Extending the Effective Range of Prevention Through Design by OSH Applications in Virtual Reality

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Abstract. Prevention through design (PtD) is presented as a concept for designing out risks early in design and across the life cycle. PtD is an internationally recognized initiative and it is a strategy linked to safety disciplines, to the hierarchy of controls, and to new technologies. With two research projects it has been demonstrated how to use VR as new technology for PtD modeling and simulation and as a means for improving OSH early in work systems design. Investigations of virtual reconstructions of virtual accidents supported course of events and root-cause analyses. Dynamic visualizations triggered discussions about safety and usability issues in design. Risk assessments of virtual river locks with standardized components facilitate measures for risk reduction to be fed back to machinery planning. Benefits and limitations of VR applications on PtD were discussed and suggestions for fostering endeavor of PtD were given.

Keywords: Prevention through design · Virtual reality · Risk assessment · Accident analysis · Usability · Occupational safety and health

1 Introduction

Prevention through Design (PtD) is a concept of relevance for all industry and services sectors by applying its principles in the design and redesign of work premises, tools, equipment, machinery, substances and work processes. Definitions about PtD may vary given the different views of what is covered by PtD and when and how to apply the concept. A common denominator for PtD, however, is that it is heading to prevention of occupational injuries, illnesses, and fatalities by including prevention considerations in all designs that impact workers [1]. PtD is interwoven with safety engineering, ergonomics and human factors applications aiming at adapting work systems design to human requirements [2, 3]. PtD effectively contributes to the hierarchy of controls for measures of hazard and risk reduction and for improving OSH at work [4–7]. PtD is an OSH strategy for designing out risks at source and by considering safety and health implications throughout the work systems life cycle [1]. PtD is also relevant for new technologies, processes and materials during their conception and before their introduction into the market [8].

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1.1 PtD and Ergonomics

Safety engineering as a rule factors human safety into the design process. Traditional links between concepts of PtD, human factors and ergonomics are related to an ergonomics approach for work system design with human-system interaction at the core and systems design aiming at optimizing human well-being, health and safety, and overall system performance. Similar to PtD, design principles in ergonomics call for adaptation of technical system components to foster safe and healthy human behavior at work [e.g. 2].

Early developments in industrial psychology [9] influenced perspectives on systems design and interdependencies of entities in psychotechnics were discussed [10]: While subject psychotechnics rather referred to an adaptation of operator's psychological traits and competencies to requirements and conditions of job and environment, object psychotechnics in contrast covered designs and procedures for optimal adaptation of technical and production factors to the operator's psychological nature. Though, nowadays interactions between technical, organizational and personal subsystems are taken into account in work systems design [3, 7], this early distinction already points out at least two perspectives for interventions, with the latter being preferred in PtD and assumed to be effective and sustainable.

1.2 PtD and the Hierarchy of Controls

Even though legal requirements for OSH and risk assessments may differ across countries, the hierarchy of controls remains fairly similar and provides some guidance for selecting effective measures for risk reduction and prevention in systems design. In Germany, a hierarchy of controls traditionally follows levels like (a) eliminating hazard (e.g. substitution), (b) technical measures (e.g. safeguard), (c) organizational measures (e.g. job rotation), (d) personal measures (e.g. personal protective equipment, PPE), and (e) instructional measures (e.g. warning sign). Albeit shorter, this hierarchy is similar to the ten level 'general principles of prevention' as listed in the EU OSH Framework Directive [4]. The hierarchy in OHSAS 18001 [6] also has five levels, however, with PPE listed lowest. Different perspectives on the hierarchy may also widen opportunities for interventions [7].

OSH legislation e.g. in Europe or Australia with directives and guidelines are regarded especially useful in facilitating PtD. Manufacturers are required to design safe machinery that meet a set of minimal health and safety requirement and employers are held responsible for providing safe work equipment to the employees [11]. As a consequence, technology for designing safe equipment is available across countries; however, business decision makers and purchasers may not always value or request for it or manufacturers may not create demand for it by promoting it on the market [12]. Despite differences in OSH legislation across countries, PtD principles are equally important everywhere. The concept of PtD is a guiding principle for priority consideration of high level measures to combat hazards and risks at the work across the life cycle from early on.

1.3 PtD as a Strategy and an OSH Initiative

Notwithstanding its long tradition, PtD has been re-launched by OSH organizations for promoting initiatives to achieve a cultural change so that preventing work related accidents and health problems and enhancing OSH is the norm. PtD has been risen to among the most important topics for improving OSH today [1, 13]. PtD is not only a concept; it is an OSH strategy with ambitious goals for designing safe and healthy work from early on that requires commitment and active involvement of management and workers.

PtD is an US national initiative, internationally recognized not only by OSH organizations. A strong impact on the initiative resulted from activities of the Institute for 'Safety through Design' calling for an integration of hazard analysis and risk assessment methods early in design, redesign, and engineering stages, and taking all actions necessary so that risks of injury or damage are at an acceptable level [14]. Reports on successful concept application, activities, case studies, success stories, challenges and overall progress could be gathered and documented at the Safety by Design workshop held by the New Technology and Work Network [15], at the NIOSH PtD workshop [e.g. 16], and at the NIOSH conference on 'PtD: A new way of doing business' [e.g. 17], to name but a few. Activities resulted in the development of a PtD plan for the US national initiative and in a progress report on the initiatives' state including mission statement, aggregated outcomes in research, education, practice, and policy as well as future objectives for 2015-2020 [1].

1.4 PtD and New Technologies

The prospect of increasing impact of information technologies and others on work organization, tasks, and processes calls for identification and assessing health and safety risks associated with new technologies and for integration of OSH principles in their development [8]. The potential of new technologies to change the nature of work and to affect the work environment may not only bring great opportunities but also health and safety risks. It is therefore helpful to draw on a PtD strategy in that it allows transfer of existing knowledge to new applications and work environments [e.g. 18], consideration of OSH and usability implications early in the design stage while anticipating the life cycle [e.g. 17], and use of technologies themselves for improving OSH in future work place design (e.g. simulating future work processes) [13].

Inclusion of all stakeholders (e.g. engineering, procurement, OSH officials) in the design loop is seen an important factor for conducting successful business [19]. Digital planning information in combination with simulation and visualization techniques assist in creation and progress of new designs, in analysis and assessment of design options and related hazards while being also able to outline future work situations and achievements [20, 21]. Across industry and services sectors activities should result in improved understanding and knowledge of new technologies as well as development of safe and usable design solutions while at the same time demonstrating good practice in PtD.

1.5 Virtual Reality in and for OSH

Simulation techniques such as virtual reality (VR) have been mentioned among new technologies to be addressed as those shaping the future nature of work. However, they also provide a means to analyze, assess and eliminate hazards and risks in applications of new technologies and to develop and apply PtD for new technologies early in design with a focus on usability across the life cycle [13].

Over the past decades, VR has matured into a simulation tool for humans to interact with dynamic, three-dimensional virtual environments and into a methodology for different areas of applications. In industry and services VR allows applied research in human-machine system analysis, design, and evaluation for training, for demonstration, and for visualisation purposes [22]. VR has the potential to better bridge gaps between experimental research and traditional investigations at the shop-floor level while using specific advantages of simulation research [23] and being careful with human, material and financial resources. In addition, VR enables creating scenarios not desirable or too dangerous to face in reality, or providing past, present and future systems in the context of use [24–28]; by that extending the effective range of interventions for PtD. This opened up new perspectives for applications on OSH principles and PtD by fostering prospective rather than corrective accident investigations and hazard and risk assessments early in design.

2 Prevention Through Design by Analysis of Accidents and Near-Misses from a VR Study on Usability of Safety Devices

Occupational accidents including near misses or incidents in industry and services are preventable by conducting effective investigations that identify causal factors and develop actions and that avoid similar events in the future. Conducting accident investigations is challenging and unfortunately, accidents or near misses are not always investigated [29]. This often is due to lack of information about potential causal relationships and knowledge gaps about how, when and what has happened under specific but unknown circumstances. Accident investigations rely on information, methods and procedures, but also draw on experience with similar situations as well as mental simulation and imagination of inspectors conducting assessments.

VR applications have already demonstrated its potential to support accident investigations. By visualizing and reconstructing post-accident scenarios VR provides vivid experiences for inspectors and may trigger reasoning about potential causes [e.g. 30]. Accidental situations were implemented in virtual training scenarios intended to support operators to cope with situations and to learn strategies preventing accidents in the future [e.g. 31]. Though applications of VR for systems design are mainly used to investigate design solutions [24, 32–34], they also provide a basis for generating training scenarios [35], and they may even result in virtually hazardous situations with accidents or near misses eventually going to happen.

In a VR study on the usability of an additional safety measure for mobile elevating work platforms (MEWP) 22 inexperienced and experienced drivers were asked to perform inspection tasks for about 2 h each in an industrial hall [34]. Work scenarios have been developed to allow for close to reality inspections while driving with a MEWP in an industrial hall. They have also be designed to deliberately provoke accidents and near misses by constricting access to work places, reducing illumination of working areas and adding obstacles in the environment. As a consequence, virtual accidents occurred as rare events and accidentally as in reality, i.e. collisions of the MEWP or its driver with objects in the working environment. Some collisions were similar to those already mentioned in accident reports from Germany [27, 36].

Whether and how VR may also be of benefit for investigations of those virtual accidents has been addressed in a subsequent study. In contrast to traditional accident investigations, it was possible to reconstruct and replay work sequences based on data logged during the VR study for events (i.e. collisions) and movements (i.e. controls, MEWP, driver) in the industrial setting. Dynamic visualizations in 3D as reconstructions of MEWP movements in the industrial hall provided insights about time and location of collisions including information about the course of events, directions and speed of the MEWP as well as driver activities. MEWP control movements could be displayed in parallel. As is possible in VR simulations, sequences with accidents could be observed from different points of view such as the MEWP driver or an observer at ground position.

Accident prone locations in the industrial hall have been identified and served further illustration. Among them was an inspection place in mid industrial hall. Once the driver arrived, his/her view was limited to the MEWP platform. Leaving this place with the platform being close to one of the walls (see Fig. 1) occasionally resulted in collisions of the telescopic MEWP or the driver. From an observers point of view it is recognizable that lowering the MEWP platform does not follow a vertical line but circular arc (i.e. downwards and backwards). In this situation for the drivers it is most probably not possible to acquire all information required about relative position, control options and trajectory of the MEWP beam. Imperfect or incomplete information acquisition resulted in erroneous decision making and action implementation. According to dynamic reconstructions of virtual accidents and near misses by VR simulations it has been reasonable to assume impairments of human information processing (e.g. limited perception, complex action implementation for simple trajectory of MEWP beam, task-MEWP misfit) [37, 38]. Additional circumstances such as impaired vision or obstacles may have also affected MEWP movements in this exemplary accident situation.

Simulating the course of events of accidents provided information about when (e.g. first half of a session performing inspection tasks), where (e.g. low inspection place at mid industrial hall), what happened (e.g. MEWP departure from constricted opening of inspection place) with what kind of consequences (e.g. back of the head collides with wall). Information available is advantageous to explore measures for reducing the risk of future accidents by referring to PtD principles. Overall results suggested that VR simulations in close to reality work scenarios can support accident investigations by improving insights into relevant processes and by providing potential explanations.

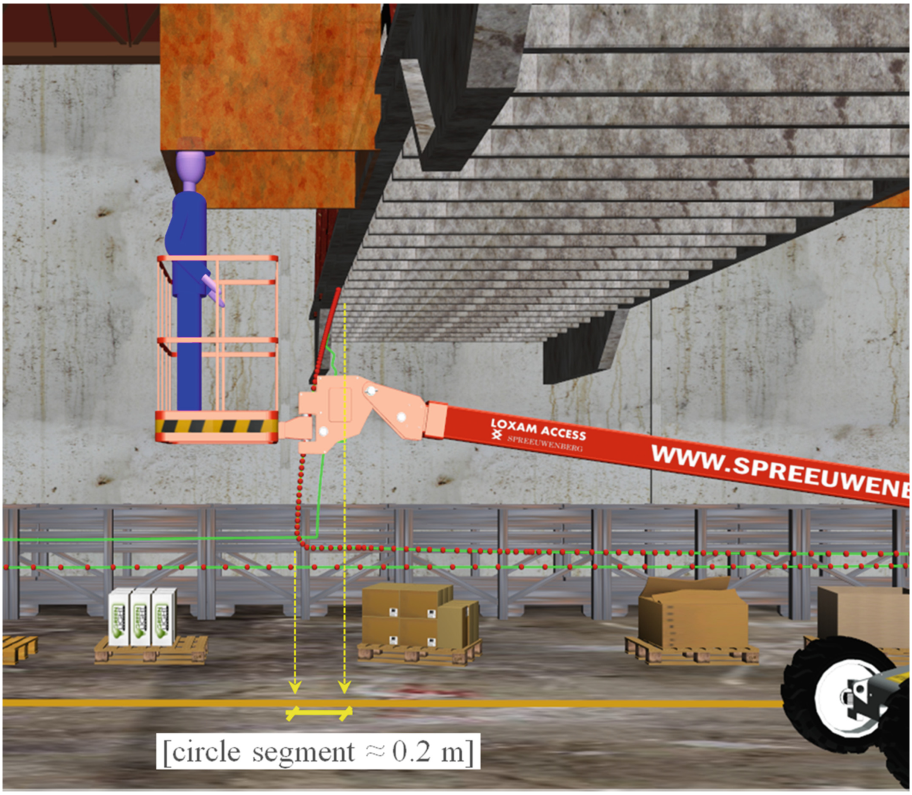

Fig. 1. Accident prone situation in dynamic reconstruction of VR work environment

3 Prevention Through Design by OSH Improvements in Standardisation of Machinery Components

Use and application of standardized components is very common in machinery development and design. Standardized components and elements for prospective tools and machines may for example refer to screws as described in international or national standards (e.g. ISO), bearings of manufacturers having a long reputation for their reliability and quality in engineering industries (e.g. manufacturer standard), and more complex units when giving electric drives priority over hydraulic drives due to application requirements (e.g. company standard). Benefits of standardized components are seen for all types of machinery including special purpose machinery manufacturing. It is no longer necessary to invent new designs and interfaces for these components, to manufacture them separately, to specifically propose procedures for testing functionality and safety requirements, and to develop specific procedures for maintenance. Finding a suitable balance between standardization and individualization, however, often remains a challenge in machinery design.

Recently, the German Federal Ministry of Transport and Digital Infrastructure has given high priority to standardization of machinery components in the context of the some 7,500 km German network of inland waterways. Among many facilities at waterways, river locks are special purpose machinery with several components from mechanical engineering (e.g. gates, inspection safety closings) and construction engineering (e.g. lock chamber, cavern for gate drive). Standardization of river lock components is seen important since it has the potential to simplify the planning process, to speed up the construction process, to draw upon spare capacity for increasing freight transport volumes, to decrease maintenance efforts, to improve OSH, and to reduce costs across the life cycle [39]. An expert group on standardization of river locks has therefore been appointed by the Federal Ministry to identify components yielding good practice in river lock design, operations and maintenance. Most relevant components have already been agreed upon [40] and several are already going to be used for future river lock construction [e.g. 41].

With the PtD perspective, improvements in OSH are seen most effective early in design, because once machinery is built, it should be in service for long and redesign due to safety issues would be resource-demanding, if not impossible, when river lock construction has already been completed. This is where a current research project takes up, aiming at improving OSH for standardized components preferably in the planning stage for a new river lock. Improving OSH has a life cycle perspective in that hazards and risks of standardized components not yet taken into account by the expert group should be assessed. Standardized components should be used for all future river locks in the German network of waterways. The endeavor is challenging because hazard and risk assessment of machinery components itself does not result in machinery safety; i.e. the whole is greater than the sum of the parts. In addition, the future river lock in its future context of use (i.e. life cycle) should be included in OSH assessments; even though it is not yet available.

Assessments for OSH improvements are guided along legal requirements relevant across the life cycle. Hazard and risk documentation requirements according to the EU Construction Site Directive [42] will be supported as it has an impact on machinery operation and maintenance activities. Risk assessments will be performed for the whole machinery according to the EU Machinery Directive [5]. Risk assessments according to the EU OSH Framework Directive [4] will be supported by developing procedures for maintenance activities.

It is possible to draw on experiences already gained in a feasibility study on whether and how to use VR modelling of a river lock extension for risk assessment support according to EU Machinery Directive [5, 43] (see Fig. 2). The current project, however, goes beyond in that it refers to standardized components, to a new river lock, to different types of risk assessments and operational stages as well as to procedure development and documentation support. For VR master planning model development an iterative multi-step procedure has been established and agreed upon [44] based on literature reviews and recommendations from studies in similar contexts [24, 32, 35, 45–48]:

- Clarify and specify purposes for setting up a VR model
- Understand and describe the context of use
- Define and select scenarios

- Select all relevant information and identify the source of information
- Design model components and specify level of detail
- Specify and develop tools for human-system interaction within scenarios
- Merge components, environments, dynamics and interactions into master model
- Evaluate the usability of the VR model
- Apply the VR model for risk assessment support

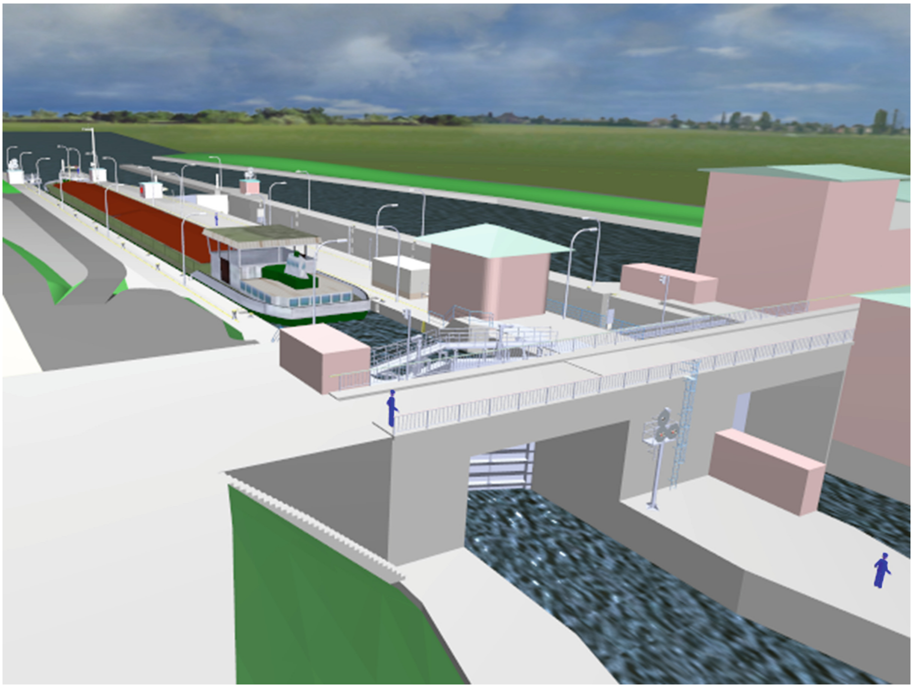

Fig. 2. VR model for risk assessments of a virtual river lock extension in a feasibility study

The procedure presented is specific, as it will result in a VR model for a future river lock with standardized components; however, it is also generic as it can easily be adapted for model development of any other machinery or work system.

The project refers to a new river lock currently under planning (i.e. Wanne-Eickel Nordschleuse) for barges up to 190 m long and 12.5 m wide, replacing an old and smaller one, and using standardized components. Standardized components that may not be included for this river lock under planning will be considered separately in specific versions of the VR master model. Scenarios for river lock operations have already been compiled and documented with further details about machinery components involved and dynamics required for simulation.

Among the most important scenarios are upstream and downstream locking of barges and draining of river lock for chamber and gate maintenance. This is because both scenarios refer to the machinery as a whole, integrate individual activities at different locations at the lock and integrate several other scenarios in the course of events. With a view to EU Machinery Directive [5] it was seen important to start with aft and head of the river lock and to cover mechanical and construction engineering parts of the machinery and their interactions. With a view to the EU OSH Framework Directive [4] it was seen important to focus on maintenance operations with several operators involved (e.g. draining of river lock and gate maintenance) and on safety issues with regard to the lock superstructure (e.g. guard railing, maintenance for lightning and camera systems). Information gathered from both types of risk assessments will also feed safety plan documentation requirements according to the EU Construction Site Directive [42]. With an emphasis on PtD at river locks it is advisable to take a complement approach with regard to risk assessments and design requirements from all EU Directives [4, 5, 42].

4 Discussion and Conclusion

PtD has a long tradition in systems design in industry and services as it is closely connected to safety engineering, ergonomics and human factors. The concept is interwoven with risk assessments and has high priority in the hierarchy of controls. PtD became an OSH initiative and has been established as a strategy for designing out hazards and risks associated with the entire life cycle [1].

Knowledge available and experiences gained by successful PtD should demonstrate how PtD can be achieved and what could be done to put PtD into practice. However, research into PtD is important to transfer and translate scientific findings into practice or to conduct applied research in settings relevant for practice. New modelling and simulation methods such as VR have been suggested when establishing and changing work tasks and processes as well as developing or adjusting related machinery, work equipment and materials [8, 13]. Two VR studies have been chosen to illustrate successful PtD in practical contexts.

In the study on virtual inspection task performance with MEWP it was possible to investigate virtual accidents and near misses that occurred as rare events and similar to those already documented in accident reports in reality. While accident investigations in reality often rely on observations of final consequences of unsafe design only, reconstructions of accidents in VR simulated applications enable insights into the course of events, human system interactions, and potential root causes of the accidents. Thereby, measures for hazard and risk reduction and usability issues can be addressed more specifically, effectively and early in design.

PtD in the VR study on risk assessments of machinery design and maintenance activities is based on original planning information for a future river lock using standardized components. The dynamic VR model in 1:1 scale provides common ground for easy comprehension, imagination and discussions among interdisciplinary inspection teams and supports risk assessments and design reviews by additional VR simulation features. Measures for risk reduction can be developed and fed back in the planning stage of the river lock including its standardized components. The assessments with the VR planning model cannot fully replace those in reality to be conducted when construction is finished or when maintenance activities are due. Assessments of virtual models will, however, ease those for standardized river locks in reality. Besides, some of the hazards and risks will then be already designed out so that they are of no more concern for future human system interaction; avoiding also some redesign and downtimes in future river lock operations.

In the studies presented, VR modeling and simulation has been used as both, new technologies as well as means to enhance safety and health at work, respectively. It could be demonstrated that VR applications are particularly useful when designing safe workplaces and should be further developed [13]. Both applications designed in VR provided support for and illustrated the PtD concept and principles. In addition, by creating scenarios not or not yet available in reality, VR also extended the effective range of interventions for PtD. PtD has the potential to affect prevention culture in that it is proactive in contrast to more traditional and reactive risk management approaches. More PtD research is needed for safe development of technologies, processes and substances during their conception and before their introduction into the market [8].

Since simulations such as in the VR studies are based on modelling of reality with reduced complexity, care must be taken when results from VR simulation studies should be directly applied to practice. Benefits and limitations for successful PtD applications as identified in both VR projects, however, will also hold for other machinery and work systems in industry and services. This provides a sound basis for guiding similar projects along lessons learned and experiences gained in the studies presented.

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