years and the mean time in present employment 12 years. The average number of sessions was 6, range from 4 to 8 in the respective cases. The average frequency of participation of the persons in a group was 5 sessions during the safety analysis. In Cases 2 and 7 two different female persons took part in the safety analysis sessions. All other participants were males.

5.2 Methods

The methods employed in this work comprised method development and implementation, observation during implementation, and interview and questionnaire after the case studies. The method included implementing participatory ergonomics and virtual environments in safety analysis. The research was carried out during the years 1995 to 2001. Figure 32 illustrates the implementation phases of the method, and the span of the case studies, interviews and questionnaire.

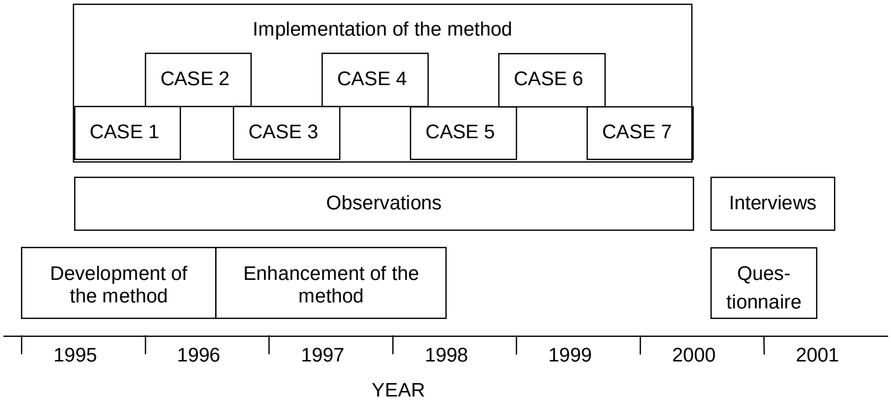


Figure 32. The span of the method in this work.

Development of the method included implementation of standard EN 1050 as a hazards identification tool, and also of the participatory approach and VEs when applying task analysis (TA) and works safety analysis (WSA).

5.2.1 Method of machinery safety analysis

A new method for the safety analysis of machinery was developed in this work. Its structure is illustrated in Figure 33. The method involves a combination of four elements: participatory ergonomics, task analysis, safety analysis and virtual environments. These elements are active concurrently as an integral evaluation procedure.

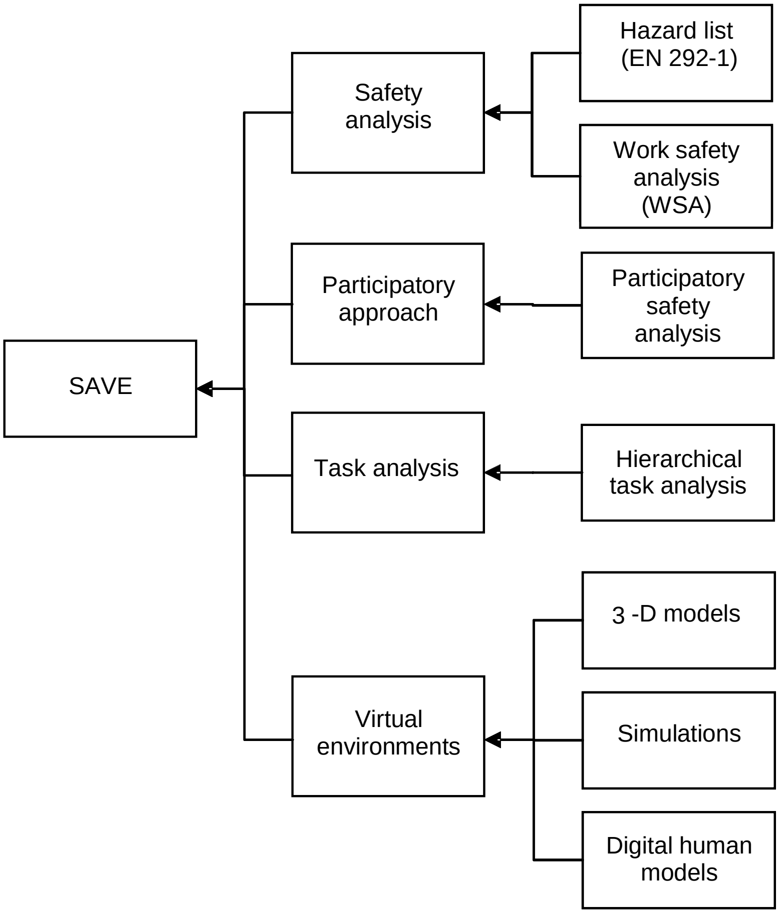


Figure 33. The structure of the SAVE method.

The SAVE method implements the participatory ergonomics approach, task analysis method and virtual environment technology in work safety analysis. The acronym SAVE stands for Safety Analysis and Virtual Environments.

All parts of the method can be used separately, the SAVE method being in effect a combination of these approaches and methods. The new feature for safety analysis is the use of VEs during the analysis.

5.2.1.1 Safety analysis

The approaches implemented in this work were a hazard identification method according to the standard EN 1050, and the work safety analysis WSA. First hazard identification with the hazard list in the standard EN 1050 was introduced to the group and a short training period was given. After analysing the systems with the list in Cases 1 and 2 the WSA method was implemented in other cases. An example of the WSA form is presented in Appendix A. The WSA method was supported by task analysis (TA) to enhance the description of new jobs and work tasks.

Altogether 6–8 times the groups had their meetings with the researcher and in addition 3–5 times with the project manager. The first two analysis meetings considered manufacturing functions and work task identifications. Meetings after these preliminary sessions included analysis of hazards during work tasks according to the hazard list presented in the EN standard (EN 1050) and preliminary plans for safety measures.

Estimation of risk was conducted as a function of probability and consequences (R = P x C). The scale of risks was as follows (Table 13):

Table 13. Risk index and specification.

Risk index	Specification
1	Extremely low
2	Fairly low
3	Moderate
4	High
6	Markedly high
9	Extremely high

Probability (P) was scaled in three levels, presented in Table 14. The minimum value on the scale was 1, which indicates that an incident may occur once in the operational time of the machine or environment. The value zero was not used; zero value would indicate that no incident would ever occur.

Table 14. Probability and specification.

Probability score	Specification	Description
1	Possible	May occur once in the operational time of the machine
2	Probable	It is assumed to occur sometimes during the operational time of the machine
3	Very probable	It is assumed that an incident will occur several times during the operational time of the machine

Consequence (C) is scaled as presented in Table 15. The scale also has three levels, the minimum value indicating minor influence on the health of person or persons but no influence on the process. The maximum value indicates severe injuries, death, serious effects on the production, and long term shutdown period.

Table 15. Consequence and specification of risk.

Consequence score	Specification	Description
1	Minor	No influence on the process, minor influence on the health of persons
2	Moderate	Moderate accident or incident, moderate influence on production, short shut-down period
3	Severe	Severe injuries, death, severe influences on production, long term shut-down period

All the possible hazards were identified with the EN 1050 list (Case 1 and 2) or with the WSA method (Case 3, 4, 5, 6 and 7). The hazards were listed and the risk were estimated in the forms which included also the description of safety measures (risk reduction) that have been already undertaken or should be developed before or after the installation of the system depending on the risk estimation, the availability of technology and costs. The risk evaluation after the risk reduction was left to the company and did not include in the case studies

5.2.1.2 Participatory safety analysis

The procedure involved group work in which persons with different background of work history and education participated. The company selected the persons for the group, but the researcher gave some basic guidelines in the early stages of selection. The group was to include 2–5 workers who would work in the department in the future and who had several (5–10) years of experience in the same kind of job and work environment, designers, project manager, foremen, safety experts, and the researcher as consultant and secretary. The number of workers was dependent on the process in question, so that when the system had several machines and work tasks, more workers participated in the group, and when maintenance was of special interest, from 1 to 3 workers in that department were invited to the group. The group would thus comprise 6–12 persons. The work involved from 5 to 10 meetings during a project.

The analysis groups consisted of personnel from different occupational backgrounds such as:

- *Design and development*: designers of production, automation and manufacturing, and managers of research and development
- *Production and manufacturing*: managers of production and manufacturing, foremen, workers
- *Maintenance:* managers, foremen and workers in maintenance
- *Occupational health and safety:* safety managers, safety representatives, safety specialists, physiotherapists
- *In-plant training:* job trainers, training managers.

During the meetings members were encouraged to participate actively, and to comment and suggest ideas. Solutions were called into question and discussed in detail. Every participant was encouraged and expected to make comments. The situation of the analysis work in the whole investment project was explained to all the participants. This also included clarification of the equality of the participants during meetings. The researcher acted also as a chairperson in order to establish neutral atmosphere during the meetings. Designers who had made the designs in hand were encouraged to report the backgrounds, basic requirements and the solutions of the designs, although most of the drawings were from the supplier. The meetings had a schedule from 3–6 hours, with the normal breaks in a working day. Some of the participants attended the meetings one half of a shift when they were on morning shift. For some the meetings constituted overtime work between shifts, but only during their day-off time.

5.2.1.3 Hierarchical task analysis

The task analysis conducted here was applied to support the WSA method as WSA is based more on observation of a work in situ than on work in the design phase. The task analysis included description and conceptual modelling of the production process, description of the work tasks, and evaluation of tasks critical for the production process. A flow chart description of the process entailed tasks was created (Figure 34). The whole process was divided into tasks and subtasks. The critical tasks were identified by the analysis group and evaluated in relation to the process.

The flow chart was designed to illustrate the process to the members of the analysis group. The chart is followed through by step-by-step procedure defining first the starting task and continuing with all relevant tasks, including subsidiary assignments. This was an iteration process where all participants could contribute to the identification of tasks. Task analysis can be performed for an ongoing or a new work process.

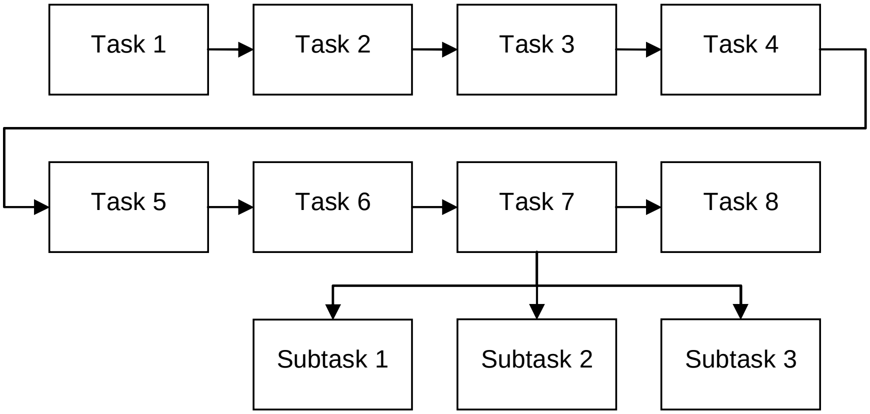


Figure 34. Example of task description with tasks and subtasks, and the interconnections with different tasks.

Task analysis was implemented in the case studies to identify all the tasks in the new process and to assist in the design of jobs (positions) and tasks.

5.2.1.4 Virtual environments

Virtual environment system

The work was carried out with a VE system, which included software and hardware based on the technology on the market. The system configuration is presented in the Figure 35. The system consisted of work station computer (Computer 1) Impact® (in Cases 5 to 7 Octane®, Silicon Graphics Inc.), modelling and simulation software Envision® (Delmia Inc., previously Deneb Inc.) and Head Mounted Display Eyegen3® (Virtual Research System Inc.), tracking system Motion Star® (Polhemus Inc), and projector (Maximum). More detail is given in Table 17 and Table 18.

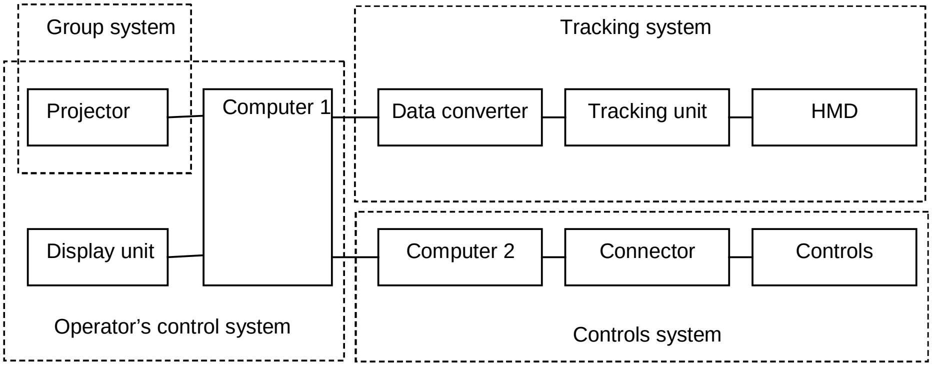


Figure 35. The VE system configuration.

The system was divided into four subsystems. The operator's control system consisted of main computer (SGI), display unit and VR software. The tracking system consisted of head-mounted display, tracking unit and the data converter unit. The control system consisted of control equipment, connectors and the PC-level computer (Computer 2). The group system consisted of projector and screen.

These subsystems were utilised in three levels of immersion: "high level immersion" with HMD and tracking system, "mid level immersion" with stereoscopic views with shutter lenses and desktop display and "low level immersion" with only projector views without stereoscopic display. The simulator use was considered as a high level of immersion use.

The virtual environment system was built with the purpose of using 3-D models, simulation and digital human models in safety analysis processes. The structure of this system is presented in Figure 36.

The VEs system was developed initially during other research projects and was implemented and developed further during the case studies of this work. The 3-D models in the case studies were built according to the drawings and pictures of the target systems. The size of the models varied from 29 953 polygons to 106 718 polygons. The amount of polygons was dependent on the size of the analysed system, elaborateness of the model and version of the software.

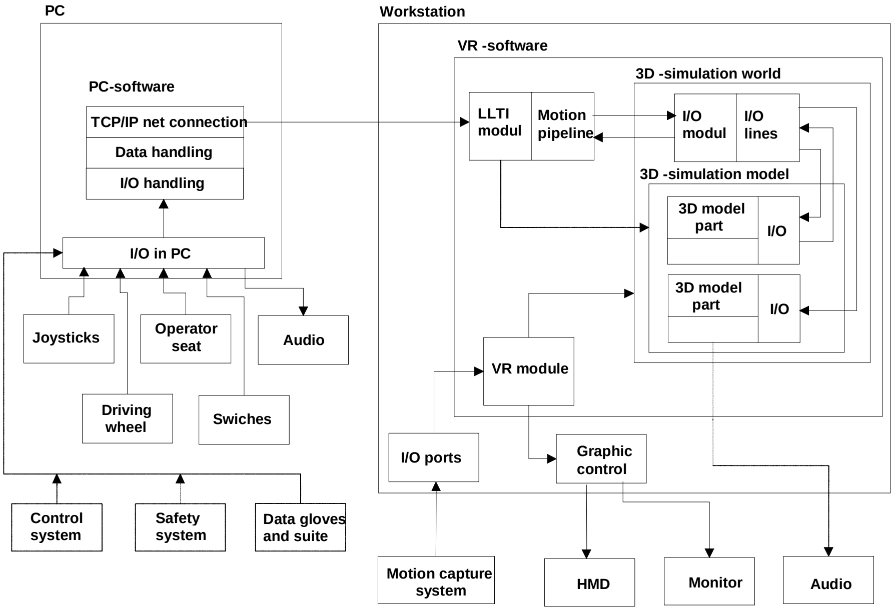


Figure 36. The virtual environments system structure (Helminen 1997).

The digital human model of the software was applied only in static mode. The dimensions of the digital human model with its six different modes were based on international anthropometric statistics.

Desktop virtual environment system

The virtual environments were introduced to the safety analysis group with projector images on the screen and in specific situations also displayed with stereoscopic view to desktop or in HMD. Figure 37 represents an example of a situation during the safety analysis with virtual environments. The arrangement in the Figure 34 is an example of the desktop virtual environment. The desktop virtual environment system consisted from operator’s system and group systems presented in Figure 35.

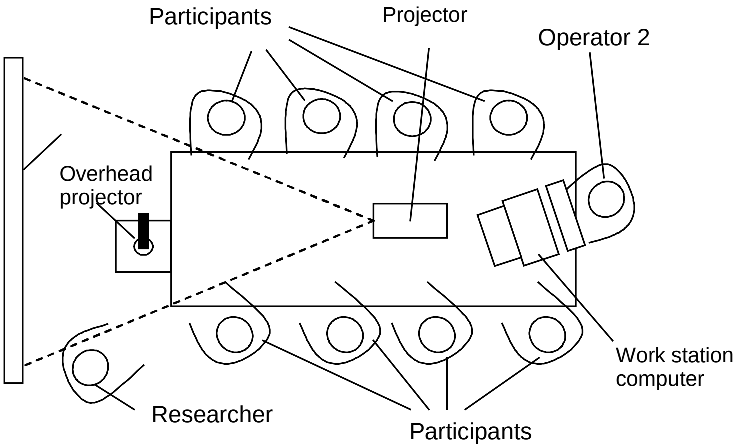


Figure 37. Arrangement of the usage of desktop virtual environments during safety analysis.

The use of a virtual environment was divided into six modes, which were applied in different cases (Table 16). The 3-D model mode indicated that only models selecting different angles were used. The simulation mode included in addition to 3-D models functional simulation of the machines and their equipment. The digital human model mode indicated that in addition to the previous modes, digital human model of the software was also used in the virtual environments.

Table 16. The modes of virtual environment in this work.

Case	Virtual environment mode					
	3-D model	Simulation *)	Digital human models	Simulator	HMD	Stereoscopic
Case 1	X	X	X		(X) **)	
Case 2	X	X	X	X	X	X
Case 3	X	X	X	X	X	X
Case 4	X	X	X			
Case 5	X	X	X			(X) **)
Case 6	X	X	X			(X) **)
Case 7	X	X	X			

Markings: X = implemented, *) simulation regarding motions of machines, **) used partly only

Simulator mode represented a mode of virtual environment where simulator system was used. The HMD mode represented a mode of virtual environment where head mounted display was applied in the case. The stereoscopic mode indicated that stereo views were used when using HMD or desktop display.

The stereoscopic view arrangement was active only with the work station computer. The projector did not support the stereotype projection. Two to three shutter glasses were in use when analysing with stereoscopic views in a desktop virtual environment.

Simulator system

A schematic presentation of the simulator system is in Figure 38. The simulator system was developed by the team and is presented earlier by Helminen (1997) and Määttä et al. (1999a). The idea of the simulator was to develop a system, which could be used for different kinds of operative simulation. The main target was operations where the operator is in a sitting position. The system could be used for simulations e.g. of driving, process operation and material handling.

The simulator system consisted from operator’s system, group system, tracking system and control system, which are presented in Figure 39.

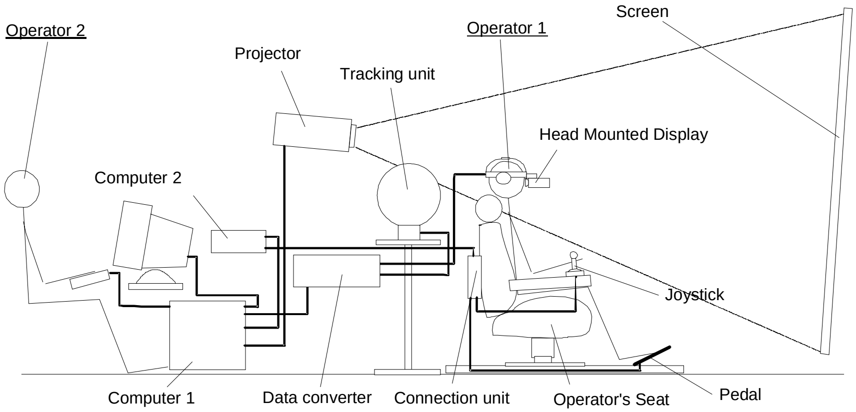


Figure 38. Schematic presentation of the simulator system used in this work in Cases 2 and 3.

The description of the simulator system equipment is presented in Table 17. Altogether 16 control devices could be connected to the system, which consisted of operator seat, connection unit, two joysticks, one or two pedals, steering wheel (optional), and head-mounted display (HMD), tracking system, and/or a screen including two computers, data converter and projector (Figure 39).

Table 17. Descriptions of the simulator system equipment.

Unit	Computer 1	Computer 2	Tracking unit	Display unit	Projector
Description	SGI Impact, Processor R 4 400 250 MHz, 128 MB Main, 4 GB MM, ICO -card	HP, 486 MHz, 64 MB, measurement card DT3001	Tracker, Polhemus Inc, electro-magnetic (unit 1), Long-Range Tracker Option (unit 2)	17”, SGI Display	Maximum, resolution 1024 x 768

The view created with the projector was to illustrate the view of the user (operator 1) for the analysis group. Operator 2 with the VE software and hardware created the view for operator 1. The tracking system controlled the view of operator 1 according to his or her head movement. The specifications of the HMD are presented in Table 18.

Table 18. The HMD specifications in the work.

Specification	Type of display	Field of view	Resolution Pixels	Weight kg	Stereo-scopic
Eyegen3, Virtual Research Systems Inc.	Dual 1,3”, diagonal Active CRT	40 dec diagonal	493x250, NTSC	ca 1,0	yes

The tracking system was based on a magnetic field with six sensors. One sensor was on the HMD. The theoretical space of tracking with tracking unit 1 was a sphere of 0.65 m radius from the centre of the unit and with tracking unit 2 (Long Range Option) 1.1 m. The practical space of tracking the HMD with no or little interference was from 0.1 to 0.5 m with tracking unit 1 and with tracking unit 2 from 0.1 to 0.9 m from the centre of the unit (Helminen 1997). The interference in the larger distance was indicated as distortion or oscillation in the view of the HMD.

Figure 39. Simulator system for analysis of the sitting operation used in the case studies 2 and 3.

The simulator system was so constructed that installation during case studies was possible on the company’s premises. When conducting analyses on company premises the control devices were two joysticks developed for computer games and available on the market. Otherwise these control devices in the simulator were the same as for industrial use, and were in fact the controls used in the cabin of a mobile working machine. The seat of the simulator was also identical to that in the real cabin. During the case studies on the industrial company premises a seat of office type was used. The simulator system was applied in Cases 2 and 3.

5.2.1.5 Procedure

The structure of the methodology of this work is presented in Figure 40. The method consisted of different stages starting from task definition, and ending in implementing and controlling. The SAVE method applies to some extent the methodology structure presented by Kuivanen (1993). The SAVE method includes task analysis in addition to the methodology presented by Kuivanen. The risk assessment and evaluation are included in the SAVE method according to the risk assessment procedure in EN 1050.

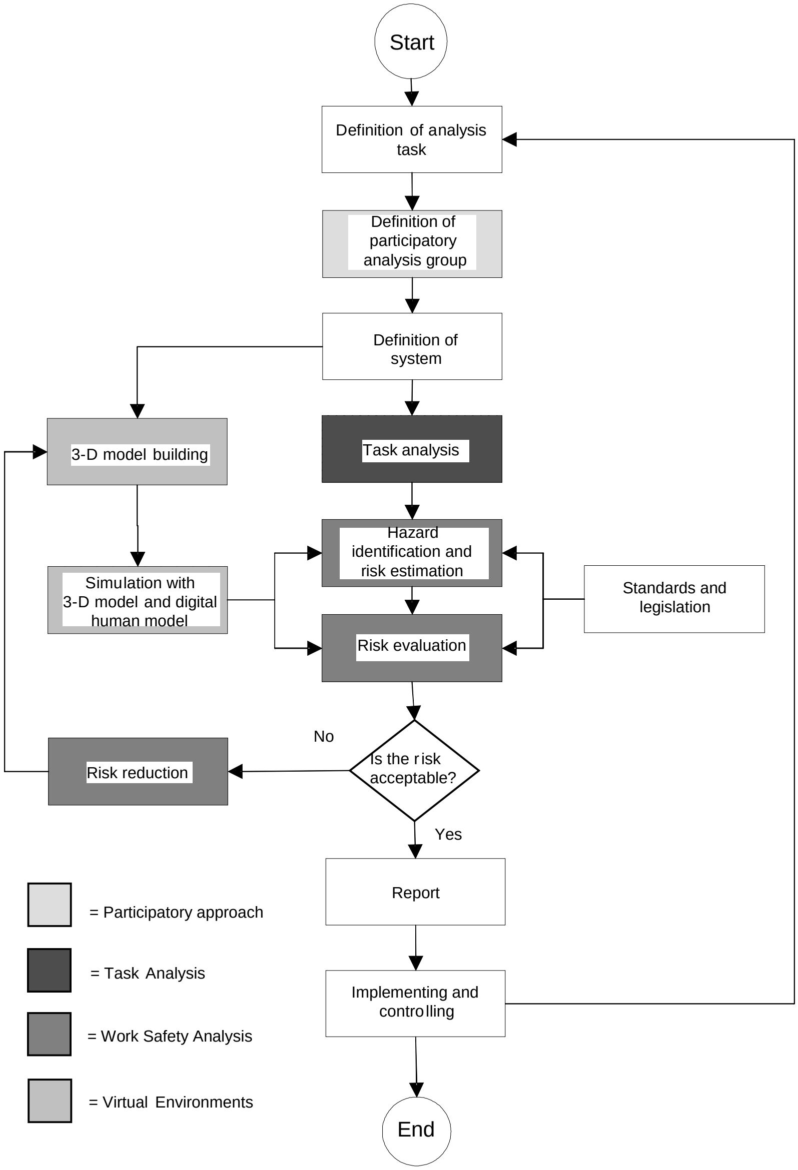


Figure 40. Flow chart of the SAVE method.

A. Definition of safety analysis task

Before a task is initiated it should be defined as adequately as possible. In first place there is a need to accomplish the task. This could arise from the company's continuous development activities or from new investments, which have a marked impact on processes or work tasks.

B. Participatory analysis group definition

To acquire all the knowledge necessary for the problem-solving task, an analysis group with persons from different background will be created. The rationale implemented here is the participatory design or ergonomics concept. The group should consist of workers (preferably from 2 to 3 people) from the target process, a production manager, foreman, safety specialists (safety manager, safety representative, and occupational health care person), designer(s), project manager, "analysis process owner" (project manager or person responsible for the analysis project) and safety consultant (optional). The optimal size of the group will depend on the task and target system. Usually from 6 to 8 persons constitute a suitable number, but a group of even 10 people or more is still effective.

C. Information definition

The system to be analysed should be defined as accurately as possible. In this phase the definition and the boundaries of the system will be explicitly formulated. Also the information needed for the start-up procedure will be defined in this phase. This includes e.g. drawings (layout, machinery, building structures etc.) also for 3-D model building, descriptions of the process and products, material involved in the process, environmental issues, labour resource plans, safety instructions and list of hazards (if available).

D. Task analysis

Task analysis includes descriptions of the work tasks and connections between the tasks, and also to the overall process. In task analysis the hierarchy and the connections between the different tasks will be visualised. The account can be performed according to the description of the workers working with a similar process or according to the task plan of the manufacturer of a machine.

E. 3-D model building

In this phase the 3-D models will be built from the drawings and pictures, if available. The model may consist of the entire process structures or parts of them. The details of the model modules depend on their influence on safety issues and can be changed during the analysis process. In the starting phase of the modelling the details may be less important and the models are then built roughly with no specific details, but according to dimensions laid down in the drawings. The kinematics of the modules could also be modelled in his phase. The functionality of the process modules is important when evaluating the influence of movements on safety.

F. Standards and legislation

In this phase a compilation of the relevant standards and adequate legislation requirements will be made. The norms will include international safety standards and the national and company's own standards. Legislation requirements include international and national laws and regulations on machinery safety and the responsibility of the employer.

G. Hazard identification and risk estimation

In this phase all possible hazards are identified and evaluated according to the analysis method tool (WSA) in spite of any possible initial risk reduction. This is to train the participants for identifying hazards which may possibly have impacts on humans and production. In this phase the group also evaluate the influence of a certain hazard and the safety measures for production. This phase is one part of the whole safety analysis method. Each hazard and safety measure is evaluated concomitant with the process.

H. Simulation with 3-D models and digital human models

In this phase computer-assisted simulation is applied for the evaluation of functions and movements of the machinery system against safety requirements.

By means of the software the different process phases are animated for hazard identification, risk estimation and risk evaluation of the safety analysis task. The simulation model is built according to the design and descriptions of the production process. Each phase of the process is evaluated according to the required functionality.

I. Risk evaluation

In this phase the group evaluate the level of safety compared to the pre-stated level in different safety measures devised by the designers with 3-D models and simulations. The design and the hazard list will include some safety measures to be analysed by the group according to the safety analysis method.

J. Risk reduction

If the safety measures in the design are not adequate in terms of the required safety level, the group will design new safety measures for a certain problem. In this procedure the group can use 3-D models to create different options for risk evaluation.

If the safety measures are not adequate after the new risk evaluation the group will design new measures, i.e. complete the safety design. This could be done by new 3-D model building and also tested with simulation and digital human models. The new design will be evaluated in the same way as previously until the risk reduction (safety measures) is adequate.

K. Report

Each safety analysis form will be collected and included in the safety analysis report. The report is a short description of the work completed by the analysis group and includes the conclusions and recommendations arrived at in safety analysis.

L. Implementation and controlling

The safety measures recommended in the analysis report will be implemented according to the implementation plan of the company. After the implementation of the system safety issues are controlled by the safety group or according to the safety management action plan. If safety problems arise after the implementation phase, new tasks will be defined for a safety analysis group.

5.2.2 Observations

The SAVE method was here implemented in seven safety analysis projects in a steel factory. All possible hazards were to be identified in spite of any possible initial risk reduction. During the implementation observation method was used to identify when modes of VE, i.e. 3-D models, simulation and human models, were used for analysing hazards, and how participation developed during the case studies. The VE was identified as being used when a model was moved and at least a half of the participants were watching the view of the model for analysis purposes during the safety analysis.

Observation was based on the perception that the model projected on the screen was actively in use during safety analysis. The author made notes to analysis forms according to identified hazards and the VE mode of usage. The author also checked these observations afterwards of each session. The safety analysis was conducted according to the safety analysis procedure.

The 3-D models were in use when the hazards were identified with the picture on the screen and the operator (assistant researcher) moved it or pointed it. The author subjectively evaluated by vision the number of persons in the group who were observing the pictures. The number of observers changed during the analysis according to different hazardous situations. The assistant researcher (operator 2) or the author controlled the views of the target system model on the screen. Some of the group members also made guidance to control the view according to the situation in hand and to the focus on the hazardous situation.

Simulations were in use when the function of a machine was programmed or operated with the software and displayed for the group. In this case also only a certain function of a part of the machine could be simulated. Simulation included e.g. crane hoist movements, steel converter movements, steel ladle car movements, movements of ladle turrets, movements of tilting devices, movements of mixer containers, movements of injection devices, and movements of trucks, cars and workers.

Human models were in use when a digital human model of the applied software was inserted into the system 3-D model in a particular place with or without simulated movements to evaluate the safety of the situation or the part of the machine. This kind of situation occurred e.g. when there was a possibility to have insufficient space for safety (safety zone) in curtain part of a model. This was also the case when a machine or part of it would pass the area or space where a worker would be moving or working when the new machine system was implemented.

The author made also observations about the participation activity during the safety analysis. The observations were based on the author's perceptions of the group work dynamics and the roles and activeness of the participants during the analysis work in the factory meeting room.

Furthermore observation method was used for evaluation of the use of SAVE method in different cases. Especially the expressions during the analysis work in the group were of interest. The observations were based on the author's impressions of the behaviour of the participants during sessions. Observations were made on the usability of the WSA, the Task analysis and the VEs, and the VE technology used in the Participatory analysis group sessions. Special attention was paid to the hazard identification situations during the sessions.

5.2.3 Interviews

After a year of all the safety analysis projects structured interviews (Appendix B) were carried out to collect the participants experiences and opinions of the implementation of the SAVE method during the investment projects. Altogether 9 participants of the seven cases took part of the interview (Table 19). The participants were project managers, maintenance manager, production development technician, foreman, and workers from the case projects discussed in this work (Table 20). The author made the selection of the interviewees according to the participation of the cases and the role of the safety analysis group. The project managers helped to make the interview arrangements in the factory. The interviews were held mostly personally but in one situation also as a group session. All the interviews were recorded on the audio tape.

Table 19. Interviewed persons.

Position	Persons	Number of persons	Participated in N cases N	Interview session	
				Individual	Group
Project manager (PM)	PM1	1	1	1	
	PM2	1	2		1
Maintenance manager (MM)	MM1	1	3	1	
Production development technician (PDT)	PDT1	1	3	1	
	PDT2	1	1	1	
Foreman (FM)	FM1	1	2		1
	FM2	1	1		1
Worker (WR)	WR1	1	2		1
	WR2	1	1		1
Sum		9	16	4	5

Some of the persons in the interviews had participated more than two projects of the cases of this work. The situations for the interviews were arranged so that they interrupted as less as possible the current work situations of the persons. The persons were participating also in other development projects than safety analysis during the investment processes.

At the beginning of the interviews a short presentation of the particular case was introduced to the participants to remind the situation of the safety analysis to one’s mind. The opinions of the interviewees were collected as independently as possible.

Table 20. Subjects in the interviews.

Gender/number	male/ 9	
Occupation	Technician 4, Engineer (BSc) 2, Engineer (MSc) 1, Worker 2	
Title	Project Manager, Development Technician, Maintenance Manager, Project Technician, Development Engineer, Development Manager, Caster	
Training in safety analysis	Yes = 5, One day training given by the company specialists No = 4	
	Mean	Range
Age in years	48,9	44-56
Years in recent company	24,6	12-35
Years in recent work	10,6	0,5-30
Number of analysis groups	1,8	1- 6
Number of meetings/analysis	9,1	3- 20
Number of safety analysis before	1,4	0-3

During the interviews a list of questions was used as a guideline. The questions were focused e.g. on the benefits of virtual environments in safety analysis as general and in continuous developing activities, on the familiarity of the safety analysis method, and on the needs for improvements of VEs implementation in industrial use.

5.2.4 Questionnaire

A questionnaire was used to collect the experiences and comments on the use of virtual environments in safety analysis of machinery (Appendix C). The main objective was to obtain information on how the participants evaluated the usefulness of VEs in safety analysis. The questions in the questionnaire were performed to indicate different views of the VEs usage. The questionnaire was performed after the all cases as indicated in Figure 32.

Altogether 20 persons from 32 participating of all the cases delivered the questionnaire to the author. The percentage for answering was 62.5%. All the participants did not answer to the questionnaire because of not working in the company, not reaching the questionnaire during the procedure, did not want to answer or did not have time to answer (12 persons).

The number of questions was chosen so that the amount of time spent in answering the questionnaire was reasonable and the answers could be completed during a working day in an appropriate situation. The project managers delivered the question forms to the participants of the case projects at the beginning of a working day or a shift or in another appropriate occasion. The purpose was that all the participants could answer freely and independently. This was not however controlled.

The author gave guidance of the questionnaire to the project manager. In addition all participants who might have queries about the questionnaire and the procedure could contact the author by phone, letter or e-mail. The contact information was delivered in the questionnaire form. The answering time was three weeks from the day of delivering the questions. The reply of the questionnaire was requested one time during the answering period.

All answers could be delivered anonymously and put in a closed envelope provided by the author. All participants could send the questionnaire freely and independently by sealed envelope to the author or to the project manager who forwarded then the bundle of questionnaire to the author in sealed envelopes.

6. Results

6.1 Results of hazard identification in case studies

In the seven cases altogether 1193 hazardous situations were identified (Table 21). Among all the identified hazards 692 out of 1193, i.e. 57.9%, were identified when using virtual environments. Of all these findings 3-D models were involved in the identification procedure in 58.0% (in 692 cases), simulation in 25.2% (301) and digital human models in 10.3% (123), respectively.

The 3-D models were the most frequently used in Cases 5, 4, 6, 7 and 3, where models were in use when identifying hazards in 65.0%, 60.1%, 58.3%, 58.1% and 57.9% of all the identified hazards, respectively. Simulation and digital human models were used the most frequently in Case 3 with 46.6% and 22.8% of all identified hazards, respectively.

*Table 21. Identified hazards in safety analysis of the cases *).*

Cases	Hazards	M	S	H	M	S	H
			Number			Ratio,%	
Case 1	77	24	10	8	31.2	13.0	10.4
Case 2	62	27	18	7	46.5	29.0	11.3
Case 3	57	33	26	13	57.9	46.6	22.8
Case 4	466	280	134	42	60.1	28.8	9.0
Case 5	280	182	42	20	65.0	15.0	7.1
Case 6	127	74	34	24	58.3	26.8	18.9
Case 7	124	72	37	9	58.1	29.8	7.3
Total	**1193**	**692**	**301**	**123**	**58.0**	**25.2**	**10.3**

M = 3-D modelling

S = simulation

H = digital human model

**) "Identified hazards" were all the identified possible hazards in spite of the initial designed reduction of the risk*

From all the identified hazards 179 situations (15.0%) were evaluated with risk index 4 or over (Table 22). The risk index means that probability to have a hazard was at least probable and consequences were at least moderate. Virtual environments were in use when identifying 153 of hazardous situations with risk index of 4 or over. This represents 85.5% of all these identified hazards.

Table 22. Identified hazards according to risk index in all cases.

Risk index	Identified hazards (IH)	Identified with virtual environments (VEs)	Ratio VE/IH (%)
1 Extremely low	442	189	42.8
2 Very low	323	202	62.5
3 Moderate	249	148	59.4
4 High	109	92	84.4
6 Very high	48	42	87.5
9 Extremely high	22	19	81.8
Sum	1193	692	57.9

During the analysis safety measures were listed as recommendations for safety design. The measures focused solely on the main hazards. Part of the recommended safety measures concentrated on technical improvements, which were identified during the analysis and were taken into consideration in the design. One part of the safety measures could be taken into consideration later during the run-up phase of the machinery. The recommended measures also included suggestions for minimising the effects of hazards or to improving training and instructions. Decisions on and realisation of the measures were left to the company.

In addition to the safety analysis the group made evaluations of the views from the crane cabin and control room in Cases 2, 3 and 4. Especially the views from the cabin to the lifting areas of the ladle turrets and turntable were evaluated in Case 3. Different models of lifting equipment were also available when evaluating the views and recommendations for improvement were given.

The view from the crane cabin to ladle carriage was improved by removing a wall about 0.5 m further from the rails so that the crane operator could see the whole lifting equipment and the attachment points of the ladle. This recommendation was extremely important to the company from the standpoint of better safety and more effective operation. The replacement of the wall in the drawing before the installation of the casting machine saved the company significantly in investment expenses. The saving was based on the shorter run-up time, less production loss and less extra work.

In addition, designs for safer lifts of a segment in the machine were designed using 3-D models and simulations in Case 5. Also the height of the control room and the position of the seat inside the control room were evaluated with the models and a recommendation given in Cases 1, 4 and 7. The so-called blind spots in the critical process were identified and analysed in Cases 2, 3 and 7. Some suggestions with 3-D models for camera installations were given.

The 3-D models were used in safety analysis over 50% in the Cases 3, 4, 5, 6 and 7. The 3-D models, simulation and digital human models were used less in Case 1 and Case 2 (Figure 31). In these Cases 31.2% and 46.5% of all hazards were identified with using VEs, respectively. The use of VEs varied from 31.2% to 65.0% in the cases. The usage of simulation in all cases varied from 13.0% to 46.6%, and the usage of digital human models from 7.1% to 22.8%.

When identifying hazards, burns, impact, crushing and slip, trip and fall hazards represented 75.1% of all hazards identified (Table 23). When using 3-D models these hazards represented 83.5% of all identified hazards. The most frequently identified hazards with the use of 3-D models were crushing, and slip, trip, and fall hazards, with 79.6% and 75.2% of all identified hazards respectively. The digital human model was in use in identification of 28.1% of all identified crushing hazards, whereas the digital human model was in use on the average in identification of 10.3% of all identified hazards. The summary of the results is presented in Appendix D.

Table 23. Summary of the most frequently identified hazards.

			Virtual environments *)						
			Number			Proportion, %			
Hazards		All	M	S	H	M	S	H	
1.1	Crushing hazard	167	133	85	47	79,6	50,9	28,1	***
1.6	Impact hazard	284	183	72	29	64,4	25,4	10,2	NS
1.12	Slip, trip and fall hazards	117	88	15	5	75,2	12,8	4,3	**
3.1	Burns and scalds	328	174	74	21	53,0	22,6	6,4	NS
	Sum	896	578	246	102	64,5	27,5	11,4	NS
	All hazards	1193	692	301	123	58,0	25,2	10,3	
Proportion of all hazards, %		75,1	83,5	81,7	82,9				

Note: The number of hazard refers to the classification of hazards in EN 1050 and in Appendix D

*** = $p < 0.005$, ** $p < 0.001$; NS = not significant

*) All = All identified hazards; M = 3-D models; S = simulation; H = Digital human models

Crushing hazards were identified mostly by the use of all modes of virtual environments, i.e. with 3-D models, simulation and digital human models. In all cases 3-D models were used for the identification of hazards in from 31% to 65% of all identified hazards (Figure 41). In the first two cases the use of 3-D models was less than in other cases, ranging from 31% to 43%. The use of 3-D models in Cases 3, 4, 5, 6, and 7 was from 57% to 64%. In Appendix E is an example of hazards identified in the safety analysis in case four.

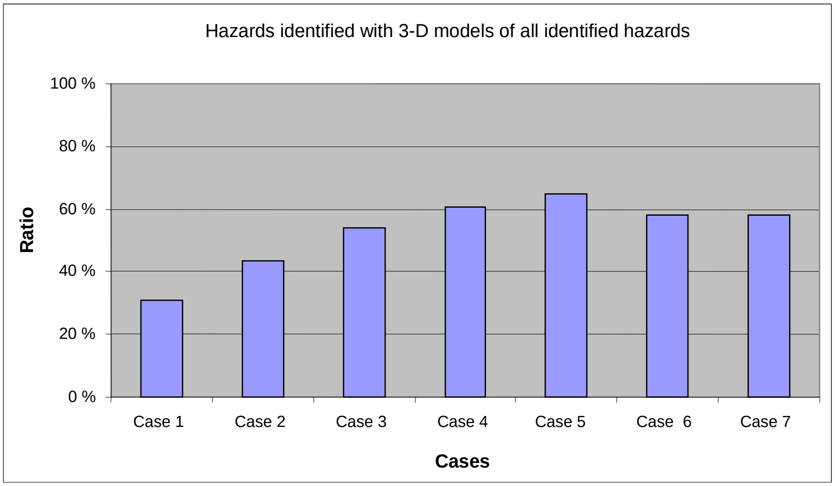


Figure 41. The proportion of hazards identified with 3-D model to all identified hazards in safety analysis of individual case (N = 1193).

The use of simulation for the identification of hazards in the cases varied from 13% to 46% (Figure 42). The lowest degree of the use of simulation was in the Case 1 and was 13%. The highest degree of the use was in the Case 3 and was 46%. The average degree of the use of simulation among all cases was 24.3%.

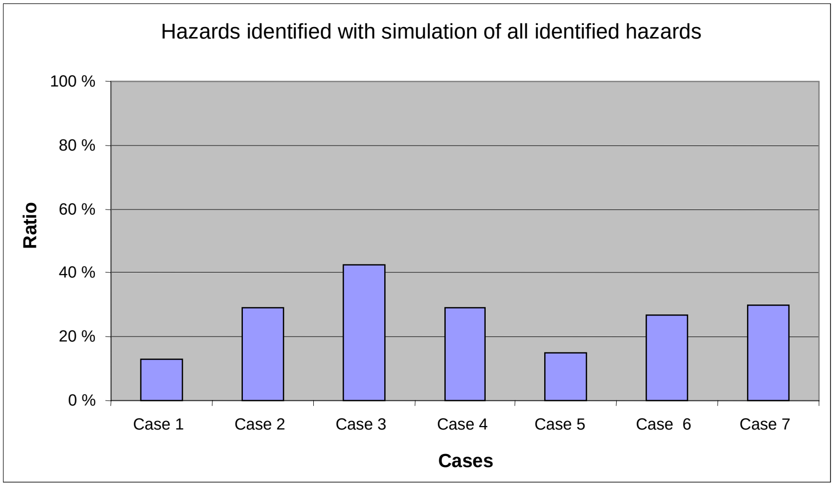


Figure 42. The proportion of hazards identified with simulation to all identified hazards in safety analysis of individual case (N = 1193).

The use of a digital human model during the identification of hazards was on the average 10,3%, varying from 8% to 23% (Figure 43). The lowest degree of use was in Cases 5 and 7, and the highest in Case 3.

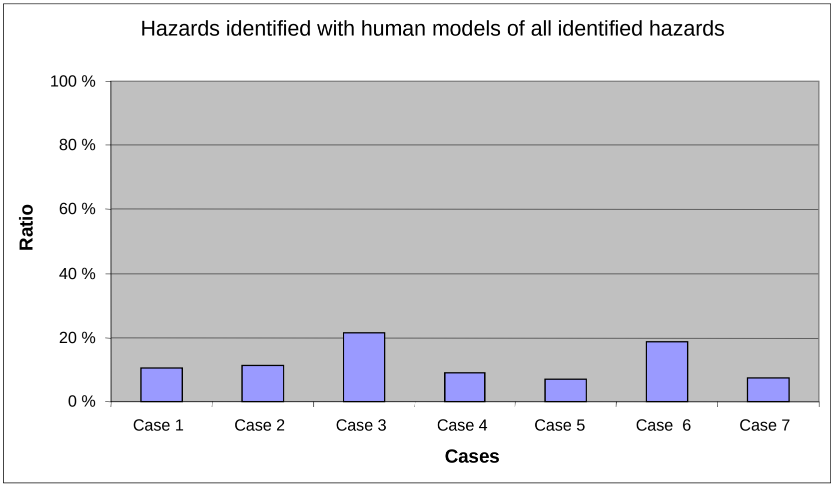


Figure 43. The proportion of hazards identified with the digital human model to all identified hazards in safety analysis of individual case (N = 1193).

The implementation of digital human models was highly dependent on the human tasks and the functions of the machinery. In addition, the initiative of the operator using the VE system influenced the degree of use of the digital human model during the safety analysis. When digital human models were initially installed in the VEs they were used more often during the analysis than when they were specially brought from the software library.

6.2 Identifications of different types of hazards with VEs

6.2.1 Crushing hazards

In the course of the safety analysis altogether 167 crushing hazards were identified. Of these, 133 hazards (79.6%) were identified with virtual environments. In Cases 1 and 7 all the identified crushing hazards were identified with VEs (Figure 44). In Cases 2, 3, 4, 5 and 6 the number of crushing hazards identified with VEs were 83%, 85%, 63%, 91% and 71% respectively. Crushing hazards were identified in Case 1 in 6 situations, in Case 2 in 12, in Case 3 in 14, in Case 4 in 43, in Case 5 in 56, in Case 6 in 31 and in Case 7 in 5 situations.

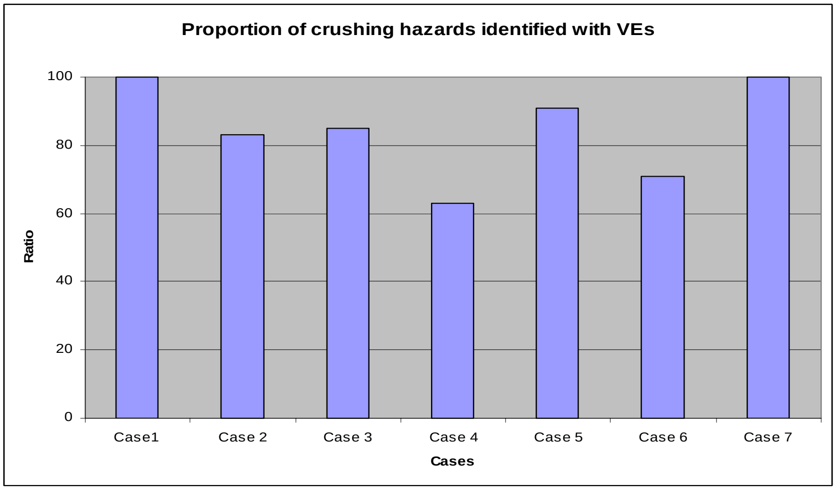


Figure 44. The proportion of crushing hazards identified with virtual environments to all identified crushing hazards in cases (N = 167).

6.2.2 Impact hazards

Altogether 284 impact hazards were identified during the safety analyses in cases. Of all these hazards 183 hazards (64.4%) were identified with virtual environments. In Cases 3 and 7 the impact hazards were identified with VEs in 83% and 77% of all identified impact hazards, respectively (Figure 45). In Cases 1, 2, 4, 5 and 6 the number of identified impact hazards with VEs were 60%, 53%, 68%, 60% and 65% respectively.

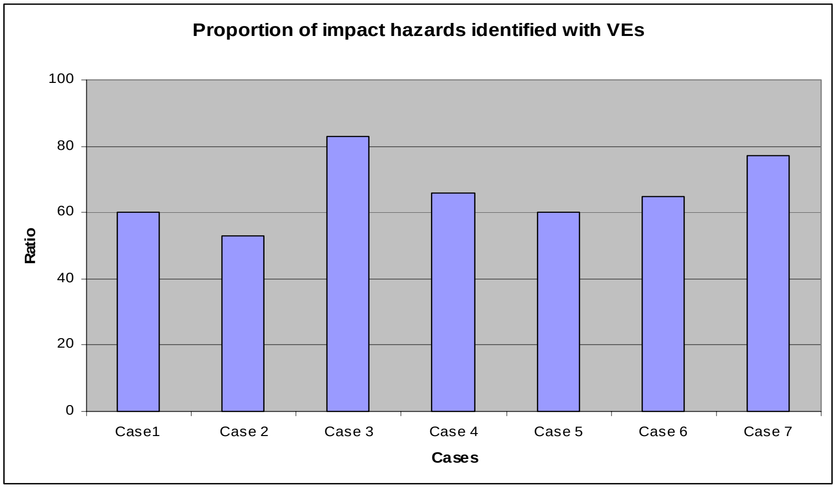


Figure 45. The proportion of impacts hazards identified with virtual environments to all identified impact hazards in cases (N = 284).

Impact hazards were identified in Case 1 in 5 situations, in Case 2 in 13, in Case 3 in 6, in Case 4 in 104, in Case 5 in 97, in Case 6 in 37 and in Case 7 in 22 situations.

6.2.3 Slip, trips and fall hazards

During the safety analysis altogether 117 slip, trips and fall hazards were identified. Of all these hazards 88 hazards (75.2%) were identified with virtual environments. In Cases 1 and 2 none of the identified slip, trips and fall hazards were identified with VEs (Figure 46). In Cases 3, 4, 5, 6 and 7 the number of identified slip, trips and fall hazards with VEs were 67%, 79%, 78%, 67% and 89% respectively. Slip, trips and fall hazards were identified in Case 1 in 4 situations, in Case 2 in 1, in Case 3 in 3, in Case 4 in 33, in Case 5 in 64, in Case 6 in 3 and in Case 7 in 9 situations.

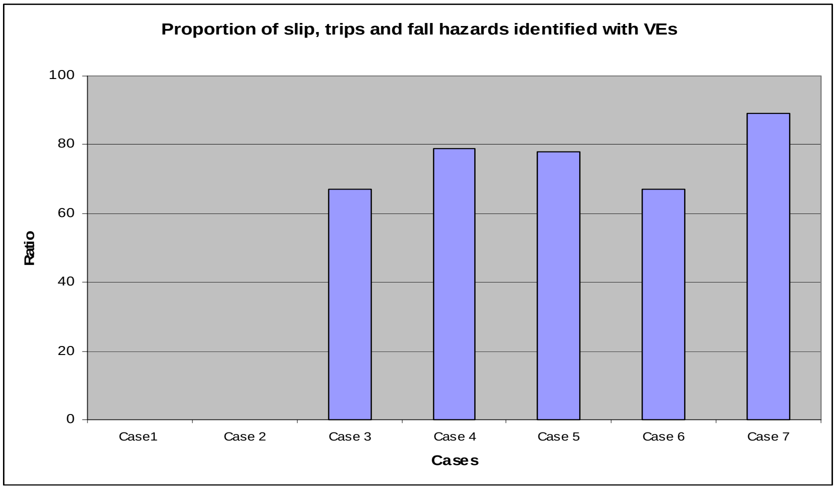


Figure 46. The proportion of slip, trips and fall hazards identified with virtual environments to all identified slip, trips and fall hazards in cases (N = 117).

6.2.4 Burn and scalds hazards

Altogether 328 burn and scalds hazards were identified during the safety analysis. Of all these hazards 174 hazards (53.0%) were identified with virtual environments. In Case 3 none of the identified burn and scalds hazards was identified with VEs (Figure 47). In Cases 1, 2, 4, 5, 6 and 7 the number of identified burn and scalds hazards with VEs were 20%, 25%, 60%, 35%, 63 and 56% respectively. Burn and scalds hazards were identified in Case 1 in 5 situations, in Case 2 in 16, in Case 3 in 4, in Case 4 in 33, in Case 5 in 40, in Case 6 in 27 and in Case 7 in 63 situations.

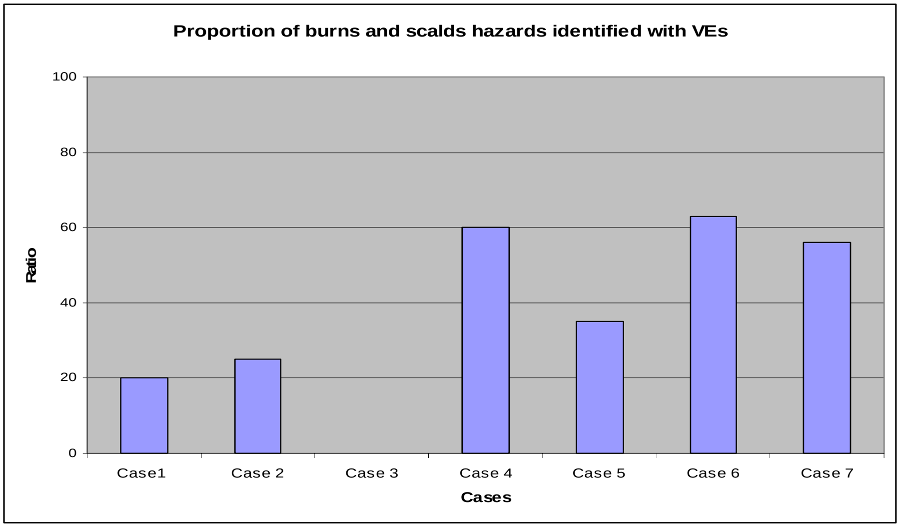


Figure 47. The proportion of burn and scalds hazards identified with virtual environments to all identified burn and scalds hazards in cases (N = 328).

The identification of the burn and scalds hazards of the machine systems were dependent on the tasks. The more the tasks included work near the hot surface the more burn and scalds were identified. In the first three cases the tasks with hot surface were identified merely without VEs.

6.2.5 Observations during the analyses

The analysis method used in this case was identification of hazards with hazard list according to standard EN 1050. At the beginning of the analysis process tasks in the plant were divided into subtasks and safety was evaluated task by task and hazard by hazard. The procedure where the risks were estimated and evaluated according to the list of standard was applicable, but the analysis work with a list was time consuming. There were some problems observed in preparing the hazard list of different tasks and in estimating the risks. The main problem was in identificating hazards according to hazard list from a specific task. The safety analysis methodology and the concepts were new and unfamiliar for most of the participants. The difficulties in preparing the hazard lists and estimating the risks indicated a need for improvement in the procedure.

The group work was active in each case. The activity was higher when the participants had worked together before the safety analysis sessions generally in similar working situations. Discussion during the sessions did notably increased when the virtual environment was in use. Especially the workers from the site of the plant participated actively during the use of the virtual environment as a visualising tool. The workers who worked as crane operators with overhead cranes in the plant were interested in the simulator used in Case 2. When analysing the work with the simulator each participant took an active role in safety and task analysis. The rise in activation during the analysis was due to new unfamiliar tool, but also to the easy and concrete way of performing the analysis. Because of the poor ergonomics in the virtual environment equipment the time spent with the VEs was not long. Typically a participant worked with it for less than half an hour in one session. This was also the maximum time as a guideline for work with VEs. Several participants worked with the simulator during a session.

The 3-D models for the safety analysis sessions were prepared mostly with less detail. Only the sizes and the main shapes were according to the real objects. The functions of a model were programmed with the tools of the applied software. When the first two cases were performed, the detail levels of models were somewhat increased. The possibility to build a model with more details was based on the more effective of hardware used in the later cases. Also the development of the softwares during the performing of the cases had affects on the details of models and on the analysis of functions in the machines.

6.3 Experiences of the use of virtual environment systems

6.3.1 Projector and screen

When using projector and screen VE system the arrangement was easy to install in the factory premises. The VE technology in this mode was familiar and did not bring new equipment to normal everyday project activities. According to observations during the cases this feature of VE system gave fluent implementation for SAVE method in the cases. This observation did strengthen during the executing of the cases.

This mode of VE technology did not demand special adjustments to implement VEs into safety analysis. The participators seemed to easily adapt to the use of VEs. This arrangement was the most used VE system in the cases. In fact, all the cases did use this arrangement as a basic VE technology in the safety analysis of this work. The large picture on the wall gave a view for everyone in the room to watch and evaluate according to his or her experiences the modelled system in the VEs.

The arrangements were also easily movable. In these cases the only equipment that was brought outside the factory was the computer and projector.

When arranging so that the researcher was at the front of the table and beside projector beam, all the participants had a possibility to see on the large screen. In fact, however, the projector in a small and low room did not give the best possible view to the picture to all participants. The obstacles in the room such as other participants and pillars had influences on the activity during the analysis. The more persons in the low room the less activity were found in the back of the room. This was, however, a general subjective observation and differed from case to another. In general the activity in the analysis groups was good.

6.3.2 Simulator and head mounted display

When simulator was used the arrangements were more demanding than with screen mode. In addition to screen with projector arrangement was added by HMD with motion tracking system, which was more difficult to move from place to another. In addition the use of HMD was difficult at the beginning of the sessions due to the new situation and ergonomic problems with the HMD.

In the first two cases a simulator chair was installed in the factory project room for the sessions. This arrangement was too space and labour demanding and therefore after one session in the research institute a more easily installable arrangement was developed. This arrangement included a normal office chair and two joysticks bought from a software store. After some tests this arrangement seemed to suit more easily for the project room use at the factory premises than the original.

The short detecting distance of the first tracking system restricted the movements with the HMD and gave problems with the use of HMD in a project room. After installing a new transmitter the use of HMD was easier.

The viewing possibility in two places at the same time, i.e. in HMD and on the white screen on the wall made the analysis and discussions with other crane drivers, foremen and safety technicians easy and active. The new way of analysing and the new equipment were interesting and at beginning of the analysis more effort was paid to test and play with the VE system. After few hours of VE system testing the focus changed to analysis work and the modelled system. The use of simulator and HMD only in small groups gave the possibility to everyone to have chance to test and to analyse with the current VE system.

The restricted time for being in the VEs made it possible to avoid disorientation, sickness or nausea. The defective ergonomics of the HMD made the work with it difficult. The adjustments of HMD were not adequate for the head and eyes. The field of view was too narrow to analyse realistic.

When using stereoscopic lenses only two persons could see the model at the same time. Because of the restriction the VE system this mode was used only in special occasions such as demonstrating the stereoscopic visualisation of the models. According to the participants experiences on the stereoscopic view the sense of immersion was better than with the screen, but in the other hand the adjustments with screen and stereoscopic lenses were time consuming. After some tests the participants stopped using the lenses and changed to use the large screen on the wall even if the picture was not so sharp than on the CRT display.

6.4 Results of interviews

According to the results of the interviews SAVE was a feasible method, which could give the assurance that the investment will work as planned and the functions are safe (Appendix E). All the persons interviewed recommended this method for similar projects. Some difference of opinion arose over the issue whether the tools and expertise of the method will be at the company's own expertise in the future.

The impacts on the economic issue were difficult to evaluate by the interviewed persons. However, the greatest evaluated saving was evaluated being nearly 100 000 € in Case 3. The implementation of the method was evaluated not being significantly expensive. The investment in safety analysis with this method and tools was perceived as valuable.

The objectives of the safety analysis in the cases were to identify all or at least most critical hazards in the system early in the design phase, to have guidelines for measures enhancing the safety, and ultimately to have a new safe production system. This was expected to be successful by using group work methodology.

The work safety analysis method was not familiar to the participants. Only two out of the nine persons knew it. From all interviewed persons 6 did not know the procedure at all. Only one person was partly familiar with the safety analysis method.

According to the interviews one of the greatest benefits of the VEs in safety analysis was the common understanding which was achieved by visualisation of the target system to all participants. VEs also gave a more realistic and easily understandable scaling effect of the target machine system than drawings. The scaling effect here means that the sizes of machines or parts could be evaluated against some familiar object such as human figure, window or door. Also the visualisation of movements in VEs enhanced understanding of the functions of a machine. VEs had positive impacts on the time spent for analysis and on training as well as on the verification of the system plans to the specifications.

The computer simulation of a system and its functions with VEs will benefit the understanding of critical points especially with a multifunctional machine system. Simulation will focus the participants to concentrate on the relevant issues at each stage of the analysis.

According to the interviews the usage of VEs was helpful in safety analysis. A number of defects in designs were detected using VEs. The interviewees remembered that in Case 3 e.g. the need to replace a wall from its original planned placement to enhance the view of the crane operator in a very critical lift was detected during the safety analysis with VEs. In Case 5 a significant need for improvements of working space in maintenance work and in a roll exchange was detected with VEs. The planned way of work was found to be impossible to accomplish. The views of operators on critical points in the process were also evaluated by the interviewees as being easy to evaluate with VEs.

The interviewees were of the opinion that VE will bring benefits to the design especially in evaluating views, placements of machines and machine parts, safety areas around machines and constructions, and work tasks with safety aspects. In addition, the planning of maintenance work and taking into consideration the needs of maintenance, the evaluation of space and movements would also derive benefits by the usage of virtual environments.

Virtual environments had economic impacts in the company according to the interviewees, especially in exposing faults in design, bottlenecks of production, and when used for training purposes. The greatest economic impact of the virtual environments was when the need for the change of a wall was identified during the analysis in Case 3. This was estimated to have meant over 100 000 euros saving in costs of rebuilding and loss of production. In addition the replacement of a reel unit during maintenance work with a machine was evaluated to have had a marked economic impact on the production of the steel strip unit. Estimation of the economic value was however difficult especially for the workers and foremen.

According to the interview all participants would use virtual environments in the future in development projects, especially in evaluating large machine systems. The use of VEs should however be evaluated on a case-by-case principle.

Virtual environments should be enhanced to be more user-friendly, rapidly programmable, used in the early design phase by designers, and easy to implement in different CAD systems. Also the VE programs and equipment should be less expensive than at the moment.

When using VEs in safety analysis the knowledge of the target system will come from the persons in the company, but the guidance with the analysis procedure and the work with VEs could be bought from outside the company. The service provider of the VE system will have the most recent knowledge and VE equipment. Some of the participants were of the opinion that the manufacturer should already have the VE system in use when designing the system.

The usage of VEs is well fitted to the participatory design. The systematic mode was an important part of the analysis, especially in analysing complex systems and in training users for the system. One worker phrased the answer for example as follows:

> *"We used VEs in training situations when these kinds of models were used in such situations where operators, technicians and electricians could evaluate the work in a new system in such a way that it forced us to analyse what should be done in a specific situation, it forced us to make the analysis in a systematic way. This was one of the best lessons we learnt from the days of the safety analysis process."* *)

The interviewees had used VEs e.g. for evaluation of the views from crane cabin and operation rooms, and of whether different machine parts could be installed in their planned positions and during maintenance when taken from their initial places. The scale factor was also seen to be important during the use of VEs for getting a common understanding of all participants and for executing safety analysis.

**) The translations are made by the author and are as direct translations from the comments of the interviewees as possible; some modifications are made to make the comments more readable.*

A project manager commented on the scale issue:

> *"At least for me the scale of the machine was at the beginning very important, in understanding the size of the machine, how it will be situated in the production line, and how it looks in the end; in this the VE was very helpful, and in addition when a mid-size human figure was situated near or in the machine, it was possible to make a more realistic picture of the machine in one's mind."*

The use of VEs opens up possibilities to detect critical points in a system and forces to check whether there is a fault in the drawing. Doing this the group in safety analysis could arrive at a common understanding of a new machinery system. Two foremen gave the following answers:

> *"We were checking the motions of a mechanical part of a system and found something that in our opinion would not work, so it had to be checked and a functional fault was detected."*

> *"It is so that you are not sure whether it will function properly in spite of your putting drawings in line and you think that that goes there and that there, you are still wondering is it OK, you are not sure. So it will still be like nothing, that as a whole. The VEs gave much information about the machinery system and assurance that the machine will work safely."*

The realistic picture of the machine was also informative to the workers, who had never before seen anything of that new machine. One of them commented:

> *"When we were working with the diagram with operators and electricians, we had these models all the time in front of us. The group coming from the line had never before had anything to do with that machine, even in drawings, so the pictures of the 3-D models were on the table, and we were checking that if we had a junk roll there so what we should do. So we were enhancing the procedure by planning where the rolling unit should be moved and so on. In doing this the models of VE were very helpful. With the help of these models workers, that haven't had an opportunity to see the machine elsewhere, had the chance to have a picture of what kind the new machine will be and how it will work."*

The common understanding was included in most of the answers and comments. One of the project managers commented:

> *"The most important factors with the VEs I think are the understanding of the functions and that all the participants have the same image of how the machine will function. At least during the analysis of the roll conveyor, where the installation and the time to utilisation were extremely short and the pressure to succeed dreadful, in that that we had a common vision to go to."*

According to the interviews the correctness of the measures in the model is important for the reliability of the evaluation and analysis. This was mentioned in five of the nine interviews. The procedure of modelling in this work was such that the 3-D models were made according to the drawings and from possible pictures and videos, and also according to some measurements from the current structure and machines. Some examples of the comments on this issue were:

> *"The most important issue, I think, is the basic information, exact measures of the equipment and machines, so that what they are at the moment. So, when you make a model, and there are faulty dimensions, the interpretation is wrong. When they use the model, they assume that the model is correct, … and if there are no dimensions and the functions of the model are to be seen and you have to make an illusion of the machine, then it could be a big mistake."*

> *"It would need exact modelling when connecting to a larger system, e.g. for the design of pipe layouts"*

> *"Where the fault in the model or in the drawing is, is a question to be handled when a fault is detected."*

Differences between drawings and models were expected to be less when the designs are made in 3-D and evaluated with VEs.

> *"It would not take a long time when all the designs are made in 3-D."*

> *"In the end it would be beneficial to the manufacturer to make all the designs in 3-D."*

According to the interview some developments were seen to be needed in VE technology. It seemed that the VE technology used was not sufficient to offer all the possible advantage that VE was expected. Some of the comments indicated this.

> *"The technology should be enhanced so that the visualisation could guarantee the most correct understanding of the target system to all."*
>
> *"The VE system should be possible to use in subsequent training issues."*
>
> *"The simulation should visualise more the inside functions in the process, so the benefits from the simulation would be greater."*

The vision of the use of VEs was that it would in the future be a part of every delivery of a machine. Some of the interviewees said they expected this to happen within the next 10 years. At the present time the use of VEs is very occasional and perhaps only with fairly extensive investment projects.

According to the interviews the greatest benefit of use of VEs was the visualisation of a new machine with its functions. The great responsibility of the model-maker in building the model with exact dimensions was also emphasised. The risk of faulty models would be smaller in the near future when the designer designs the machine and parts with 3-D modelling software. This also indicates that CAD and VEs should interact fluently and exactly.

6.5 Results of questionnaire

According to the questionnaire the main positive impacts of the virtual environment were evaluated being on (Figure 48):

- work training (question nr 24, mean value 3.9 out of 0 to 5),
- efficiency of the analysis (nr 22, mean value 3.8),
- identification of critical points (nr 7, mean value 3.8),
- common understanding of the system (nr 3, mean value 3.8),
- participatory design (nr 31, mean value 3.7),
- understanding of the functions (nr 10, mean value 3.6),
- learning in the work (nr 29, mean value 3.6),
- speeding up the analysis (nr 12, mean value 3.5) and
- understanding of drawings (nr 2, mean value 3.4).

The most positive evaluation of VEs was given when recommending it for similar work groups (question nr 18, mean value 4.3). According to the questionnaire the use of VEs did not minimise the expenses of analysis (question 13).

In addition VEs did not make the analysis situation unpleasant (question nr 16) or difficult (nr 5).The implementation of VEs did however need special knowledge (nr 19) and the time needed for modelling of VEs was evaluated as moderate (nr 11).

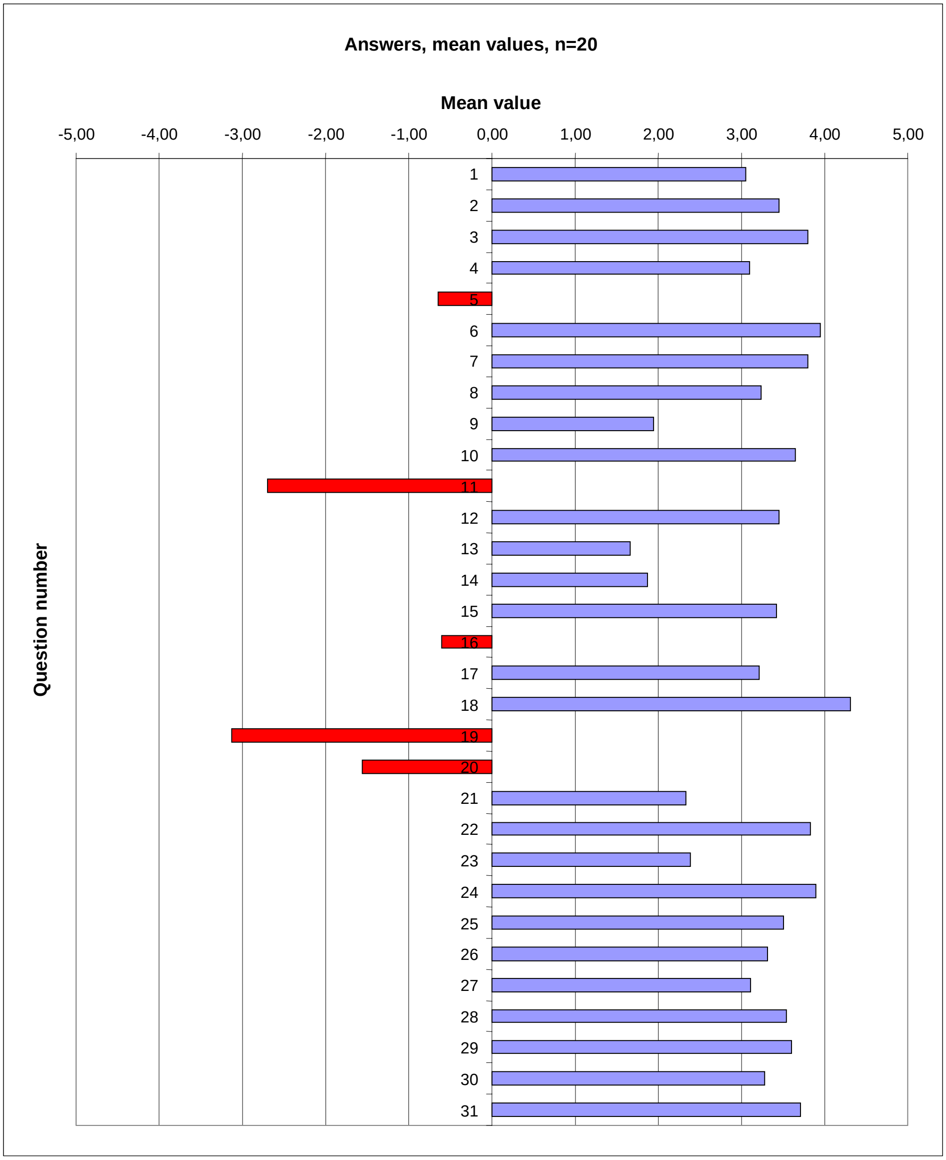


Figure 48. Mean values of the scores in the questionnaires (N = 20). The black bar on the left indicate negative impact of VE. The numbers refer to the questions in Appendix C. (Scale: 0 = not at all, 1 = very little, 2 = little, 3 = fairly, 4 = much, 5 = very much)

Among the answers received, 21 out of the 31 questions (67.7%) had a score 3.0 or over indicating positive impact of VEs. Among the answers 7 out of 31 (22.6%) had a score of 3.5 or over (Table 24). In the questionnaire 5 out of 31 questions (16.1%) were phrased negatively for the use of VEs. One answer for these questions was over 3.0, indicating moderate negative impact of VEs in the safety analysis.

Table 24. The impact of the virtual environment in safety analysis according to the questionnaire (n = 20, mean value 3.4; Score 0 = not at all, 5 = very much).

Rank nr	Question nr	Item	Description	Mean score
1	24	Work training	Much	3,9
2	22	Efficiency of the analysis	Much	3,8
3	7	Identifying critical points	Much	3,8
4	3	Common understanding of the system	Much	3,8
5	31	Participatory design	Much or fairly	3,7
6	10	Understanding of the functions	Much or fairly	3,7
7	29	Learning in work	Much or fairly	3,6
8	2	Understanding the drawings	Fairly	3,5
9	12	Speeding up the analysis	Fairly	3,5
10	30	Continuous development	Fairly	3,3
11	8	Finding faults in drawings	Fairly	3,2
12	17	Saving expenses by identification of development	Fairly	3,2
13	4	Producing new ideas	Fairly	3,1
14	1	Increased knowledge of the target	Fairly	3,1
15	17	Shortened the run-up time	Little	2,4
16	14	Exposing prominent targets for saving expenses	Little	1,9

The implementation of VEs was evaluated as having had little positive effect on shortening the run-up time of the system and exposing prominent targets for saving expenses. The impact of VEs on all the other items was evaluated as fair.

The implementation of VEs caused little disturbance to the safety analysis procedure and the atmosphere of the work during the analysis (Table 25). The use of the VEs calls for fairly special skills and modelling time, and adds little to expenses.

Table 25. Disadvantages of the implementation of the virtual environments (n = 20, mean value = 1.7).

Disadvantages of the implementation of the virtual environment

	Question nr	Question	Description	**Score**
1	16	Weakened the atmosphere of work	Not at all or very little	0,6
2	5	Disturbed the analysis process	Not at all or very little	0,7
3	20	Added to expenses	Little	1,6
4	11	Needs long modelling time	Fairly	2,7
5	19	Needs special skills	Fairly	3,1

Those participating in the safety analysis were of the opinion that implementation of the VEs could be recommended to other groups and projects and implementation should be increased (Table 26).

Table 26. Comments on the implementation of the virtual environment (n=20, mean value = 3.8).

Comments on the implementation of the simulation tool				
		Question	Description	**Points**
1	18	Can be recommended to others	Much	4,3
2	6	The use of VE should be increased	Much	4,0
3	28	Computers are in need of improvements	Fairly	3,5
4	25	Should have more human models	Fairly	3,5

According to the questionnaire there also was a need for more effective computers and more human model implementation in analysis when VEs are used.

7. Discussion

The findings in this study support the results of other studies. Kuivanen (1995) concluded that new software tools can be effective for the safety design of a robot system. Hazards can be identified and risks assessed during the design phase of the system. Bengtsson and colleagues (1997) also had similar results when studying visualisation with different kinds of drawings and simulation of a production system.

The specific objectives were as follows:

1. To provide a new methodology for machinery safety analysis, to be adopted by the users in order to train them to identify hazards and to use the new manufacturing system safely.

In this work a new SAVE method was developed, based on Work Safety Analysis, participatory approach, task analysis and visualisation with VEs. The results of the case studies implied that the method is applicable for the safety analysis of machinery in design phase. The participants in the safety analysis groups found the method useful for safety analysis of a new machinery still in the design phase. The method was also recommended for other similar projects.

2. To provide new knowledge of the use of the participatory approach when computerised visualisation is used in safety analysis.

Judging from the results the participatory approach is applicable in safety analysis. The knowledge and experiences of workers can be brought directly to the evaluation procedure. The participatory approach seemed to need practice in that the concepts and the language should be mutually understood. The selection of the co-operative experts in the level closest possible to the production system was also seen as important factor to have a fluent and productive atmosphere during the analysis sessions. This was successful based on the work of project managers and foremen in the cases. Co-operation during the analysis processes was good and the workers were active in the group. The results of this were based on the author’s perceptions during the case studies and are in line with the results of other studies implementing the participatory approach in ergonomics and design procedure (e.g. Noro 1991, Leppänen et al. 1991, Eklund 1999, Kadefors and Forsman 2000).

3. To provide new knowledge of the role of computerised visualisation in the safety analysis process.

Computerised visualisation had an important role in the safety analysis of the cases. Visualisation was accomplished with VEs, which were evaluated as an applicable tool for visualising machinery and its functions. The role of visualisation is to create a mutual understanding of the target system analysed by a safety analysis method. The result of this work is in line with results of other studies (e.g. Kadefors and Forsman 2000, Sundin 2001)

Issues such as the details and the accuracy of a model will play an important role in developing the reliability of three-dimensional models in virtual environments. Participant will rely on the model-maker having built the model according to the drawings and other available information with optimal knowledge. If the dimensions of the model diverge from what they should be, the results of the analysis will not be reliable. A three-dimensional model, however, can also offer a tool for checking the dimensions and positions of parts of a machine in a drawing. The ability to see the model from different and independent view points is one key characteristic of virtual environments. This feature gives the possibility to analyse mechanical hazards of a machine or machinery systems. This study indicated that three-dimensional models could be beneficial in the case of about half of all hazards in a machine system in a steel plant. The proportional significance of the effects of using three-dimensional model in safety analysis will depend on the characteristics of the target system. A system which involves more electrical, biological or other hazards than mechanical will not derive the same benefits from using three-dimensional models.

4. To provide new knowledge of the role of the digital human model in safety analysis.

The results on the implications of digital human models indicated that they are useful in safety analysis. The portion of the usage in the respective cases was less than expected. This could be due to the characteristics of the systems analysed and the poor usefulness of the digital human models. The easy-to-use characteristic of a digital human model is a very important issue in implementing human manikin in the evaluation of human machine interaction with VEs. The results of the case studies were similar to those of Leskinen and Haijanen (1997), Grobelny and Karwowski (2000) and Sundin (2001).

7.1 Safety analysis

The safety analysis method used in this work was selected to be as user-friendly as possible and with the idea that at the same time the company can obtain the basic safety information of the system for their CE marking mechanism. The analysis was at first based on the old EN standard, but during the implementation was changed to WSA. This was due to the easier analysis procedure with WSA than the EN standard. The former was a difficult and laborious procedure. The experiences in this work were the same as in the work of Kivistö-Rahnasto (2000). One conclusion was that the machinery safety directive and the standards do not provide a sufficient basis for the manufacturer or the customer to evaluate the adequacy of safety measures taken and the acceptability of the remaining risks. Risk assessment according to EN standards can be unreliable when design is conducted without the necessary safety design capabilities.

The rating of the hazards in the machine system was at first difficult to evaluate, but after taking relativity into account, the evaluation was effective. The use of pair comparison with risk estimation had the effect of producing more reliable results than without. The difficulties in estimating risks were due to unfamiliarity with the method.

The differences in hazard identifications with VEs between the cases were partly due to the different processes, machines, tasks and environments in cases but also due to the learning process in the groups when carrying out safety analysis. When hazard identification with VEs became more familiar VEs also were more actively applied in safety analyses.

7.2 Participatory design

The participatory design method is also useful in safety analysis. The positive effects on the quality of analysis are

- wide knowledge among participants is usable in the analysis process,
- effects of appreciation of workers’ opinions and knowledge,
- effect of the participants having equal opportunity to have influence the design,
- possibility to concentrate on the task itself rather than on tasks as encountered in the real job.

The participative approach had positive effects also due to different viewpoints arising in the analysis process. Usually a consensus is quite easily reachable, but the dynamic of group work will still have an influence on the work. A strong personality can have more influence on the evaluation results than a quiet person. Therefore all participants should be familiar to the group work. The spokesman of the session is in these cases the key person in handling the situation in such a way that the knowledge of the entire membership will come into use during the analysis.

In this context the author agrees with Sundin (Sundin 2001) that participatory ergonomics should be formed around the designers so that the employees involved can take part also in the design phase instead of participating only in the production development process afterwards. The PED approach (Participative Ergonomics Design) conforms to common practices in concurrent engineering (CE), providing benefits from working together in multidisciplinary teams.

The members of the groups working on the cases here had worked together for several years and they already had experiences of the group work; thus the activity in the sessions was good and everyone’s opinion could be taken into account during the analysis. The computerised visualisations enhanced the understanding of the process, and of functions and interrelationships of the machines, the ideas and solutions for safety measures. This finding also supports those in other studies (e.g. Sundin 2001, Bengtsson et al. 1997).

7.3 Virtual environments

The use of virtual environments in the design process could have more positive effects on the design if implemented already in the conceptual phase of the design. This is not always realistic due to the excessively concept-oriented situation, e.g. the drawings are perhaps not completed in such a way that they could be modelled, the basic idea is not visual, and there are too many variables to be solved. In the concept phase a sufficient number of different models should be available in a library, from where they can be searched and put on the conceptual model. This phase should be completed and evaluated very quickly, and in a different way than in the detail phase of the design. In the detail phase more information on the system is available and more detailed analysis can be accomplished. The use of virtual environments only in the detail phase loses the opportunity to analyse the concept of a design from the safety perspective.

The efficacy of the use of virtual environments in safety analysis will be increased when the suppliers of machine systems also use three-dimensional models, which are easily implemented in different virtual environment software. This will take place within a few years from now and was already in progress during the 1990s. A revolution in implementing virtual environment in design processes is expected in the first decades of the 21st century, when the medium size companies will take the technique in use. This requires however further development of softwares and computers, but also in the design procedures.

The concept of virtual reality can be presented in a different way than Milgram and Takemuras's (1994). Virtual reality will, in its final stage, present the full reality by a wholly artificial technique and include different new technologies, perhaps hologram technology, and new haptics and other sensation innovations. Figure 49 illustrates the new mode of presenting virtual reality and the technology within it.

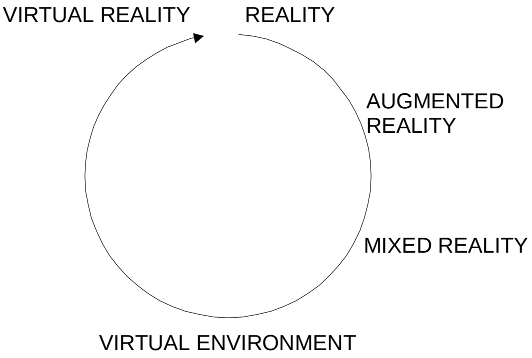


Figure 49. Virtual reality as a circle of technology.

The highest level of immersion in virtual reality is achieved when reality and virtual reality cannot be distinguished by human senses. Virtual reality can however be more than reality. It can bring more and in different ways information on the object in hand or related to it, than is possible in reality. Virtual reality is still in its early development stage and will enhance different areas of civilisation today and in the future. More investigation and development work is needed to deepen and broaden the use of virtual reality.

The production of virtual environments requires both software and hardware and VE is thus dependent on the development of information technology. VE has, however, its own features developed according to the needs of virtual reality implementations. In this work software and hardware were at an “engineering level”, but technology was also available in so called “high end level”. The engineering level VE system means e.g. medium size computer and graphical power, visualisation with conventional screen (desktop or screen with projector images) and off the shelf HMD with narrow field of view and a head tracking system. High end level VE means e.g. high computational and graphical power, visualisation with CAVE™ or wide field of view HMD with stereographic images and motion tracking system for the whole body. The engineering level seemed to be suitable for safety analysis implementing participatory approach and used on the company premises. The engineering level package consisted of an effective computer, versatile 3-D simulation software with virtual reality option, a video projector and a screen.

It would have been interesting to study the degree of virtual reality according to Kalawsky’s cube (Kalawsky 1993a) to assess the value of immersion of safety analysis. This was not, however, possible due to restrictions of recourses in the case studies. The degrees of presence, interaction and autonomy were not evaluated in this work. In fact, there is at present no such method whereby one can measure these degrees. In this work the degrees of presence, interaction and autonomy were not at their maximum values in Kalawsky’s cube, and were in fact different in each case depending on the possibility to use HMD and tracking system. According to the experiences of the case studies in this work, when the participative ergonomics approach is utilised in safety analysis work, the most practical visualisation technique is a projector with images or animations on a large screen with an option of stereoscopic mode.

A simple simulator, based on PC joysticks developed for computer games or other operation equipment with a measurement card in the computer, a screen or HMD, would be valuable for the evaluation of work tasks such as in crane operations. The value of using a simulator and a digital human model depends significantly on the task. When there is a manually operated machine, the simulator is valuable. When a task includes manual work with different postures, a digital human model would have added value in analysis.

The SAVE method will need one operator with skill in software and some knowledge of the target system, and manager who operates with the group and VEs during the safety analysis. These persons may come from inside a company, but should have knowledge and experiences of safety analysis methods, VE and group work.

The details of the models in the virtual environment were built according to the experiences drawn from modelling previous cases. The main idea was that all the machines and critical points were identifiable. The issue of details in models is interesting and has also been brought up in other papers e.g. by Kuivanen (1995), Bengtsson et al. (1997) and Sundin (2001).

7.4 Digital human models

The use of a digital human model in safety analysis is valuable when there is need to analyse space (e.g. safety distances) around working situations, field of view, strength during a task (e.g. during lifting and lowering, pulling, pushing), and task performance capability. The situations when a human model is needed vary with the characteristics of work. The cases in this work included relatively few human interactions in the process, but the human model still showed advantages during safety analysis. Benefits were found in evaluating hazards, safety distances, working conditions, and field of view in the operation room, in maintenance situations and during observation tasks. These situations comprised about ten per cent of all the hazards found in the cases. To increase the implementation of digital human models there should be more versatile and more user-friendly digital human models available for different design phases.

7.5 Validity

This work concentrated on evaluation of the use of virtual environments in safety analysis and participatory ergonomics. The approaches used for this purpose comprised observation, comparison, questionnaire, and interview methods.

The researcher made observations during the analysis work and subsequently checked them. The researcher observed the real situations when the participants were analysing the target process. The situations were thus relevant and the observations were based on the real analysis process. The engineers, managers and workers conducted the workshops as experts on the target process.

The results of observations were collected and analysed by comparison with the list of hazards, hazardous situations and hazardous events according to the standards. The safety analyses aimed to identify all the relevant hazards inherent in the target system. As experts on safety have made the list of hazards in the standard (EN 1050) for the safety of machinery, the hazard list was relevant.

Questionnaire was sent to those participants who had been on the safety analysis workshops during the cases. The persons, to whom the questionnaire was sent, were selected according to the workshop attendance lists and were checked by the project managers. The researcher according to his experiences of the use of virtual environment, safety analysis and questionnaires formulated the items in the questionnaire. The questions were aimed to identify the advantages and disadvantages of the use of virtual environment during safety analysis.

The experts for the interviews were chosen by the researcher according to the amount of participation in the safety analysis workshops and the researcher's experiences of interviews. The interviewed experts should have participated in at least two safety analyses with virtual environment conducted by the researcher. Also the time for the interviews was selected according to the available time of the experts.

7.6 Reliability

The observation data were checked afterwards by the same researcher and with some colleagues at the laboratory. There were no video films available from the sessions. The results were thus based only on the observations made by the researcher. It would have enhanced the reliability of the results if notations could have been checked from video films. The number of cases will increase the reliability in this work. The diverse nature of the cases also reduces the possible systematic error.

The number of answers in questionnaire was small for general conclusions, but the results indicate the experiences and expectations of experts who had conducted several safety analyses with virtual environment. The items in the questionnaire were as easy to understand as possible and the number of questions was adjusted to correspond to the time reserved for answering. Thus the type of questions was so constructed that participators could answer by ticking the most relevant point according to his or her evaluation. The participants could answer the questionnaire on their breaks during a workday.

The answering time from the postage to delivery and back to the researcher was two weeks, including the time from the project manager to the other participants. Thus the time for answering would have been enough to answer with close consideration. The time spent on the answers, however, might have been less than planned because of the tight schedules during the daily tasks. The researcher or the project managers did not control the answering situations. In some cases a foreman gave time to answer the questions during a shift. This was not however prescribed by the researcher. Guidelines for anonymous and individual answering were however emphasised. Every answer could have been sent separately in a closed envelope to the researcher.

The structural interview method was used in this work. The interviews were recorded and the participants in question forms also typed the answers during the interviews. The recorded interviews were also written down, so the answers and comments could be sorted according to the contents. The participants were project managers, safety specialists, foremen and workers. One interview was held as a workshop because of the time schedule of the participants and convenience of arranging the meeting place. The discussions during this meeting were more inspiring to make comments rather than restricting. The situation was also relaxed and open. Other participants could support answers given and were according to his or her evaluation or experience. Guidance on each answer was not observed. Each participant filled his or her own answering form separately before the actual interview.

The reliability of the results is based on the several methods used in the work, for example indication of hazards with seven cases, questionnaire and interviews of experts. The time between the analysis and questionnaire and interviews was from two to three years, which can have had a negative influence on the reliability of the results of these methods. This time-lapse, however, could have emphasised the issues which have been the most important. The lack of information on other issues may, however, have been ignored.

7.7 Some findings during the case studies

Analysis work is dependent on the method and on when the participatory approach is used, also on the dynamics of the group. The success of participatory design is also a function of persons activities in a group and experiences of working together. In this work the group members had experience of group sessions and worked actively during the sessions. Thus all the effort could be focused on the safety analysis. The trust between the workers and management had been established previous to these cases and had a positive impact on the cases. During the cases the trust seemed to increase when all the participants had the same opportunity to influence the analysis and were active during the process. All the participants knew each other well and had several years of experience. There seemed to be no conflict between the workers and managers. Only some doubts could have been raised by the information that the modernisation projects could not influence the number of workers in the plant. The aim of the company management was that the workers in different departments in the future would have more versatile tasks and knowledge. The work was changing from manual loading and filling tasks to more control and maintenance tasks. The possibility to perform tasks in the future in more convenient rooms and safer environments was clear motivation for the workers, who were active and knowledge-sharing during the analysis work.

The comments from the workers supported the adoption of the method using the virtual environment. This visualisation aid gave new perspective to the drawings, which were still actively used during the analysis. By using a screen it is assumed that members in a group have a more homogenous conception of the objects in hand than by only looking at drawings. This finding supports the conclusions reached by e.g. Bengtsson and others (1997) and Sundin (2001). When the stereoscopic lenses were in use the immersive function gave a more realistic illusion of the machines and environment than only the picture on the screen. Because of the individual use and the unfamiliarity of the stereoscopic mode this mode was not often used during the analysis work. One reason for this could also be that the change from their previous procedure and tools to the method of this work was already large enough for their purposes.

The simulator with VE was in use only in the first three cases. This was partly due to the nature of the cases and also to the practicability of using simulators on the company site. When the safety analysis was performed on the company premises the VE systems consisted of minimum equipment partly due to the travel arrangements and partly due to the limited room for the VE system. Also the time for the analysis sessions was limited and had an influence on the VE system chosen for the safety analysis sessions.

The cases included the investment projects of the company during the 1990s. The people involved in the safety analysis process were the same people who participated in other project sessions. They were also involved in several safety analysis projects during the investment process. Their knowledge of safety analysis with VE was thus improved with the safety sessions. This improvement had positive impacts on the time spent on the process.

Also the type of use of VEs changed from a new interesting tool to a natural tool promotive of the process. The time was not spent on training in the use of VE, but directly on the detection of hazards and hazardous situations. The training mode during the safety sessions varied from two to four sessions. To speed up the training phase, it would have a positive impact if a prior session for training were conducted with the safety analysis group. In this work the training issues were implemented during the safety sessions without any prior VE training sessions, this was on account of the lack of time reserved for the safety analysis. According to the comments received from the participants, the method used was suitable in the case situations.

7.8 Future research

Further research is needed in developing more sophisticated softwares and equipment for virtual environment technology. New procedures for design using virtual environment, more versatile digital human models, and effective and validated analysis more suitable to the design process are also needed. Guidelines to optimise computer and software power for safety analysis will enhance the use of virtual environments. A new way of advancing the virtual environment is to use an internet during design as a collaborative design procedure. This mode of design calls for research on information exchange, model management, licensing, evaluation of results etc. Standardisation of the 3-D web platform is also very important for the wide use of 3-D models and content. In fact this development is already ongoing in some consortiums in this field.

Training using the virtual environment is also still under development and requires research, e.g. cognitive studies, which address the information management within virtual and augmented reality.

The resources needed and the costs of safety analysis projects will be reduced over time by reasons of

- *Learning;* knowledge of the tool, method and target process will increase during the projects,
- *Library models*; models will be saved in the library files of a project and can be used in other projects,
- *Procedure*; more effective ways of performing the analysis will be generated,
- *3D modelling during design*; more 3-D models will be available after implementation of 3-D modelling softwares,
- *More effective design softwares*; design softwares will become more user-friendly and object-oriented,
- *Standardised software environment*; implementation of generic platforms will increase operability with other softwares.

It would have been interesting to study the impact of the virtual environment on the degree of detecting hazards in a machine system and on the time spent during safety analysis. In this work the degree of detection was assumed to be as high as possible in view of the several experts, including workers, participating in the analysis, and the systematic methodology. With a control group it would have been interesting to compare the results of using the traditional method with drawings and of using a virtual environment. This was however difficult to arrange due to the project-like nature of the cases, lack of resources and time, and also difficulties in arranging homogeneous groups for the analysis work. Only interviews and questionnaires were used in evaluation of the influence of the virtual environments on these objectives.

8. Conclusions

In this thesis a new procedure of involving use of the virtual environment during safety analysis was introduced. The procedure was tested in seven different cases during an investments program in a steel factory. The procedure also included a training element for the workers, foremen and operation managers in detecting hazards and hazardous situations in their machine system.

The use of virtual environment enhanced the participatory ergonomics approach used in safety analysis. The VE gave a common understanding of the target machine system to all participants, and thus equal possibility to evaluate the functions, work, tasks and safety of a system. VE supports the implementation of participatory ergonomics in safety analysis.

Safety analysis could be performed with more information on the target system when using VE. The visualisation of the system and its functions are very important to all participants when evaluating the safety of a system. Drawings of the system are still needed during safety analysis with VE. Visualisation with VE gives information on the scale of the target system and the relationships of different parts of a machine to the participants in a safety analysis group.

A digital human model as a human figure was in use in about 10% of the detection actions of hazards or hazardous situations in the safety analysis. The digital human model in VE gives more information on mechanical hazards such as crushing, shearing and impact than on other hazards during safety analysis. The digital human model is useful when detecting hazards during performance of a planned task or functions of a machine virtually in a virtual environment. It will also give information on the distances needed to implement safety measures for mechanical hazards.

The results of the case studies carried out in this work indicate that less than 60% of the hazards and hazardous situations in a system can be detected by virtual environments during safety analysis. The visualisation with three-dimensional models in a virtual environment system is, however, a vital element in creating a common and understandable image of the target system for all partners in participatory design or safety analysis, especially when analysing versatile and complex machine systems. This image will lead to more reliable results of safety analysis than with only drawings. The use of Virtual environments has also positive impacts on the design of safety measures.

The use of virtual environments in safety analysis has benefits in analysing systems which involve e.g. critical manual work, automation systems, several simultaneous machine actions or functions, large machines, difficult maintenance situations, and complex machine systems.

The operator of a virtual environment system is a key person for the effective handling of the model. It is beneficial for the procedure if this operator has a good knowledge of the system in question. Also the short response time of software and computer interaction has an influence on the usefulness and effectiveness of the virtual environment. The quicker the response is, the less negative attitude towards the use of VEs will be perceived.

Several technical aspects need to be faced in the future, in order to enhance the usefulness of the virtual environment system. Some of the most important aspects are:

- accurate calibration of the virtual space
- improvement of the graphical speed
- development of standards for virtual functions, e.g. assembly tasks
- testing the VE technology against real requirements.

When the standardisation of CAD and VE systems is resolved, applications in this field will increase dramatically due to the easier use and advanced compatibility of the different software and systems. Some efforts have been active on this issue.

Once equipment and software for VEs have become more versatile and less expensive the usage of VEs in plant design and development work will increase. The use of VEs in plant design will enhance the development and analysis of different design variations from several points of view, including safety.

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Appendix A: WSA form in the safety analysis

VTT MANUFACTURING ENGINEERING	**WORK SAFETY ANALYSIS** System: Steel factory Subsystem: Continuous casting plant Job: Crane operator	Date: Page: 1(1) Compiler: TM, analysis group

WORK TASK	HAZARD/HAZARD SITUATION	CAUSE	RISK	MEASURES

Appendix B: Form of interviews

You participated in investment projects of your company, during which the safety of the new system was analysed with computer models, simulation and virtual reality, i.e. with virtual environment VE. The VTT Technical Research Centre of Finland took part in the safety analysis. This interview is a part of those projects.

Would you please, could you answer to the questions attached to this paper according to your opinion? You can make additional comments and notes after each question.

Basic information:

Age: ______ years Professional education: ______________________

Years at work with current employer: _____ years

Years at work in current job (the job at the moment of safety analysis): _____ years

Description of your job: ______________________________________

How many working groups did you participate in (during the VTT projects)? _____ groups

How many meetings did you participate in with VTT? (Approximately) ____ meetings

How many safety analyses did you have before these projects (0 = none) ____ analysis

Had you had any training in safety analysis before this project? _____ no, ____ yes, if yes, when _________ , how long was/were the period/s? ________ hours/days, who gave the training? ____________________________________

QUESTIONS:

1 What were your expectations for the safety analysis, what should be the outputs, what benefits would there be from it in your opinion?
2 Was the safety analysis method implemented already familiar?
3 In your opinion what benefits will 3-D modelling bring to the safety analysis?

4 In your opinion what benefits will functional simulation bring into analysis and evaluations?

5 Did you gain any assistance from 3-D modelling? How? Where?

6 In your opinion where do you find virtual environments bring benefits to the design process?

7 Did you find economic benefits in the implementation of modelling, simulation and/or virtual environment in your company? In your opinion how great would the possible benefits be?

8 Would you implement 3-D modelling in the future in development projects, e.g. as a tool for continuous development? What about simulation and virtual environment?

9 In your opinion what would extension of the implementation of 3-D modelling, simulation and virtual environment need, or are the tools and procedures already suitable in usage?

10 In your opinion do 3-D modelling, simulation and virtual environments belong as basic functions in the companies, or will they be a service from outside the company? If outside, why so?

11 In your opinion how do 3-D modelling, simulation and virtual environment comprise a part of participative design?

12 Other issues?

Appendix C: Form of the questionnaire

You participated in an investment project of your company during which the safety of a new system was analysed with computer models, simulation and virtual reality, i.e. with virtual environment VE. The VTT Technical Research Centre of Finland took part in the safety analysis. This questionnaire constitutes part of those projects.

Would you please answer the questions attached to this paper according to your opinion using the scale given below by marking a cross in the relevant column? You can make additional comments and notes in the comment column after every question.

Put your answer in the envelope attached to this questionnaire and deliver the envelope to your supervisor, who will send it to VTT. Every answer will be dealt with confidentially. No-one's answer could be identified from the results.

Scale:

0 = not at all
1 = very little
2 = little
3 = fairly
4 = much
5 = very much
ea = no answer or don't know

Information on the respondent:

Sex: Male/Female (strike out/leave the answer) Age: ______ years
Professional education: __________________________
Years at work with current employer: _____ years
Years at work in current job (the job at the moment of safety analysis): _____ years
Description of your job: ____
How many working groups did you participate in (during VTT projects)? _____ groups
How many meetings did you participate in with VTT? (Approximately) ____ meetings
How many safety analyses did you have before these projects (0 = non) ____ analysis

Had you had any training for safety analysis before this project? _____ no, ____ yes, if yes, when _________ , how long was/were the period/s? ________ hours/days, who gave the training? ____________________________________

Questions: In your opinion …

Question number	0	1	2	3	4	5	**ea**	Comments
1 How did the safety analysis enhance your knowledge of the target?								
2 How did the use of VE enhance the understanding of the drawings?								
3 How did the use of VE constitute to the building of common understanding of the development group?								
4 How did the use of VE constitute to the building of producing new ideas?								
5 How did the use of VE make it difficult to work?								
6 How should the implementation of VE to safety analysis be increased?								
7 How did the VE increase the identification of the critical points in the system?								
8 How did the VE increase the possibility to identify faults in the drawings?								
9 How did the use of VE increase the work in safety analysis?								
10 How did the VR enhance understanding of the functions of the machine or the system?								
11 How much time did the building of models for VE take?								
12 How did the use of VE speed up the analysis work?								
13 How did the use of VE minimise the expenses of the analysis?								
14 How did the use of VE reveal substantial points for saving expenses?								
15 How did the use of VE enhance development of work practices?								
16 How did the use of VE make the working atmosphere less pleasant?								
17 How did the use of VE save expenses by revealing points for development before run-up?								
18 How do you recommend the use of VE to be implemented in other similar working group?								
19 How do you think that the use of VE needs special knowledge of implementing VE?								

20 How did the use of VE increase the expense of the analysis?								
21 How broad is the use of VE in your company?								
22 How did the use of VE increase the efficiency of the analysis?								
23 How did the use of VE minimise the run-up time of the target system?								
24 How does the use of VE help in work training in your opinion?								
25 How does the use of VE need human models in work training?								
26 How does the use of VE need additional functional simulation to produce sufficient advantage from the models?								
27 How will the use of VE increase in companies in near future (during 2-3 years) in your opinion?								
28 How does the use of VE need further development of hardware and software to achieve significant expansion of implementation?								
29 How does the use of VE enhance learning in work?								
30 How does the use of VE enhance continuous improvement in work?								
31 How did the use of VE enhance the participatory design?								

Other observations or comments:

You can continue on the back of this paper.

Thank you very much for your answers and comments!

Timo Määttä

You can obtain additional information from your supervisor or me (the undersigned).

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Appendix D: Summary results of the safety analysis

*Table D. Summary of the results in hazard identifications in Cases 1–7 (**N** = 1193). (The hazard numbers refer to standard EN 1050)*

Hazards		All [a)]	M [b)]	S [c)]	H [d)]	Proportion [e)]		
1	**Mechanical hazards, caused by:**							
1,1	crushing hazard	167	133	85	47	79,6%	50,9%	28,1%
1,2	shearing hazard	24	14	11	3	58,3%	45,8%	12,5%
1,3	cutting or severing hazard	8	5	2	1	62,5%	25,0%	12,5%
1,4	entanglement hazard	7	5	4	2	71,4%	57,1%	28,6%
1,5	drawing-in or trapping hazard							
1,6	impact hazard	284	183	72	29	64,4%	25,4%	10,2%
1,7	stabbing or puncture hazard	1	1	0	0			
1,8	friction or abrasion hazard							
1,9	high pressure fluid injection hazard	11	2	0	0			
1,10	ejection of parts (of machinery and processed materials/workpieces)	8	4	3	0			
1,11	loss of stability of machinery and machine parts	31	21	9	0	67,7%	29,0%	
1,12	slip, trip and fall hazards in relationship with machinery (because of their mechanical nature)	117	88	16	5	75,2%	13,7%	4,3%
2	**Electrical hazards, caused for example by:**							
2,1	electrical contact (direct or indirect)	4	0	0	0			
2,2	electrostatic phenomena	2	0	0	0			
2,3	thermal radiation or other phenomena such as ejection of molten particles, and chemical effects from short circuits, overloads etc.	2	0	0	0			
2,4	external influences on electrical equipment	7	0	0	0			
3	**Thermal hazards resulting in:**							
3,1	burns and scalds, by a possible contact of persons, by flames or explosions and also by the radiation of heat sources	328	174	74	21	53,0%	22,6%	6,4%
3,2	health damaging effects by hot or cold work environment	2	0	0	0			
4	**Hazards generated by noise, resulting in:**							
4,1	hearing losses (deafness), other physiological disorders (e.g. loss of balance, loss of awareness)	7	0	0	0			

4,2	interference with speech, communication, acoustic signals etc.	10	0	0	0			
5	**Hazards generated by vibration (resulting in a variety of neurological and vascular disorders)**							
6	**Hazards generated by radiation, especially by:**							
6,1	electrical arcs	2	0	0	0			
6,2	lasers	1	1	0	0			
6,3	ionising radiation source							
6,4	machines making use of high frequency electromagnetic fields							
7	Hazards generated by materials and substances processed, used or exhausted by machinery for example:							
7,1	hazards resulting from contact with or inhalation of harmful fluids, gases, mists, fumes and dusts	30	7	0	0	23,3%	0,0%	0,0%
7,2	fire or explosion hazard	32	6	1	0	18,8%	3,1%	0,0%
7,3	biological and microbiological (viral or bacterial) hazards							
8	Hazards generated by neglecting ergonomic principles in machine design (mismatch of machinery with human characteristics and abilities) caused for example by:							
8,1	unhealthy postures or excessive efforts	15	9	7	7	60,0%	46,7%	46,7%
8,2	inadequate consideration of human hand-arm or foot-leg anatomy	2	2	0	0			
8,3	neglected use of personal protection equipment	1	0	0	0			
8,4	inadequate area lighting	7	5	5	4			
8,5	mental overload or underload, stress etc.							
8,6	human error	35	20	10	4	57,1%	28,6%	11,4%
9	Hazards combinations	4	0	0	0			
10	Hazards caused by failure of energy supply, breaking down of machinery parts and other functional disorders, for example:							
10.1	failure of energy supply (of energy and/or control circuits)	8	0	0	0			
10.2	unexpected ejection of machine parts or fluids	4	1	0	0			
10.3	failure, malfunction of control system (unexpected start up, unexpected overrun)	20	8	1	0	40,0%	5,0%	0,0%
10.4	errors of fitting	3	0	0	0			
10.5	overturn, unexpected loss of machine stability	2	1	1	0			
11	**Hazards caused by (temporary) missing and/or incorrectly positioned safety related measures/ means, for example:**							
11.1	all kinds of guard	3	0	0	0			

11.2	all kinds of safety related (protection) devices	1	1	0	0			
11.3	starting and stopping devices	1	1	0	0			
11.4	safety signs and signals	1	0	0	0			
11.5	all kinds of information or warning devices							
11.6	energy supply disconnecting devices							
11.7	emergency devices	1	0	0	0			
11.8	feeding/removal means of workpieces							
11.9	essential equipment and accessories for safe adjusting and/or maintaining							
11.10	equipment evacuating gases, etc.							
	Summary	1193	692	301	123	58,0%	25,2%	10,3%

a) all identified hazards

b) identified hazards with 3-D models

c) identified hazards with simulation

d) identified hazards with digital human model

e) proportions of identified hazards with 3-D models, simulation and digital human model to all identified hazards

Appendix E: An example of the hazard identification with the help of VEs

Table E. Results of the hazards identification in safety analysis of an individual case with help of VEs.

Hazards		**All (A)**	**A/S %**	**3-D**	**SL**	**DH**	3-D/A %	SL/A %	DH/A %
1	**Mechanical hazards, caused by:**								
1,1	Crushing hazard	56	20,0	51	33	19	91,1	58,9	33,9
1,2	Shearing hazard	3	1,1	2	2	0	66,7	66,7	0,0
1,6	Impact hazard	97	34,6	58	7	1	59,8	7,2	1,0
1,9	High pressure fluid injection hazard	5	1,8	1			20,0	0,0	0,0
1,12	Slip, trip and fall hazards in relationship with machinery (because of their mechanical nature)	64	22,9	50			78,1	0,0	0,0
3	**Thermal hazards resulting in:**								
3,1	burns and scalds, by a possible contact of persons, by flames or explosions and also by the radiation of heat sources	40	14,3	13			32,5	0,0	0,0
7	**Hazards generated by materials and substances processed, used or exhausted by machinery for example:**								
7,1	hazards resulting from contact with or inhalation of harmful fluids, gases, mists, fumes and dusts	3	1,1				0,0	0,0	0,0
7,2	fire or explosion hazard	3	1,1	1			33,3	0,0	0,0
10	**Hazards caused by failure of energy supply, breaking down of machinery parts and other functional disorders, for example:**								
10,3	failure, malfunction of control system (unexpected start up, unexpected overrun)	9	3,2	6			66,7	0,0	0,0
	Summary	280	100,0	182	42	20	65,0	15,0	7,1

All = All identified hazards in a category; S = All identified hazards
A/S =all identified hazards in category versus all hazards
3-D = identified hazards with 3-D models
SL = identified hazards with simulation
HD = identified hazards with digital human model

Appendix F: Results of the interviews

Table F. Information on the subjects in the interview.

Gender	male		
Occupation	Technician 4, Engineer (BSc) 3, Engineer (MSc) 1, Worker 1		
Title	Project Manager, Development Technician, Maintenance Manager, Project Technician, Development Engineer, Development Manager, Founder		
Training in safety analysis	Yes = 5, One day training given by the company specialists No = 4		
	Mean	Range	
Age in years	48,9	44–56	
Years in current company	24,6	12–35	
Years in current work	10,6	0,5–30	
Number of analysis groups	1,9	1–6	
Number of meetings/analysis	9,1	3–20	
Number of safety analyses before	1,4	0–3	

Questions (participants A to I):

1 What were your expectations in performing the safety analysis, what should be the results, what benefits did you expect to have from it?

A	“Performing with a group: to identify the hazards, safety risks and their probability, the goal being a safe workplace. According to the hazards changes for increasing safety and procedures.
B	“To identify the risks and minimise them (risks for persons, equipment and production loss)”
C	“Safe work practices, (operation/maintenance), work levels and their placements, working order in problematic situations”.
D	“Checking machinery design, safe performance of operation and maintenance work”.
E	“Safety risks in maintenance and service work, changes to the equipment for improving safety”.
F	“Possible improvements to equipment, also for safety reasons, danger areas in operation and maintenance (possible changes to accessory equipment, procedures)”, to evaluate the safety level of equipment in general”.
G	“Secure, safe operation for the system, CE marking, licence for radio operation, remote operation”.
H	“Guidance for the design, to seek the most critical points and the risk.”
I	“Hazards related to work and equipment, elimination of hazards already in the design phase”.

2 Did you previously know the safety analysis method used in the projects?

A	“No”
B	“Yes, roughly”
C	“No”
D	“No”
E	“No”
F	“Yes”
G	“Partly”
H	“No”
I	“No”

3 In your opinion, what benefits will 3-D modelling bring to safety analysis?

A	“All persons will experience the environment as “concrete”, most people could not visualise from the drawings. Small and large faults in design will be well exposed”.
B	“Relativity in understanding the size of the equipment, movements and operation, harmonising the subjects in handling issues (more than imagination)
C	“Systematic handling of issues in the design phase.”
D	“The motions of the equipment are easier to see than from the drawings, the training aspect.”
E	“The scales etc. are easier to comprehend”.
F	“The scale of equipment to human and the field of view to different targets, operation rooms etc.”
G	“More visualisation, ensure and speed up the design, make training easier.”
H	“Good assistance method in translating the drawing into motion and actions will bring issues more clearly to the fore, when seeking e.g. the boundaries and relationships of equipment or system”.
I	“Will clarify the evaluation of the target”

4 In your opinion, what benefits will computer simulation of a system and its functions bring to safety analysis?

A	“It’s easier to analyse, contact with the coming reality can be created by simulation. The analysis is easier to accomplish.”
B	“The participants will obtain a common picture as a whole; with visualisation it’s easier to have influence on the problems, the understanding of several concurrent operations.”
C	“Systematic approach for the design phase”.
D	“Quicker and more versatile appraisal”.
E	“Taking into account the motion of the equipment, simulation of the replacement of a partial system, the fact that all replacements of equipment would not be possible to accomplish as the designer planned, was brought out in simulation.”

F	"–" (No answer)
G	“Made sure the safety of the motions in operation, the pictures and the motions will focus the participants on the issues at hand.”
H	“When seeking more efficient operation especially in a batch-like process, where the material flows move as cycles by different mechanisms, simulation will specify the bottlenecks more clearly.”
I	“Will help in taking account of the details.

5 Did you derive any help from 3-D modelling in safety analysis? How? Where?

A	“Yes. The wall of a structure e.g. had to be moved 0.5 m. The lifting equipment was developed to be more functional, view, placement of the equipment in the operation room and the windows, placement of the operation panel.”
B	“Yes! One could make realistic the free space needed and the safe procedures in maintenance operations, and the simulated motions of the equipment exposed failures in operations, and problems.”
C	“The design of work platforms, changing or maintenance of parts or equipment, views to different targets (during operation).”
D	“Yes, the fact that the release of a rolling unit would be impossible was exposed by simulated motions of the rolling unit, securing the axles to impacts in different operation situations.”
E	“Yes, has helped in studying risk areas.”
F	“Just these scale effects, views, pathways.”
G	“Will visualise, makes things easier to understand e.g. in designing what to see.”
H	“Was helpful, we got basic information on design”.
I	“Helpful in studying the changing work of a tank in a machine, the tasks at the casting area.”

6 Where do you find that the virtual environment (virtual reality) will bring benefits to design?

A	“The views in workplaces, from the operation room to workplaces, placement of equipment, ergonomics.”
B	“Planning the maintenance work and taking into account the needs of maintenance (free spaces), studying the motions, studying operator aspects, based on which the work places for the operator was situated.”
C	“Studies of the placements of equipment, will they fit in their places, can they be replaced or maintained, the placement of cameras (operation).”
D	“Design of pathways, checking the mechanical design of complex equipment.”
E	“The views can be studied, e.g. from the hoist, operation room etc., studying the motions of equipment, etc.”
F	“I think the placements of this equipment will be clarified best by this method.”
G	“A person is a part of a model and so can evaluate the “real” world, and not imagine.”

H	“The persons can be placed in the plant or system, and study e.g. safety factors.”
I	“Better evaluation of distances, improvement of work practices.”

7 Do you think that modelling, simulation and/or virtual reality had economic impacts in the company? How great would the possible benefits be?

A	“Yes it had, e.g. design failures were exposed. About 0.5 million FIM.”
B	“Exposing the faulty functions, discovering bottlenecks => re-evaluation of the performances.”
C	“Yes, it had; ??? FIM.”
D	“The change of a rolling unit would not be successful during the week session => estimate 8 hours more time for the repair per two years.”
E	“They can be used in pre-training in the system; the space needed for the replacement of a partial system could be taken into account in the design.”
F	“Difficult to estimate the financial benefit, but the design would be on rather thin ice if this study is not used, thus the risk of failure is high.”
G	“They made possible quick design and removed failures => input at least twice back (1 Billion FIM).”
H	“Difficult to estimate the financial benefits, but modelling etc. has been a part in the whole process, and the project has been initiated and in action as in the plan (almost), they have had impacts on reaching the unhampered production.”
I	“Over 100 000 Euros, especially the replacement of the wall when simulating the lifts.”

8 Would you implement 3-D modelling in the future in development projects, e.g. as a tool for continuous improvement? And simulation and virtual environment?

A	“Yes, but it must still always be evaluated case by case whether there is benefit in using modelling. Both can be implemented.”
B	“Yes. Not in the evaluation of a simple system, but for complex and demanding systems.”
C	“Yes”
D	“Simulation during e.g. the development process of equipment could be useful => will the bottleneck move to another place after the alteration.”
E	“Extremely important in large, complex machinery systems.”
F	“Yes, if large changes are planned for the equipment, the same goes with the simulation.”
G	“Three times yes! for the further development of these systems, for the basic design of a new, large systems.”
H	“Yes”
I	“3-D modelling for the development of some specified systems, same with the virtual environment.”

9 What improvements do 3-D modelling, simulation or the implementation of virtual environment need to have wider implementation, or are the tools and procedures already suitable for use?”

A	“The functionality of the programs in compact machines. Reasonably easy programmability. The price of equipment and programs should be lower. The tools and procedure are ready as such, but development in equipment is still needed.”
B	“The tool should be a direct tool for the designer, thus the work done with the CAD system would be as suitable as possible for the modelling.”
C	"?" (no answer)
D	“The tool program should be an easy to use every man’s simulator, surely could be developed.”
E	“The product design software should be used directly; the systems should work with each other.”
F	“Surely should be improved, but can’t say what in particular.”
G	“Co-operation with specialist, service from outside the company, good and functional procedure.”
H	“The importance of basic information will rise when getting deeper into the process, the role of a presenter will also be emphasised also to answer difficult questions, developing visualisation, and training aids.”
I	“The quicker ability to change the virtual environments, modelling work.”

10 Do you think that 3-D modelling, simulation and virtual environment belong to companies’ own activities, or will these services be bought from outside the company in the future? If bought outside, why?

A	“In the company the equipment and know-how could be focused on the design department. Bought, because the implementation is not broad enough.”
B	“The knowledge should partly be the inner know-how of the company so that activity and results could be uniform, and the knowledge of the program as to what is possible to do, the actual performances should be bought from outside the company.”
C	“Probably will be bought from outside the company, the knowledge and the equipment are ready, do not bind own resources.”
D	“My estimation is that the simulation will form an essential part of an investment in the future (made by the producer).”
E	“The producer should consider this already in the design phase".
F	“I think this is a service that will be bought outside, because from company focusing on these issues will have the latest (best) knowledge.”
G	“Knowledge service outside, our company will focus on its own know how.”
H	“I believe, that will be bought mostly outside, it could also be implemented as a training tool in some cases.”

11 How are 3-D modelling, simulation and virtual environment connected to the participatory design in your opinion?”

A	“Well”
B	“They are a part of the design in demanding situations, especially when the time to realisation is short and the success has essential financial impact.”
C	“Same as before, see 5 and 6.”
D	“As before in design issues, training is a big advantage at least in one project in addition to just functional and mechanical design.”
E	“Should be observed in the design phase of equipment.”
F	“I think these issues should probably in the future be taken into consideration at least in large investment projects as a part of the design.”
G	“Important tool, the only one with which it can be done!!!”
H	“Well, and the comments of the workers are important, the figure of the target is more coherent.”
I	“Evaluation of a design is easier with these methods.”

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Virtual environments in machinery safety analysis

Abstract

Safety is a feature that someone or some ones have planned for a product. To ensure that safety issues have been properly considered in the design phase of a product or production system different methods and procedures and tools have been developed. Safety analyses already in design phase have been basics for ensuring product or production system safety features. To engage all possible knowledge in the safety design participatory approach and different tools have been developed and implemented.

The rapid development of computers and software has made it possible to investigate systems in virtual environments (VEs), which are potential tools for safety analyses in design phases. The use of virtual environments in safety analysis for production evaluation purposes have remained minimal, reasons being lack of methods and knowledge of their applicability in safety analysis. The objective of this work was to evaluate the impacts of VEs on safety analysis.

A new method (SAVE) of applying VEs for safety analysis was developed and tested in the work settings. The method involves a procedure, based on Participatory Approach (PA), Task Analysis (TA), Work Safety Analysis (WSA), standard EN 1050 and three-dimensional (3-D) modelling of the objects being analysed.

The materials of this thesis comprised machinery systems of five plants in a steel factory, implementing ongoing modernisation projects. The plants were hot steel storage plant, steel converter plant, secondary metallurgy station, continuous casting plant and strip production plant. The machinery systems were cranes, mixers, desulphurisation station, remote-handled cars, steel converters, ladle turrets, continuous casting machines, coilbox machine and coil conveyer.

The results indicate that the SAVE method was applicable for safety analysis in machinery layout design phase. Safety analysis will clearly benefit from the use of VEs. According to the results 58% of all identified hazards in a steel factory could be identified with VEs. Simulation with a virtual environment was assisting the identification of hazards in 25% and digital human models in 10% of all identified hazards. A common understanding of designs, possibilities of evaluating and developing the system by the workers and of providing training for operators and maintenance persons were the major contribution when using VEs in safety analysis and applying participatory approach. VEs with an analysis group improved the identification of critical safety situations during the analysis.

Once equipment and software for VEs have become more versatile and less expensive the usage of VEs in plant design and development work will increase. This, however, calls for further investigation of more effective implementation procedures and cost management. The use of VEs in plant design will enhance the development and analysis of different design variations from several points of view, including safety.

Keywords
virtual environment, virtual reality, safety analysis, risk assessment, hazards, machine safety, risks,
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